IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF NORTH CAROLINA
Civil Action No.: 7:23-CV-00897

| | |
|---|---|
| IN RE: | ) |
| | ) |
| CAMP LEJEUNE WATER LITIGATION | ) |
| | ) |
| This Pleading Relates to: | ) |
| | ) |
| ALL CASES. | ) |
| | ) |
| | ) |

**PLAINTIFFS' LEADERSHIP GROUP'S MEMORANDUM OF LAW IN SUPPORT OF MOTION TO EXCLUDE CERTAIN OPINIONS OF ALEXANDROS SPILIOTOPOULOS, PH.D.**

Pursuant to Federal Rule of Evidence 702 and *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 609 U.S. 579 (1993), and for the reasons that follow, the Plaintiffs' Leadership Group ("PLG") respectfully moves the Court to exclude certain opinions of Alexandros Spiliotopoulos, Ph.D.

## I. INTRODUCTION AND RELIEF SOUGHT

This motion seeks an order excluding certain opinions of Alexandros Spiliotopoulos, Ph.D., a hydrogeologist employed by S.S. Papadopulos & Associates (SSPA) who was hired by the U.S. Department of Justice (DOJ) to critique Plaintiffs' expert reports regarding groundwater contamination at Camp Lejeune. [Ex. 1, Spiliotopoulos Deposition at 152:20-22 ("My work here is only to critique the quality of the modeling work and outcome of that modeling."); 188:16-18]

Although Plaintiffs take issue with all of Dr. Spiliotopoulos's opinions, Plaintiffs have filed – consistent with the case law – a targeted motion, and will employ cross examination to address the remainder of their disagreements. Plaintiffs move to exclude Dr. Spiliotopoulos's opinions

regarding:

- ATSDR's uncertainty and sensitivity analyses [Ex. 2, Spiliotopoulos Report, at 48-55; 87-92]
- Section 3.3 of Dr. Spiliotopoulos's report, titled "Timeline and Scientific Discourse on ATSDR's Camp Lejeune Water Modeling" [Ex. 2, Spiliotopoulos Report, at 16-24]
- ATSDR's intent and purpose with respect to conducting its water modeling [Ex. 2, Spiliotopoulos Report, at 18-20, 23, 25]
- How ATSDR's modeling results can or should be used by epidemiologists, doctors, or public health professionals [Ex. 2, Spiliotopoulos Report, at 25]
- ATSDR's modeling approaches that were allegedly "cutting-edge" and/or still in the research stages [Ex. 2, Spiliotopoulos Report, at 21, 26-27]
- Contaminant losses during treatment [Ex. 2, Spiliotopoulos Report, at 30]
- PCE source release start date at ABC One-Hour Cleaners [Ex. 2, Spiliotopoulos Report, at 36]
- "Erroneous" HP-634 concentration data [Ex. 2, Spiliotopoulos Report, at 80]

## II. LEGAL STANDARD

Expert testimony is admissible only if the expert is qualified, the testimony is relevant, and the testimony is based on reliable scientific methodology. *Daubert v. Merrell Dow Pharms, Inc*., 509 U.S. 579, 594-95 (1993); Fed. R. Evid. 702. Factors that guide the reliability analysis may include: (1) whether a theory or technique can be (or has been) tested; (2) whether it has been subjected to peer review and publication; (3) its potential rate of error; (4) whether standards exist to control the technique's operation; and (5) the degree of acceptance of the methodology within the relevant scientific community. *Daubert*, 509 U.S. at 593-94; *Nix v. Chemours Co. FC*, No. 7:17-CV-189-D, 7:17-CV-197-D, 7:17-CV-201-D, 2023 WL 6471690, at *7 (E.D.N.C. Oct. 4, 2023). The objective of the reliability requirement is to "make certain that an expert, whether basing testimony upon professional studies or personal experience, employs in the

courtroom the same level of intellectual rigor that characterizes the practice of an expert in the relevant field." *Kumho Tire Co., Ltd. v. Carmichael*, 526 U.S. 137, 152 (1999). Responsive and rebuttal experts are obligated to demonstrate that they used reliable methodology both in forming their opinions and in critiquing those of Plaintiffs' experts. *In re Ethicon Inc. Pelvic Repair Systems Prod. Liab. Litig.*, MDL No. 2327, 2018 WL 11245148, *3 (S.D. W.Va. July 26, 2018); *see also Funderburk v. South Carolina Elec. & Gas Co*., 395 F.Supp.3d 695, 716-17 (D.S.C. 2019). As the proponent of Dr. Spiliotopoulos's testimony, DOJ has the burden of showing it to be reliable. Fed. R. Evid. 702 (requiring proponent to demonstrate "to the court that it is more likely than not" that, *inter alia*, "the testimony is the product of reliable principles and methods").

Another factor that courts consider in the reliability analysis is whether the expert developed his opinions expressly for the purpose of testifying. *Daubert v. Merrell Dow Pharms, Inc*., 43 F.3d 1311, 1317 (9th Cir. 1995) ("One very significant fact to be considered is whether the experts are proposing to testify about matters growing naturally and directly out of research they have conducted independent of the litigation, or whether they have developed their opinions expressly for purposes of testifying."); Fed. R. Evid. 702, Advisory Comm. Notes (2000 Amendments); *Kadel v. Folwell*, 620 F.Supp.3d 339, 361 (M.D.N.C. 2022). "An 'expert' opinion is considered unreliable and inadmissible under *Daubert* where ... the expert has developed the opinions expressly for purposes of testifying in the case ...." *Wehling v. Sandoz Pharm. Corp*., 162 F.3d 1158, at *5 (4th Cir. 1998) (unpublished).

## III. QUALIFICATIONS OF DR. SPILIOTOPOULOS

Dr. Spiliotopoulos holds no professional licenses or certifications. He is not a licensed professional engineer or a licensed geologist. [Ex. 1, Spiliotopoulos Deposition, at 14:13-15:13] He has published only two articles in the peer-reviewed literature. *Id*. at 24:23-25:1. He has never

served on, or been invited to serve on, any expert peer review panel or the editorial board for any professional publication. *Id*. at 18:14-19; 22:12-23:4. This is the first time he has served as an expert in a litigation matter. *Id*. at 7:19-23.

All of Dr. Spiliotopoulos's professional work related to Camp Lejeune has been done for the purpose of litigation. *Id*. at 118:15-20; 120:8-17. He has not published in the literature or presented at any conferences regarding Camp Lejeune. *Id*. at 23:15-17; 25:17-19. In 2005, Dr. Spiliotopoulos, who was employed by SSPA at the time, attended the ATSDR's Expert Peer Review Panel on ATSDR's Historical Reconstruction Analysis, Camp Lejeune, North Carolina, as an observer. *Id*. at 120:25-121:2. Dr. Spiliotopoulos attended this two-day Peer Review Panel at the request of his supervisors at SSPA, including Dr. Remy Hennet, the DOJ's other retained expert on ATSDR's modeling. *Id*. at 115:8-21; 123:21-24. The Expert Peer Review Panel was held by ATSDR during the time frame that it was actively performing modeling in order to solicit feedback from the pertinent scientific community regarding its methodology. *Id*. at 121:15-122:13; 165:2-166:12; 170:12-171:2. Dr. Spiliotopoulos did not, during the two-day meeting or at any time thereafter, offer any advice, critique, or constructive feedback to ATSDR. *Id*. at 121:15-19; 122:21-125:20. The DOJ insists that all of Dr. Spiliotopoulos's and Dr. Hennet's work related to Camp Lejeune for the past twenty years has been performed for or in anticipation of litigation. DE-354 at 12-13; Ex. 3, 4/21/25 DOJ Letter, at 3.

## IV. ARGUMENT

### A. Dr. Spiliotopoulos's Opinions related to ATSDR's Uncertainty and Sensitivity Analyses are Unreliable and should be Excluded.

As an initial matter, there is no heightened admissibility standard or burden of proof for the uncertainty analysis in this case. Without citation to any authority, Dr. Spiliotopoulos asserts that "when models are used for hindcasting or forecasting conditions that are directly translated to

substantially more important decisions, such as health impacts, the implications of model uncertainty have to be viewed more critically." [Ex. 2, Spiliotopoulos Report, at 28] Here, Dr. Spiliotopoulos is comparing the use of models to determine historical contaminant levels such as at Camp Lejeune to "the evaluation of the nature and extent of contamination and/or design of a system for containing a contaminant plume, aquifer restoration to certain cleanup standards, or evaluation of ultimate fate and transport of a contaminant plume." *Id*. The purpose of cleanup and containment is to protect human health and the environment from toxic exposures. Dr. Spiliotopoulos's proposition, without explanation or authority, of a heightened standard for the evaluation of model uncertainty for Camp Lejeune is insupportable and should be rejected.

Dr. Spiliotopoulos's opinions critiquing the uncertainty and sensitivity analyses conducted by ATSDR for Tarawa Terrace and Hadnot Point are not reliable. Dr. Spiliotopoulos fails to identify the standard or methodology that he is applying or that he believes ATSDR should have used. He cites no peer-reviewed literature or other authorities in support of his critiques of ATSDR's methodology. In addition, his criticisms of the Tarawa Terrace and Hadnot Point analyses are contradictory, and he fails to apply the same standards he uses in his non-litigation work to his opinions here.

For its uncertainty analysis for Tarawa Terrace, ATSDR employed a Monte Carlo simulation approach to conduct a probabilistic analysis to provide a range of possible model outcomes. ATSDR selected the most sensitive and uncertain parameters to use in its Monte Carlo analysis using the results from its sensitivity analyses. [Ex. 4, Chapter I, Parameter Sensitivity, Uncertainty and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport and Distribution of Drinking Water, at I31]. Probability density functions (PDFs) for model input parameters for the Monte Carlo analysis were derived from the

use of an algorithm (PRNG, or Pseudo-Random Number Generator). The identification and justification for the mean, minimum, maximum and standard deviation values used to generate the PDFs are described in detail by ATSDR, including with citation to literature, as appropriate. *Id*. at I37-I42. For example, ATSDR explained how and why it chose the minimum and maximum values for the distribution coefficient, bulk density, and effective porosity. *Id*. at I37. The use of a probability density function "is an option within standard practice for random sampling of parameter values for a MC [Monte Carlo] analysis when information or theory indicates that a parameter has a statistically normal or log-normal distribution." [Ex. 5, Konikow Rebuttal Report, at 16, citing Zheng & Bennett, Applied Contaminant Transport Modeling (2nd ed. 2002)].[1]

Without citation to authority of any kind, Dr. Spiliotopoulos criticizes the parameter ranges used by ATSDR for its Tarawa Terrace uncertainty analyses, claiming they are "narrow and biased." [Ex. 2, Spiliotopoulos Report, at 48] However, later in his report, when Dr. Spiliotopoulos turns to criticizing ATSDR's sensitivity and uncertainty analyses for Hadnot Point, he states that "for the Tarawa Terrace uncertainty analysis, ATSDR defined *reasonable ranges* for the calibrated parameter values." *Id*. at 87 (emphasis added). Moreover, earlier in his report, Dr. Spiliotopoulos criticizes ATSDR's Tarawa Terrace work on the grounds that "ATSDR selected a range of acceptable values for key parameters … for their uncertainty analysis based solely on professional judgment and literature sources." *Id*. at 52. Then later in the report, Dr. Spiliotopoulos appears to change course again and endorse the Tarawa Terrace methodology: "Recall that in the Tarawa Terrace model, ATSDR defined a range of values for transport parameters based on literature

[1] Dr. Konikow quotes Zheng & Bennett as follows: "The Monte Carlo method is by far the most commonly used method for analysis of uncertainty associated with complex numerical methods." (at page 353) "The heart of the Monte Carlo method is the generation of multiple realizations (or samples) of input parameters that are considered to be random variables. Each random variable is assumed to follow a certain probabilistic model characterized by its probability density function (PDF)." Ex. 5, Konikow Rebuttal Report, at 16.

sources and professional judgment. ATSDR proceeded with defining probabilistic distributions of these parameters, to calculate parameter values for the uncertainty analysis." *Id*. at 88. He then states: "For the Hadnot Point model, ATSDR did not conduct such an analysis for defining appropriate parameter ranges. Instead, ATSDR selected extreme values for the fate and transport parameters, corresponding to the 2.5 and 97.5 percentile of the parameter range." *Id*. While ATSDR identifies, explains, and applies consistent methodology, Dr. Spiliotopoulos does nothing more than disagree with ATSDR in an inconsistent and unsupported fashion.

According to Dr. Spiliotopoulos, there is no standard or guideline for how an uncertainty analysis for groundwater flow and contaminant transport should be done. [Ex. 1, Spiliotopoulos Deposition at 98:16-21] Similarly, Dr. Spiliotopoulos testified that there is no standard or guideline for how to conduct a sensitivity analysis; rather, "[t]his is something you evaluate on a case-by-case basis." *Id*. at 99:13-19. Plaintiffs disagree that no standards exist, but note that Dr. Spiliotopoulos, in making these statements, admits that his opinions are subjective – based on a criteria along the lines of "he knows it when he sees it."

Dr. Spiliotopoulos also fails to apply the same standards he uses in his non-litigation work to his opinions here. He was the lead modeler at the Hanford site, where plutonium was enriched in the 1940s as part of the Manhattan project, to develop a groundwater flow and contaminant transport model for a chromium 6 contaminant plume. [Ex. 1, Spiliotopoulos Deposition at 67:20-68:25; 328:24 (describing Hanford as "one of the most high profile" projects he has worked on in his career)] He used the model to develop a remedial optimization process design to achieve river protection and aquifer cleanup goals, including the decision to drill 70 extraction and injection wells. *Id*. at 78:14-17; 80:18-81:9; 91:13-20. For this model, and for this decision-making process, he performed a limited uncertainty analysis – for hydraulic conductivity (flow), but not for

contaminant transport. *Id*. at 85:22-87:7. He did not perform an uncertainty analysis or history matching regarding his model's chromium 6 predictions because he had "very limited data." *Id*. at 86:8-87:7. Dr. Spiliotopoulos criticized the uncertainty analysis for Hadnot Point as being limited to the effects of historical pumping variability, *id*. at 91-92; yet the uncertainty analysis for Hanford was at least as limited. And there is no indication that the parameter range used for Hanford met the not-too-narrow and not-too wide standard applied by Dr. Spiliotopoulos here.

Dr. Spiliotopoulos's opinions critiquing ATSDR's methodology fail all of the *Daubert* factors: his theory or technique has not been tested; it has not been subject to peer review; the error rate is unknown; he claims no relevant standards exist and therefore has applied none here; and he has pointed to nothing that indicates that his theory has been accepted or endorsed by the relevant scientific community. In the absence of pre-litigation research or peer review, it is imperative that an expert "point to some objective source – a learned treatise, the policy statement of a professional association, a published article in a reputable scientific journal or the like – to show that they have followed the scientific method, as it is practiced by (at least) a recognized minority of scientists in their field." *Daubert*, 43 F.3d at 1318-19. Dr. Spiliotopoulos has failed to point to any external source to validate his "methodology."

Significantly – and especially in contrast to the ATSDR, which performed nearly a decade of modeling work for Camp Lejeune entirely independent of any litigation – *all* of the work Dr. Spiliotopoulos has done to form his opinions in this case was done for or in anticipation of litigation, *i.e*., "expressly for the purpose of testifying." *Daubert*, 43 F.3d at 1317. Moreover, Dr. Spiliotopoulos has not applied the same standards here as he uses in his non-litigation work. *See Kumho Tire*, 526 U.S. at 152. This, in combination with the five other *Daubert* factors bearing on reliability, weighs in favor of excluding Dr. Spiliotopoulos's opinions regarding the ATSDR's

uncertainty and sensitivity analyses.

The deficits in Dr. Spiliotopoulos's methodology are similar to the concerns expressed by the Supreme Court regarding the tire expert's methodology in *Kumho Tire*. As in *Kumho Tire,* Dr. Spiliotopoulos's mode of analysis is subjective. *See Kumho Tire,* 526 U.S. at 155. Nowhere does he explain how he can differentiate between an acceptable and unacceptable uncertainty and sensitivity analysis. *See id*. According to Dr. Spiliotopoulos, the range of parameters was too narrow for Tarawa Terrace and too wide for Hadnot Point, but he never says what an appropriate range is (*i.e*., what would be just right), or how ATSDR was supposed to know this (*i.e*., no standard, literature or other method has been identified). As in *Kumho Tire*, Dr. Spiliotopoulos has failed to identify other experts who use his range-of-parameter test or who make the fine distinctions he is making here to support his conclusions. *See id*. at 157 ("We have found no indication in the record that other experts in the industry use Carlson's two-factor test or that tire experts such as Carlson normally make the very fine distinctions about, say, the symmetry of comparatively greater shoulder tread wear that were necessary, on Carlson's own theory, to support his conclusions"). As in *Kumho Tire*, despite the prevalence of water modeling, Dr. Spiliotopoulos does not cite to any articles or papers that validate his approach. *See id*. ("Nor, despite the prevalence of tire testing, does anyone refer to any articles or papers that validate Carlson's approach.").

Dr. Spiliotopoulos's critique of ATSDR's uncertainty and sensitivity analyses was crafted at the DOJ's request for purposes of litigation and is not based on a reliable scientific methodology. He has not published in the peer-reviewed literature on this subject. His report does not cite to such literature, standards, or any other authority in his field in support of his criticisms. Rather, Dr. Spiliotopoulos's opinions are classic *ipse dixit* and should be excluded. *See General Elec. Co. v.*

*Joiner*, 522 U.S. 136, 146 (1997) ("nothing in either *Daubert* or the Federal Rules of Evidence requires a district court to admit opinion evidence that is connected to existing data only by the *ipse dixit* of the expert."); *Small v. WellDyne, Inc*., 927 F.3d 169, 177 (4th Cir. 2019) ("Without testing, supporting literature in the pertinent field, peer reviewed publications or some basis to assess the level of reliability, expert opinion testimony can easily, but improperly, devolve into nothing more than proclaiming an opinion is true "because I say so.")

**B. Factual Narratives and Opinions Disclaimed by Dr. Spiliotopoulos should be Excluded.**

**1. The narrative timeline should be excluded.**

Section 3.3 of Dr. Spiliotopoulos's report, titled "Timeline and Scientific Discourse on ATSDR's Camp Lejeune Water Modeling" [Ex. 2, Spiliotopoulos Report, at 16-24] is a single-spaced, nine-page narration that includes more than twenty-five bullet points of favorable lengthy quotes from documents, lawyer arguments, and opinions that Dr. Spiliotopoulos disavowed during his deposition. Dr. Spiliotopoulos's summary of events, narration of select documents, and opinions on the intent, motive or state-of-mind of third parties are not proper topics of expert testimony and should be excluded.

For example, although Dr. Spiliotopoulos's timeline includes citations and quotes from epidemiology studies regarding Camp Lejeune, Dr. Spiliotopoulos testified that he has not read any such studies. [Ex. 2, Spiliotopoulos Report, at 24; Ex. 1, Spiliotopoulos Deposition, at 151:13-152:13] As set forth below, the timeline includes quotations and opinions regarding ATSDR's intent and purpose regarding its modeling; how the modeling can or should be used by health experts; and alleged "cutting-edge" methods used by ATSDR, all of which Dr. Spiliotopoulos

testified he is not opining on and/or are not relevant to his opinions.[2]

Factual narratives in expert reports that are divorced from expert opinions (or as in this case even knowledge) are inadmissible. *City of Huntington v. Amerisourcebergen Drug Corp*., No. 3:17-01362, 2021 WL 1436672, at *3 (S.D. W.Va. April 15, 2021); *In re Davol, Inc./C.R. Bard, Inc., Polypropylene Hernia Mesh Prod. Liab. Litig.,* 546 F.Supp.3d 666, 677-79 (S.D. Ohio 2021) (excluding testimony based on portions of report that do not analyze, contextualize, or interpret pertinent historical recounting but rather amount to quoting uncomplicated and/or straightforward documents). The PLG requests that Dr. Spiliotopoulos be precluded from document narration with no application of expertise and from opining on the subject matters set forth in the timeline in Section 3 of his expert report.

**2. Opinions regarding ATSDR's intent and purpose should be excluded.**

Dr. Spiliotopoulos's report includes opinions regarding ATSDR's intent and purpose with respect to conducting its water modeling, including that "the water modeling was intended to support an epidemiological study and not for the purpose of making exposure assessments in individuals." [Ex. 2, Spiliotopoulos Report, at 23; *see also* 18-20, 25] However, Dr. Spiliotopoulos testified that whether ATSDR's modeling has in fact been used to make exposure assessments in individuals is not relevant to his opinions. [Ex. 1, Spiliotopoulos Deposition at 152:15-153:9; 154:1-10] In any event, expert testimony regarding motive, intent and state of mind is not admissible for multiple reasons, including that it is speculative and unhelpful to the finder of fact.

[2] This testimony, combined with several citations within the report to publications from the National Judicial College [Harter, et al. (2018) *Adjudicating Groundwater: A Judge's Guide to Understanding Groundwater and Modeling*. Reno, NV: National Judicial College (cited 3 times); National Judicial College and Dividing the Waters (2010) Hydrologic Modeling Benchbook], raises questions as to who wrote certain portions of Dr. Spiliotopoulos's report. Despite requests from PLG, DOJ has not produced time records that would allow PLG and this Court to adduce the amount of time spent by Dr. Spiliotopoulos writing his report. DE-354 at 5-7; 11-12.

*City of Huntington v. Amerisourcebergen Drug Corp*., No. 3:17-01362, 2021 WL 1320716, at *2-3 (S.D. W.Va. April 8, 2021); *In re Ethicon Inc. Pelvic Repair Systems Prod. Liab. Litig.*, MDL No. 2327, 2018 WL 11245148, *5 (S.D. W.Va. July 26, 2018).

**3. Dr. Spiliotopoulos lacks qualifications to opine on the use of modeling results by health professionals.**

Dr. Spiliotopoulos is not a doctor, epidemiologist, or public health expert. He has never worked on a project that had as its goal determining or measuring human exposure to contaminants. [Ex. 1, Spiliotopoulos Deposition at 67:9-12] He has not read any of the epidemiological studies regarding Camp Lejeune. *Id*. at 151:13-152:13. He testified that whether ATSDR's modeling was used to make exposure assessments in individuals is not relevant to his opinions. *Id*. at 152:15-153:9. He has no experience or expertise that qualifies him to offer an opinion as to whether or how a health professional can or should use ATSDR's modeling results to assess individual exposures to contaminants or to conduct an epidemiological study, and any such opinion should be excluded. *See, e.g., Cooper v. Lab. Corp. of Am. Holdings, Inc.*, 150 F.3d 376, 380-81 (4th Cir. 1998) (finding that a witness who had a "general knowledge of chemistry" and "experience with breath alcohol testing" was not an expert "in the field of urine alcohol testing"); *Kadel v. Folwell*, 620 F.Supp.3d 339, 360 (M.D.N.C. 2022) ("'General knowledge,' skill, experience, training or education is insufficient to qualify an expert, and an expert qualified in one field may be unqualified to testify in others.").

4. **Disclaimed opinion on "cutting-edge" modeling methods should be precluded.**

Dr. Spiliotopoulos's report references modeling approaches of ATSDR that allegedly were "cutting-edge" and/or still in the research stages. [*E.g*., Ex. 2, Spiliotopoulos Report, at 21, 26-27] When asked at deposition to identify these modeling techniques, he testified: "That's not part of the opinions that I provide. So I don't have an opinion on that." [Ex. 1, Spiliotopoulos

Deposition at 147:14-148:7] Therefore, Dr. Spiliotopoulos should be precluded from offering the opinion at any hearing or trial of this matter that any of ATSDR's modeling methodologies were cutting-edge or still in the research stages.

### C. Parroted Opinions of Other Experts should be Excluded.

#### 1. Dr. Spiliotopoulos should be precluded from offering Dr. Hennet's opinions regarding contaminant losses during treatment.

Dr. Spiliotopoulos offers the opinion that "ATSDR ignored any contaminant losses that would occur during treatment." [Ex. 2, Spiliotopoulos Report, at 30; 68 n.235] At deposition, Dr. Spiliotopoulos testified that he did not perform any calculations related to this opinion and that he is relying on the calculations and opinions of Dr. Hennet for this opinion. [Ex. 1, Spiliotopoulos Deposition at 192:19-193:10] Expert opinions that merely parrot or regurgitate another expert's opinion with no additional findings,[3] like Dr. Spiliotopoulos's opinion here, are not helpful or admissible. *Funderburk v. South Carolina Elec. & Gas Co*., 395 F.Supp.3d 695, 721-22 (D.S.C. 2019) (excluding repeated opinion of another expert where no additional corroboration, validation, or explanation was provided); *In re Davol, Inc./C.R. Bard, Inc., Polypropylene Hernia Mesh Prod. Liab. Litig.,* 546 F.Supp.3d 666, 676 (S.D. Ohio 2021).

#### 2. Dr. Spiliotopoulos should be precluded from offering Dr. Brigham's opinion regarding the source release start date at ABC One-Hour Cleaners.

Dr. Spiliotopoulos offers the opinion that "The PCE Source Release Start Date at ABC One-Hour Cleaners Was Incorrect," but he testified that he relies entirely on the DOJ's retained historian Dr. Brigham for "the foundation for supporting this argument." [Ex. 2, Spiliotopoulos Report, at 36; Ex. 1, Spiliotopoulos Deposition, at 222:22-223:18] This is an additional parroting

[3] Plaintiffs do not dispute that Dr. Spiliotopoulos may rely on the opinion of another expert such as Dr. Hennet assuming it would be appropriate to do so in his field, but take issue with Dr. Spiliotopoulos offering this opinion as his own with no additional corroboration, validation or explanation.

of another expert's opinion that the Court should exclude.[4] *See Funderburk*, 395 F.Supp.3d at 721-22; *Davol*, 546 F.Supp.3d at 676.

**D. Dr. Spiliotopoulos's Results-Driven Opinion regarding HP-634 Concentration Data should be Excluded.**

Relying primarily on Dr. Hennet's report,[5] Dr. Spiliotopoulos opines that a sample collected on January 16, 1985, at well HP-634 with a measurement of 1,300 ug/L TCE "should be considered erroneous." [Ex. 2, Spiliotopoulos Report, at 80] Other than reliance on Dr. Hennet, the sum total of Dr. Spiliotopoulos's analysis in support of this opinion is that HP-634 is upgradient from two contaminant sources that were near the well, "therefore, contamination could not have reached that well when it was not operational,"[6] and that there was a non-detection when the well was sampled on December 4, 1984, when it was operational. *Id*.

Dr. Spiliotopoulos's bare-bones analysis is not based on sufficient facts or data, nor is it the product of reliable principles and methods. Fed. R. Evid. 702. Dr. Spiliotopoulos did not perform any calculations or provide any measurements in support of his assertion that "contamination could not have reached that well when it was not operational." While the well was operational, a cone of depression would have formed around it, which results in the movement of water and contaminants from nearby areas towards the well. [Ex. 5, Konikow Rebuttal Report, at 22] This is demonstrated at Figure A19, where, as of November 1984, TCE is shown to have moved very close to Well 634 from its previous location in the industrial area in all three model layers, and specifically, in Model Layer 3, the TCE plume is coincident with the location of well

[4] Plaintiffs do not dispute that Dr. Spiliotopoulos may rely on the opinion of another expert such as Dr. Brigham assuming it would be appropriate to do so in his field, but take issue with Dr. Spiliotopoulos offering this opinion as his own with no additional corroboration, validation or explanation.
[5] Dr. Spiliotopoulos concludes his analysis on this issue by stating: "See Dr. Hennet's expert report for a more detailed discussion of this issue." Ex. 2, Spiliotopoulos Report, at 80.
[6] Plaintiffs dispute that HP-634 was not operational on January 16, 1985. See Ex. 6, Maslia Rebuttal Report, at 19-23.

HP-634. *Id*. at 22-23. If HP-634 had been shut down as of January 16, 1985, which Plaintiffs do not concede, there would have been a slow recovery period, during which water and contaminants would continue to move toward well HP-634. *Id*. Dr. Spiliotopoulos provides no calculations, evidence, or explanation as to why the contaminants could not have reached HP-634 during the short time frame after it was allegedly shut down until January 16, 1985. Nor has Dr. Spiliotopoulos explained the relatively high levels of DCE and VC in the same sample, which refute the 1,300 ug/L TCE measurement being an isolated "outlier." *Id*.

The non-detect measurement from December 4, 1984 also does not support Dr. Spiliotopoulos's assertion. The value of contaminants measured at Camp Lejeune changed by similarly large magnitudes at other wells in short time frames. For example, the value of PCE at TT-26 changed from 1580 to 3.8 ug/L in successive samples taken 4 weeks apart, mirroring the change at HP-634 from non-detect to 1,300 ug/L in a similar 4-week time frame. *Id*. This variability in sampling data is characteristic of groundwater-quality data and is expected at sites like Camp Lejeune.

Dr. Spiliotopoulos's labeling of the 1300 ug/L sample as "erroneous" without the identification of a reliable methodology, performance of any calculations or measurements, or citation to authority is speculative and unreliable and is the sort of cherry-picking of data that the Fourth Circuit rejects. "Result-driven analysis, or cherry-picking, undermines principles of the scientific method and is a quintessential example of applying methodologies (valid or otherwise) in an unreliable fashion. '[C]ourts have consistently excluded expert testimony that 'cherry-picks' relevant data,' because such an approach 'does not reflect scientific knowledge, is not derived by the scientific method, and is not 'good science.'" *In re Lipitor*, 892 F.3d 624, 634 (4th Cir. 2018) (citations omitted).

To the extent that Dr. Spiliotopoulos relies on Dr. Hennet's opinion here, simultaneously with the filing of this motion the PLG has filed a motion to exclude Certain Opinions of Dr. Remy Hennet, including his opinions regarding HP-634, and the PLG incorporates that analysis into this memorandum. In addition, Dr. Spiliotopoulos should not be permitted to merely parrot or regurgitate Dr. Hennet's opinions with no additional reliable findings. *See Funderburk*, 395 F.Supp.3d at 721-22; *Davol*, 546 F.Supp.3d at 676.

## CONCLUSION

For the foregoing reasons, the PLG respectfully requests the Court to exclude the opinions discussed herein offered by Alexandros Spiliotopoulos, Ph.D.

*[Signature page to follow.]*

DATED this 29th day of April 2025.


*/s/ J. Edward Bell, III*
J. Edward Bell, III (admitted *pro hac vice*)
Bell Legal Group, LLC
219 Ridge St.
Georgetown, SC 29440
Telephone: (843) 546-2408
jeb@belllegalgroup.com

*Lead Counsel for Plaintiffs*

*/s/ Zina Bash*
Zina Bash (admitted *pro hac vice*)
Keller Postman LLC
111 Congress Avenue, Suite 500
Austin, TX 78701
Telephone: 956-345-9462
zina.bash@kellerpostman.com

*Co-Lead Counsel for Plaintiffs and Government Liaison Counsel*

*/s/ Elizabeth J. Cabraser*
Elizabeth J. Cabraser (admitted *pro hac vice*)
Lieff Cabraser Heimann & Bernstein, LLP
275 Battery Street, 29th Floor
San Francisco, CA 94111
Telephone: (415) 956-1000
*ecabraser@lchb.com*

*Co-Lead Counsel for Plaintiffs*

*/s/ W. Michael Dowling*
W. Michael Dowling (NC Bar No. 42790)
The Dowling Firm PLLC
Post Office Box 27843
Raleigh, North Carolina 27611
Telephone: (919) 529-3351
mike@dowlingfirm.com

*Co-Lead Counsel for Plaintiffs*

*/s/ Robin L. Greenwald*
Robin L. Greenwald (admitted *pro hac vice*)
Weitz & Luxenberg, P.C.
700 Broadway
New York, NY 10003
Telephone: 212-558-5802
rgreenwald@weitzlux.com

*Co-Lead Counsel for Plaintiffs*

*/s/ James A. Roberts, III*
James A. Roberts, III
Lewis & Roberts, PLLC
3700 Glenwood Ave., Ste. 410
Raleigh, NC 27612
Telephone: (919) 981-0191
jar@lewis-roberts.com

*Co-Lead Counsel for Plaintiffs*

*/s/ Mona Lisa Wallace*
Mona Lisa Wallace (N.C. Bar No.: 009021)
Wallace & Graham, P.A.
525 North Main Street
Salisbury, North Carolina 28144
Tel: 704-633-5244
mwallace@wallacegraham.com

*Co-Lead Counsel for Plaintiffs*

**CERTIFICATE OF SERVICE**

I, J. Edward Bell, III, hereby certify that the foregoing document was electronically filed on the Court's CM/ECF system on this date, and that all counsel of record will be served with notice of the said filing via the CM/ECF system.

This the 29th day of April 2025.

*/s/ J. Edward Bell, III*

J. Edward Bell, III

**IN THE UNITED STATES DISTRICT COURT**
**FOR THE EASTERN DISTRICT OF NORTH CAROLINA**
**SOUTHERN DIVISION**
**Civil Action No.: 7:23-CV-897**

| | |
|---|---|
| IN RE: | ) |
| | ) |
| CAMP LEJEUNE WATER LITIGATION | ) |
| | ) |
| This Pleading Relates to: | ) |
| | ) |
| ALL CASES. | ) |
| | ) |
| | ) |

**TABLE OF EXHIBITS**
**IN SUPPORT OF PLAINTIFFS' MOTION TO EXCLUDE CERTAIN OPINIONS OF ALEXANDROS SPILIOTOPOULOS, PH.D.**

Ex. 1 – March 18, 2025 Deposition of Alexandros Spiliotopoulos, PhD

Ex. 2 – December 9, 2024 Expert Report of Alexandros Spiliotopoulos, PhD

Ex. 3 – April 21, 2025 DOJ Letter to PLG

Ex. 4 – ATSDR Tarawa Terrace Reconstruction, Chapter I: Parameter Sensitivity, Uncertainty and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport and Distribution of Drinking Water

Ex. 5 – January 13, 2025 Expert Rebuttal Report of Leonard Konikow, PhD

Ex. 6 – January 14, 2025 Expert Rebuttal Report of Morris Maslia, PE

# EXHIBIT 1

IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF NORTH CAROLINA
SOUTHERN DIVISION
NO. 7:23-CV-897

IN RE: )
)
CAMP LEJEUNE WATER LITIGATION )
)
)
This Document Relates to: )
ALL CASES )
_____)

VIDEOTAPED DEPOSITION OF

ALEXANDROS SPILIOTOPOULOS, PH.D.,

a witness herein, called by the Plaintiffs for examination, taken by and before Ann Medis, RPR, CLR, CSR-WA, and Notary Public in and for the Commonwealth of Pennsylvania, via Zoom Videoconference, at the offices of Department of Justice Civil Litigation 1100 L Street NW, Washington, DC 20005, on Tuesday, March 18, 2025, commencing at 9:22 a.m.

A P P E A R A N C E S

On behalf of Plaintiff

WEITZ & LUXENBERG, P.C.
BY: LAURA J. BAUGHMAN, ESQUIRE
DEVIN BOLTON, ESQUIRE
700 Broadway
New York, New York 10003
212.558.5915
lbaughman@weitzlux.com
dbolton@weitzlux.com

On behalf of Defendant United States of America

U.S. DEPARTMENT OF JUSTICE
BY: HAROON ANWAR, ESQUIRE
KAILEY SILVERSTEIN, ESQUIRE
GIOVANNI ANTONUCCI, ESQUIRE
1100 L Street NW
Washington, DC 20005
202.552.9843
haroonanwar@usdog.gov

Also present via Zoom

Jeff Davis
Allison O'Leary
Deanna Havai
Leonard Konikow
Morris Maslia
Remy Hannet

April Carter, videographer

* I N D E X *



* INDEX OF SPILIOTOPOULOS EXHIBITS *



kkkk

* INDEX OF SPILIOTOPOULOS EXHIBITS (Continued) *



- - - -

P R O C E E D I N G S

- - - -

THE VIDEOGRAPHER: We are now on the record. My name is April Carter. I'm a videographer for Golkow. Today's date is March 18, 2025, and the time is 9:22 a.m. This video deposition is being held at 1100 L Street Northwest, Washington, D.C. 20005, in the matter of In Re: Camp LeJeune Water Contamination, for the Court of the Eastern District of North Carolina. The deponent is Alexandros Spilotopoulos.

Will counsel please identify themselves, in-person counsel please identify themselves for the record.

MS. BAUGHMAN: Laura Baughman from Weitz & Luxenberg for the plaintiffs.

MS. BOLTON: Devin Bolton for the plaintiffs.

MR. ANWAR: Haroon Anwar for the United States.

MR. ANTONUCCI: Giovanni Antonucci for the United States.

MS. SILVERSTEIN: Kailey Silverstein for the United States.

THE VIDEOGRAPHER: Thank you. Will the court reporter please swear in the witness.

ALEXANDROS SPILIOTOPOULOS, PH.D.,

having been first duly sworn, was examined and testified as follows:

EXAMINATION

BY MS. BAUGHMAN:

Q. Please state your name.

A. Alexandros Spilotopoulos.

Q. Do you go by Dr. Spilotopoulos?

A. Sure.

Q. Dr. Spilotopoulos, my name is Laura Baughman. I'm an attorney, and I represent the plaintiffs in the plaintiffs and the plaintiff leadership group in this case.

Do you understand that?

A. Yes.

Q. Do you understand that you're under oath today?

A. Yes.

Q. And that your testimony is the same as if you were in court before the judge?

A. Yes.

Q. If you don't understand any question I ask you today, will you please let me know?

A. Yes.
Q. Otherwise, if you answer a question, I'm going to assume that you understood it. Is that fair?
A. Yes.
Q. We are going to take breaks today usually once every hour, hour and a half, but if you need a break at any time, just let me know, and we'll take a break. Okay? The only thing I'd is that you answer the question that I've asked you before we take a break. Okay?
A. Yes.
Q. Is there any reason you cannot testify fully and truthfully today?
A. No.
Q. For example, you're not on any medications or have any health issues?
A. No.
Q. Have you ever served as an expert in a litigation before?
A. I have not.
Q. You have not?
A. I have not.
Q. Prior to this case, had you ever prepared an expert report for litigation?

A. I have contributed work as far as supporting expert reports, but I have not prepared one by myself.

Q. So you helped other people write their reports; is that fair?

A. That is correct.

Q. But you didn't sign off on them?

A. No.

Q. Have you ever testified in a deposition before?

A. No. This is the first time.

Q. Have you ever testified at a trial before?

A. No.

Q. Or before Congress?

A. No.

Q. Or in any other capacity under oath?

A. No.

Q. What did you do to prepare for the deposition today?

A. I briefly reviewed my expert report and I had a meeting with the lawyers yesterday, too, in the office here.

Q. Just one meeting to prepare?

A. For today, yes.

Q. How long was that?
A. Some part of the day, but not the entire day yesterday.
Q. Like four or five hours?
A. Something like that.
Q. Did anyone attend other than lawyers and yourself?
A. No.
Q. Did you review documents to prepare?
A. I looked at Chapter A of the two reports, I believe. The chapter -- the contaminant transport chapter for Taraway Terrace. I believe that's what I looked at very quickly on a couple of things.
Q. Other than looking at those documents and your report and talking to the lawyers, did you do anything else to prepare for today's deposition?
A. No.
Q. Did you speak with anyone other than the attorneys to prepare for today's deposition?
A. No.
(Spiliotopoulos Exhibit 1 was marked.)
BY MS. BAUGHMAN:
Q. I'm going to hand you -- I've handed you

what the court reporter has marked as Exhibit 1 to your deposition.

And is that a true and accurate copy of your current CV?

(There was a discussion off the record.)

MR. ANWAR: Let's go off the record for one minute.

THE VIDEOGRAPHER: Off the record at 9:28.

(Recess from 9:28 a.m. to 9:37 a.m.)

THE VIDEOGRAPHER: On the record at 9:37.

BY QUESTIONER:

Q. Dr. Spilotopoulos, before the technical issues we just had, I handed you what we've marked as Exhibit 1 to your deposition. And my question is: Is that a true and accurate copy of your current CV?

A. I'll be happy to answer the question. I just wanted for a second to go back to my previous. You asked me how I prepared for this.

Q. Yes.

A. I just wanted to make sure that I provide a complete answer. Yesterday I met with the lawyers for a few hours. A few weeks ago I

had met with them again on a number of things, and we went over some -- the process of the deposition as well. So I don't know if that counts as preparation, but I just wanted to make sure that it's on the record.

Q. So you had two meetings with the lawyers to prepare?

A. Yes.

Q. About how many hours did you spend preparing for the deposition?

A. A few hours as well I would say, but that included other things that were discussed at the same time.

Q. I mean total if you added them all together.

A. Seven, eight hours maybe total.

Q. So let's go back to Exhibit 1. Is Exhibit 1 a true and accurate copy of your current CV?

A. Well, it looks right as far as I can recall from the last time I put it together as part of the expert report that I produced.

Q. Right. To be clear, what I marked as Exhibit 1 is the version of the CV that was attached to your expert report in this case. So

when you attached that, that was the true, accurate, current CV; correct?

A. Yes.

Q. And you don't have anything to add today; true?

A. No. I don't think so, no.

Q. So you have a Ph.D. from the University of Vermont from 1999; correct?

A. Yes. I have my bachelor's in civil engineering from the University of Patras in Greece focusing on hydraulics and hydrology. I also did a thesis on groundwater flow at the time.

And then I completed Ph.D. at University of Vermont '94 to '99 under the advisorship of Dr. George Pinder on the optimization of groundwater management problems, looking at groundwater modeling and optimization techniques.

Q. So Dr. George Pinder was your advisor for your Ph.D.?

A. That is correct. And I had a co-advisor, Dr. George Karatzas at the University of Vermont.

Q. So do you consider Dr. Pinder to be an expert in the area of groundwater modeling?

A. Yes. Actually, Dr. Pinder is one of the

pioneers in the field of groundwater modeling.

Q. Likely also in -- let me start over.

Do you also consider Dr. Pinder to be an expert in hydrogeology?

A. Yes.

Q. I think I know the answer to this, but what's your opinion of Dr. Pinder? Is he respected in the fields of groundwater modeling and hydrogeology?

A. He's very well respected in the field.

Q. Do you consider him to be authoritative in the field?

MR. ANWAR: Object to form.

THE WITNESS: I consider him an expert, yes.

BY MS. BAUGHMAN:

Q. Do you consider yourself to be an expert in hydrogeology?

A. I do.

Q. On your CV, Exhibit 1, it says on the first page Example Areas of Expertise. And you've listed four of those; right?

A. Yes, as general fields of expertise, yes.

Q. And those are fields that you consider

yourself to be an expert in; fair?

A. I have expertise and experience in these fields, yes.

Q. Including groundwater modeling?

A. Yes, I do.

Q. Do you have any other areas of expertise to add other than hydrogeology, groundwater modeling, and the other three categories on your CV?

A. No. These areas I described as generally cover the areas of expertise that I have.

Q. Are you a licensed professional engineer?

A. No, I'm not.

Q. So there's an exam that you can take to get your PE or professional engineering license; correct?

A. That is true.

Q. And you didn't pursue that?

A. I have not.

Q. Are you a licensed geologist?

A. No.

Q. Do you hold any professional licenses?

A. As a civil and environmental engineer

from Greece, yes, at the time that I worked there as a professional engineer.

Q. So you have a license from Greece?

A. Yes.

Q. Is that current?

A. No. I haven't kept it up I moved to the United States in 2004.

Q. So since 2004, have you held any professional licenses?

A. No, I have not.

Q. Do you hold any professional certifications?

A. No.

Q. Now, on your CV, you list -- under Professional Societies on the first page there in the right-hand column, there's two societies, the National Groundwater Association and the American Geophysical Union; right.

A. That is correct.

Q. Have you held any offices in those societies?

A. No. I'm just a member of those societies.

Q. Regarding the American Geophysical Union, are you a fellow of that organization?

A. No, I am not.
Q. Do you know, what does it mean to be a fellow of the American Geophysical Union?
A. It's a distinction I believe, but I don't know the details of what it entails.
Q. It's an honor; right?
MR. ANWAR: Object to form.
THE WITNESS: Possibly I'm not sure what exactly it entails. I understand that it's some kind of distinction.
BY MS. BAUGHMAN:
Q. Had you ever tried to pursue becoming a fellow?
A. No, I have not.
Q. Are you aware if Dr. Konikow is a fellow of the American Geophysical Union?
A. Possibly. I'm not sure. It is possible, if I recall correctly, but I'm not sure.
Q. Have you ever met Dr. Konikow?
A. I have.
Q. In what context?
A. At least twice socially, a friend's house. I don't recall that I had another personal encounter with him other than I believe when I saw him at the expert panel meeting in 2005 in

Atlanta.

Q. Did you speak to him at that panel meeting?

A. No, I did not. I did not know him personally at the time.

Q. Have you ever worked with Dr. Konikow?

A. No, I have not.

Q. And Dr. Konikow is well respected in the fields of groundwater hydrogeology and hydrogeology. Fair?

A. Yes.

Q. Like Dr. Pinder, he's considered one of the pioneers in the field. Do you agree?

MR. ANWAR: Object to form.

THE WITNESS: I don't know that I can make a comparison like that. I'll just yes, he's a respected member of the scientific community in our field.

BY MS. BAUGHMAN:

Q. You just mentioned the expert review panel. I'm going to ask you some questions about that. But you're referring to is the 2005 expert peer-review panel for the ATSDR modeling work we're here to talk about today; correct?

A. The expert panel that was held in

Atlanta in 2005.

Q. Which was about the ATSDR's modeling work that your report is the subject of; correct?

A. That we're discussing, yes, the groundwater modeling that was ultimately developed by ATSDR.

Q. Dr. Konikow, he was an invited member on the peer-review panel for that meeting; correct?

A. Yes. Dr. Konikow was a member of that panel.

Q. You weren't part of the expert panel; right?

A. I was not.

Q. Have you ever served on an expert peer-review panel?

A. I have not.

Q. Have you been invited to serve on an expert peer-review panel?

A. I have not.

Q. Have you ever received any professional awards for your work?

A. You have to define the type of awards you're talking about.

Q. Any award.

A. I have had recognitions for work that I

had done as part of my undergraduate work and presentations that I gave then. I have awards or recognitions on presentations that I have done at different conferences. I believe some of that may be in my résumé.

Q. So talking about since you've been a professional, after school, which awards have you received?

A. Best paper presentation in a conference.

Q. Anything else?

A. Not that I can recall.

Q. How many times did you receive an award for a presentation at a conference?

A. I'm trying to remember if it was once or twice.

Q. And to the extent you received that, it's reflected on your CV; is that true?

A. I do not recall if I have it included there. I have to check.

Q. What year did you receive that award or awards?

A. That's a good question. It was a few years ago. I believe it was waste management conference, if I remember correctly.

Q. Do you know which paper it was?

A. No. I don't recall which paper it was about.

Q. Was it like 10 years ago, 15?

A. Within the last 10 years maybe, something like that, but I'm not sure. I have to check.

Q. Do you know if it was once or more than once that you received such an award?

A. I'm sure once. There might be another one, but I don't recall.

Q. And you can't identify which paper?

A. Not off the top of my head.

Q. You've listed your papers in your CV, right, that you've presented at conferences?

A. Yes.

Q. Can you look at the CV and tell me which paper or papers you got an award for?

A. The 2019 paper, superior paper and papers of note. 2019 Spilotopoulos, DiFilippo, Khambhbhammettu, Web-Assisted Methods And tools, et cetera, et cetera.

And there's a paper that I presented back in 2007 on the analysis of aquifer test data and that presentation was part of the MODFLOW and More 2006 conference in Colorado, which was

included in the book by Sterrett in Groundwater and Wells, the 3rd edition.

Q. And you received an award for that as well?

A. That was not an award. It was just included in a book. It was some kind of recognition award that was done.

Q. You're saying your paper was included in a book, but you didn't receive an award for that paper; fair?

A. Fair.

Q. So any other awards you can tell us about that you received in your professional career?

A. Not that I can think of at this moment.

Q. Was your paper, the paper that you just referenced, was it included in the book or just cited in the book?

A. I think it was included in an appendix in a book or it's an electronic version. I do not recall.

Q. Can you tell us under oath whether that paper was actually included in the book?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure I remember in

what form it was included there, but it was referenced -- I can't recall if it was included in the appendix or described in the appendix, but there was a clear reference to that work.

BY MS. BAUGHMAN:

Q. So it might be just a reference?

A. I will have to look at more detail and give you a complete answer on this.

Q. Are you a member of the National Academy of Engineering?

A. I am not.

Q. Have you served on the editorial board for any professional publication?

A. I have not.

Q. So, for example, you haven't been the editor and chief of any publication?

A. I have not.

Q. Have you been a reviewer for any professional publications?

A. I have not.

Q. Have you ever been asked to be a reviewer for any professional publication?

A. There have been discussions as to whether that could be done. I don't have an official indication or I have not done it.

Q. So you haven't been officially invited to be an reviewer for any publication; is that true?

A. That is true.

Q. You've listed your publications on your CV on pages 4 and 5; right?

A. Yes.

Q. Is what's listed on Exhibit 1, pages 4 and 5, is that a complete list of your professional publications?

A. Yes.

Q. It definitely includes all your publications within the last 10 years. Truth?

A. Yes.

Q. Have you ever published anything about Camp LeJeune?

A. I have not.

Q. Which of your publications concern the modeling the fate and transport of contaminants in groundwater?

A. You want me to list them one by one based on what's in the CV?

Q. First of all, all of the publications on your CV, are they all peer reviewed?

A. Not all of them.

Q. So, for example, the ones that you present at conferences, do you consider those peer-reviewed publications?

A. They are reviewed so they can be accepted, yes, many of them.

Q. So you consider conference presentations to be peer reviewed?

A. I would think so, yes.

Q. Did you get comments and edits back on your papers before you were able to present it at the conference?

A. Yes.

Q. And is that the normal protocol for conferences?

MR. ANWAR: Object to form.

THE WITNESS: Not always.

BY MS. BAUGHMAN:

Q. So, I mean, you have here maybe 10, 15 papers, because some of these listed under the publications and presentations are just presentations; right?

A. It's a mix.

Q. Go ahead and -- is it fair to say you really only have two publications that are in peer-reviewed journals?

A. Yes.

Q. And of those two, did they concern modeling the fate and transport of contaminants in groundwater?

A. At least one of them directly and the other one, forms and shapes of doing this kind of work, tools for doing that, yes.

Q. So you have one publication that directly concerns modeling the fate and transport of contaminants in groundwater and one that concerns that indirectly; true?

A. Or tools to perform that analysis, yes.

Q. That's the sum total of your peer-reviewed publications on modeling fate and transport contaminants in groundwater; right?

A. Yes.

Q. Have you presented at any conference about Camp LeJeune?

A. I have not.

Q. And have you presented at any conference regarding the modeling of fate and transport of contaminants in groundwater?

A. I'm sorry. Can you repeat? I'm trying to say if it's relevant to Camp LeJeune what you just asked. Can you repeat the question, please?

Q. I'm asking a more general question, not just about Camp LeJeune.

Have you done presentations regarding the modeling of fate and transport of contaminants in groundwater?

A. Several, yes.

Q. Which ones concern that?

A. The first one just happened last week.

Q. Wait. So for the record, you're talking about the March 12, 2025 presentation on an integrated approach for developing contaminant upwelling estimates?

A. Correct. The second one, Remedy Challenges, Novel Approaches and Lessons Learned.

Q. Okay. By the way, are those first two -- those were given within the last week or so -- are those -- were there papers associated with those presentations?

A. Yes. They're included in the proceedings.

Q. Are those available now online?

A. I'm not sure that the proceedings are already produced.

Q. Go ahead and continue. Which of your?

A. Number four, Web Assisted Methods and

tools for Efficient Remedy Design.

Q. Okay.

THE WITNESS:

Number 5, Evaluating environmental remediation Performance. Well, that one is primarily with a aggression analysis. So statistics, but it involves to some extent modeling as well.

BY MS. BAUGHMAN:

Q. By the way, I'm not talking about just modeling. Let's be clear. There's groundwater flow modeling, right, and then there's modeling of the fate and transport of contaminants. So I'm asking about the fate and transport of contaminants. So you're saying --

A. That as well is part of that work, yes. Implementation of a Contaminant Treatment System, MT3D.

Q. The one from 2011?

A. Yes.

Q. Modified 2D Field Generator for Deterministic and Stochastic Groundwater Modeling. That includes contaminant transport considerations.

Shannon, Spilotopoulos and Tonkin, 2011,

Estimating Contaminant Migration Pathways. Particle tracking is part of the fate and transport evaluations.

Remediation of the 100-HR-3 Operable Unit, Hanford, Washington, 2011.

Groundwater Modeling in Support of Remedial Process Optimization, 2010.

2008, Robust Pump and Treat Remedy Evaluation for MTBE Mega-Plume.

2008, Rapid Mapping to Support Accelerated Site Assessments.

The Multi-period Approach to the Solution -- that's the paper in the peer-reviewed publication.

Q. That's a journal. That's not a conference proceeding; right?

A. Yes.

Q. And then the Biconcave-Decomposition Method For The optimal Design of Pump-and-Treat Remediation Systems, 2000.

And even back in '98, the development of two optimization models multi-period, et cetera.

Q. That's a complete list?

A. Yes.

Q. I want to ask you -- if you go to page 3

of your CV, you list on the top right-hand side a confidential client that you did some work for.

Can you tell me who that client was?

A. I cannot.

Q. Why not?

A. Because it's confidential. I have a confidentiality agreement.

Q. What about on page 4. You've got another confidential client from El Campo, Texas. Can you tell me who that is?

A. No, for exactly the same reason.

Q. Well, the El Campo, Texas work concerned modeling groundwater flow and contaminant transport using MODFLOW, right, and MT3?

A. MT3D and ATRANS.

Q. So can you identify who you did that work for?

A. I cannot. It's a client that at least at the time when I did it, there was a confidentiality agreement. I don't think that has changed since then.

Q. So you're going to refuse to answer the question?

A. I don't think I can answer the question because of the confidentiality clause.

Q. The work that you did at El Campo, was that historical reconstruction?

A. That's a very long time ago to remember the details of that work.

Q. Do you know?

A. I do not recall the details of that project.

Q. It says on your CV that you constructed, calibrated and deployed numerical and semi-analytic methods or simulating groundwater flow and contaminant transport to estimate the contaminant release history at the site based on a recent monitoring data; right?

A. Yes, that is correct.

Q. So the work was to go back in time to determine what happened in the past; right?

MR. ANWAR: Object to form.

THE WITNESS: Generally speaking, yes. I just don't recall the details of what it entailed.

BY MS. BAUGHMAN:

Q. So you can't tell us how you helped this confidential client determine what had been released in the past at that site?

A. Not off the top of my head right now.

It's been a very long time since I did that work.

Q. You can't say what modeling method you used to do that?

A. What do you mean by modeling method?

Q. Well, let's put it more generally. You weren't modeling into the future, were you? You weren't forecasting?

MR. ANWAR: Object to form.

THE WITNESS: No. I was not forecasting.

BY MS. BAUGHMAN:

Q. You were --

A. Estimating the contaminant release history at the site. At least that's the description of the work that was done then. I'm just saying that I do not recall the specifics of the work at this moment.

Q. According to your CV, you used MODFLOW and MT3DMS to try to determine what had been released in the past; right?

A. I used the simulation software to perform that work, yes.

Q. Which simulation software?

A. MODFLOW and MT3D.

Q. When you say MT3D, is that the same

thing as MT3DMS?

A. It's a variation of that.

Q. Is MT3D the precursor to MT3DMS?

A. It's a version -- MT3DMS is a version of the code that's had some different capabilities on doing certain dates, but they're very much the same foundation of the code.

Q. Were you able to use these models that you've identified, MODFLOW and MT3D, to determine the historical releases that had occurred at the El Campo site?

A. That's a very general question. Yes. In looking back in time, that's very much what you do most of the times. But the specifics I do not recall.

Q. Since you received your Ph.D. in 1999, you've worked at two different engineering consulting companies; right?

A. Where do you mean?

Q. Well, On your CV you've listed ADK Consulting Engineers and you listed S.S. Papadopulos & Associates.

Have you worked anywhere else since getting your Ph.D.?

A. I have not.

Q. So for your entire professional career, you've worked at either ADK Consulting or S.S. Papadopulos; right?

A. Correct.

Q. So ADK Consulting Engineers was in Athens; correct?

A. Yes.

Q. And you were there from 2001 to 2004?

A. From 1999 to 2004 I was in Greece. 2001 I believe was the time when I became an employee, full-time employee of ADK Consulting Engineers. Between '99 and 2001, I was working part time for them while I was serving in the Army in Greece.

Q. According to your LinkedIn profile, you were a civil engineer in the hydraulics division. Does that sound correct?

A. That is correct.

Q. And while you were at ADK, did you develop or use groundwater flow models?

A. As part of my work at ADK, no.

Q. While you were the ADK, did you develop or use any contaminant transport models?

A. I did not. For groundwater contamination?

Q. For groundwater; right.

A. I did not.

Q. So then you started S.S. Papadopulos in 2004; right?

A. Correct.

Q. You spent the majority of your career at S.S. Papadopulos; correct?

A. I spent all of my professional career so far in the United States at Papadopulos & Associates.

Q. And according to is S.S. Papadopulos' website, it is an employee-owned groundwater and environmental consulting firm. Does that sound correct?

A. That sounds right.

Q. Do you have an equity stake in the company?

A. You have to be more specific about that. What do you mean?

Q. You have ownership in is S.S. Papadopulos?

A. Yes. I have ownership. I have some ownership.

Q. Can you describe what that is? How does that work?

A. I have a number of -- small number of

shares, and all employees, we have shares of the company as well.

Q. Is it publicly owned?

A. It is not.

Q. Privately owned?

A. Private.

Q. And how is it that you get shares? Is that based on rewards, performance, evaluations?

A. Internal evaluations and promotions and contributions to the company.

Q. When was the last time you got a promotion?

A. The most recent one would have been maybe two years ago, three years ago.

Q. And are the -- is the award of shares in the company based on how much money you bring into the company?

A. I'm not the one to judge that, but my understanding is that it's a combination of project work, quality of the work, recognition of the work within our client base and how that contributes to the reputation of the company in our field.

Q. Do you also receive bonuses based on your performance?

A. Everybody in the company does depending on how well the company does on a year-by-year basis.

Q. You have designed and used groundwater models while you've been working at S.S. Papadopulos; right?

A. Yes, plenty.

Q. And you've used those models to evaluate contaminant migration in groundwater; right?

A. Yes, that is correct.

Q. You've also used groundwater models to design remediation systems?

A. That is correct.

Q. Have you used them for any other purpose?

A. What do you mean by that?

Q. When you use a groundwater model, you're using it to do something; right?

A. That's correct.

Q. I know you've used it to determine different or to recommend different remedial designs at groundwater sites, right, to clean up the groundwater?

A. The modeling work that I have done in terms of contaminant transport revolves around the

presence and migration of contamination in an aquifer. And then there are different things that we look at, design a monitoring system, evaluate the extent of contamination, design a remedy to clean up the aquifer or contain the aquifer. So there are different aspects to it.

Q. How does a flow and transport model help you to design a remedial design, to come up with a remedial design? How does that work?

A. Well, the process first involves the collection of monitoring data that can help us understand or get a quick understanding of what is happening in the aquifer depending the project. If we have a source water or if we have just a dissolved plume, the groundwater model then becomes a tool to try to approximate the conditions in the aquifer so we can simulate the plume migration, the extent of contamination. And then if it's about the design of a remedial system, determine where, for example, extraction wells should be placed to extract contaminated water or a combination of injection extraction wells, let's say, if we're trying to contain contamination. There are different objectives we look at remedial systems.

Q. So it's fair to say your models, your groundwater modeling has been used to make important decisions like on how to clean up contaminated sites?

MR. ANWAR: Object to form.

THE WITNESS: The importance is relative, but it is -- they are designed to be used for making decisions, yes.

BY MS. BAUGHMAN:

Q. In your opinion, is groundwater modeling a reliable methodology to estimate groundwater flow?

MR. ANWAR: Object to form.

THE WITNESS: What do you mean by reliable?

BY MS. BAUGHMAN:

Q. Something that you can recommend to your clients that they can rely upon.

A. In our profession, we use different methods and approaches to evaluate environmental data or water level data, for example, anything that goes into understanding groundwater flow and contaminant transport in the aquifer. And we use them in different ways to make these decisions.

Q. Is groundwater modeling a reliable

methodology?

MR. ANWAR: Object to form.

THE WITNESS: Groundwater modeling is a methodology that is used in helping us to make decisions.

BY MS. BAUGHMAN:

Q. And you consider it reliable?

A. It by itself the methodology or approach is not reliable. What makes it reliable is how well constructed, for example, the model is to perform this calculation.

Q. Is groundwater modeling a reliable methodology to determine contaminant transport?

MR. ANWAR: Object to form.

THE WITNESS: Again, the methodology itself is not reliable. There are tools that we use. How they're implemented is what makes them reliable.

(Spiliotopoulos Exhibit 2 was marked.)

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, the court reporter has handed you what we have marked as Exhibit 2 to your deposition, which is the first chapter from the book Applied Groundwater Modeling: Simulation of Flow and Effective Transport, by Anderson and

others. It's Second Edition from 2015.

This is a book that you cited repeatedly in your expert report for this case; right?

A. That is correct.

Q. I just have a very general question about it. If you turn to -- it's page 4. The pages are at the top right-hand side. At the very bottom of the page, Dr. Anderson and her colleagues wrote, "To date groundwater models are accepted as essential" --

A. I'm sorry. I'm not following you. Say that again. Where is that?

Q. The very last line.

A. Yes. Okay.

Q. Dr. Anderson wrote, "Today groundwater models are accepted as essential tools for addressing groundwater problems."

Do you agree with that statement?

A. That is a very general statement, and I agree.

Q. As I mentioned, this book Applied Groundwater Modeling, you cited multiple times in your report, didn't you?

A. I believe I had.

Q. Do you consider Applied Groundwater

Modeling by Anderson and others to be a reliable source in the area of groundwater modeling?

MR. ANWAR: Object to form.

THE WITNESS: I believe that is a very good and useful book that has many good points that are made there regarding how we construct, calibrate and use -- evaluate and use a groundwater model.

BY MS. BAUGHMAN:

Q. Now, you have used MODFLOW and MT3DMS multiple times in your career; fair?

A. Yes.

Q. You've used MODFLOW to analyze groundwater flow; right?

A. Yes.

Q. MODFLOW is a code that was created by the U.S. Geological Survey in the 1980s; right?

A. There was a precursor to MODFLOW early on, and then about sometime in the '80s, yes, I think the first version was 1988, if I remember correctly.

Q. MODFLOW --

A. In the '80s developed by the USGS, yes.

Q. Would you agree that the source code and the underlying equations for MODFLOW have been

tested extensively?

MR. ANWAR: Object to form.

THE WITNESS: Generally, yes, I agree, although there have been corrections, additions, extensions and things like that over time to make it even more efficient.

BY MS. BAUGHMAN:

Q. And how many groundwater flow models have you developed or used using MODFLOW approximately?

A. It's hard to remember because they're the ones that I have been directly been involved as leading the work and there are many others that I have participated in their development. So there's tens of models.

Q. How many?

A. Tens, many tens.

Q. Using MODFLOW?

A. Among other codes of similar capacity. But MODFLOW, yes, tens of times.

Q. You've used MT3DMS to model the fate and transport of contaminants; right?

A. Yes.

Q. And the source code and the underlying equations for MT3DMS have been extensively tested;

true?

MR. ANWAR: Object to form.

THE WITNESS: The validity of the calculations that MT3D performs, yes, they have been tested and benchmarked.

BY MS. BAUGHMAN:

Q. About how many fate and transport models have you developed or used using MT3DMS?

A. Tens of models as well.

Q. Would you agree that the use of MT3DMS in combination with MODFLOW a generally accepted and widely used methodology in your field?

MR. ANWAR: Object to form.

THE WITNESS: They're both widely used tools in simulating groundwater flow and contaminant transport in our field, yes.

BY MS. BAUGHMAN:

Q. And ATSDR used MODFLOW coupled with MT3DMS to model groundwater flow and contaminant transport at Camp LeJeune; right?

A. Yes.

Q. You agree that those were appropriate models to use for that purpose?

MR. ANWAR: Object to form.

THE WITNESS: I believe I said before

the tools themselves are tested and good to be used for groundwater flow and contaminant transport analysis. It's their construction, calibration and evaluation of their uncertainty that is critical on how they're used.

BY MS. BAUGHMAN:

Q. Obviously in your report, you have multiple criticisms of how ATSDR used the models; right?

A. That is correct.

Q. I want to start with this. You have no criticism that ATSDR chose MODFLOW and MT3DMS as tools to use for its groundwater modeling; is that true?

A. I did not criticize the use of those tools.

Q. Do you have any criticisms today of ATSDR's choice to use MODFLOW and MT3DMS as models for their modeling of groundwater flow and contaminant transport?

A. My criticism is only on how those tools were used to construct, calibrate and evaluate the uncertainty analysis of these models to be used for the calculations intended in the analysis.

Q. Your criticism is not on the choice of

those models, fair?

A. On the tools. Let's be very careful. I'm saying MT3D and MODFLOW are great tools to be used in our field for these calculations. How they're used is what's in question at times.

Q. And your criticisms of how ATSDR used MODFLOW and MT3DMS, your standards on what they should have been done and not done, would you apply those same standards to the work that you do for your clients?

A. Every situation is different. So you can never compare two models side by side unless they're exactly the same, they use the same data, they use the same -- they have the same objectives. Every time is different and has to be judged on its own merit.

So the general standards about how well one calibrates a model, for example, is something that -- there's some general standards, but then every situation is different. So you cannot apply the same metric to two models.

Q. But there are very some standards on how one should calibrate a model; fair?

A. I believe there are.

Q. You'd apply the same standards to your

work as you'd apply to ATSDR; fair?

A. We have to look specifically at two situations, and I think offer an opinion on that.

Q. Let me ask you this: In your field, are there standards that are written about how to calibrate a groundwater flow and fate and transport model?

A. There are guidelines on how to construct and calibrate a model, yes.

Q. Where are they? Can you identify them?

A. We have several standards like ASTM standards. We have the USGS guidelines on constructing the groundwater flow model. These are the ones that I can think of, off the top of my head. These standards, however, are generally enough to provide a blanket statement as to how things need to be done.

But, like I said, there are no specific metrics that come with the standard that say, and this is how it's done, you have to follow this guideline, that guideline. But again, every situation is different.

Q. What do you mean there are no specific metrics?

A. Like what is a calibration standard.

Q. There's no specific calibration standard?

A. There's no metric that says if you are within that range, for example, you have a good model; if you're in that range, you're not.

Q. And that's true in your field of groundwater modeling and hydrogeology; correct?

A. I believe so, yes.

Q. In your CV, it says that you've used in-house enhanced versions of MODFLOW and MT3DMS.

What does that mean that you have enhanced versions, in-house enhanced versions?

A. At SSPA we have been using these codes not as black box. In other words, we have experts that have contributed to the development of these codes. And since these codes are not proprietary like other experts in the field, we can go into the code and tweak it at times to do certain things that maybe the code doesn't do it in the way that is suitable for a particular problem.

In many cases, that becomes an additional package, let's say, that people call for using with MODFLOW. These are presented at conferences, papers, and often they become standard packages that are used in new versions of

the code.

Q. So any of the enhanced versions of MODFLOW and MT3DMS that are in-house, have those been published?

A. An example that comes to mind is this -- I don't think I have the paper there -- where we edited MT3D to allow for the recirculation of water that comes out of a treatment plant, from extraction wells, into the treatment plant, and back to injection wells to make sure that we properly simulate the recirculation of contaminants in the aquifer. And that's a package we developed first as an in-house tool to use for our own calculation purposes. And later on that also became a package and a tool that is now available in the newer versions of MODFLOW and MT3D.

Q. So it's been published in a journal?

A. Yes. And it's included also in the instructions manual of the newer versions of the code.

Q. Are all of the enhanced versions, in-house enhanced versions of the MODFLOW and MT3DM at SSPA, have they all been published and peer reviewed?

A. No.

Q. Would you characterize your in-house enhanced versions of MODFLOW and MT3DMS as custom methods?

A. Sometimes we have customized approaches, yes. The work that that I have been involved in, those customized methods have been documented, benchmarked and they have also been published, like the one I just mentioned.

Q. All of them have been published?

A. The ones that I can speak of.

Q. What do you mean the ones you can speak of?

A. The ones that I've worked on, that I'm familiar with.

Q. Does SSPA have any proprietary enhanced versions of the groundwater models?

A. There was a time that a version of MT3D was developed as proprietary, and I think for sometime it was something that we were offering. I'm not sure that that's the case anymore. It's a very old version of the code anyway. It was included in some modeling interfaces, for example, as is a version of choice, of course, documented, benchmarked and all that.

I don't think we offer anything. Everything we have as part of the software we develop is always open source and available for people to use.

Q. What do you mean benchmarked?

A. Benchmarking is the process where analytical methods, equations and other forms of performing a calculation are used to compare the results of this modified version to those accepted expressions of condition in the field and how we calculate that condition to make sure that code matches the results of the analytical solutions, for example, making sure of their accuracy.

Q. What's the longest time, looking forward, the longest time you've predicted contaminant fate and transport using modeling?

A. You mean any on project I ever worked on?

Q. Yes.

A. They're very different timeframes, from a few years to many years.

Q. Many years, decades?

A. Yes. In some cases, yes. But, of course, let's not forget that these calculations all come with the necessary disclaimers regarding

the uncertainty or what underlie these calculations so it's always perfectly clear what exactly they represent or what their intended purpose is, by the way, which is equally important.

Q. Have you used models to generate concentrations in monthly time steps, meaning concentrations of contaminants?

A. That has been part of calculations that I've performed. But that was something that was done in the past. There were some predictions at times. Again, the framework of these calculations is important.

Q. But you have predicted in the future contaminant concentrations in monthly time steps; right?

A. As a prediction?

Q. Yes.

A. Yes. And that was part of potential plume migration as part of an analysis to give a sense of what should be expected in a remediation project so that decisions could be made on how exactly to operate wells to contain that plume.

Q. Is that at the Hanford site?

A. That's an example of that, yes.

Q. Have you done it at other sites?

A. I can't recall the time stepping of predictions at other sites, but I have done predictive modeling, yes, as part of remediation projects to guide the remediation process and make decisions on the design of the extraction wells, for example, how much they need to pump, and then use that information then to see how it compares with data collected afterwards, see whether the predictions are good enough or update them where there is a disconnect between what the model suggested and what the data indicated later on.

Q. Have you ever performed a historical reconstruction or hind casting using groundwater modeling?

A. Hind casting is a very general description, term. We have developed models to simulate conditions in the past and perform calculations using those results, yes. But the framework, again, is something that needs to be discussed. Not every hind casting work is the same.

Q. Which projects have you done hind casting on?

A. Hanford work is behind casting. By that

I mean that we went back in time and looked at the conditions in the aquifer, plume migration in the past. We have done that for Hanford. I've done that for other projects, looking in the last 20, 25 years and migration of a plume in the aquifer, looking at data that would inform and the model construction and the model calibration.

Q. I want to ask you some more questions about Dr. Pinder, your thesis advisor for your Ph.D.

Are you aware that Dr. Pinder performed hind casting for a model that was prepared for litigation regarding PCE contamination?

A. I'm not sure which one you're referring to.

Q. Are you aware that Dr. Pinder was the plaintiff's expert in the Woburn case?

A. Yes.

Q. And he performed hind casting for Woburn, didn't he?

A. He looked at, yes. He used groundwater modeling to perform some calculations concerning past conditions.

Q. And he did that in order to do a few things. He did that in order to determine whether

the PCE contamination could reach certain groundwater wells; right?

A. I believe the issue in that case was to determine whether certain wells were impacted by one or another source.

Q. And also when they were impacted; right?

A. I'm not sure about that. I think the main issue was which sources contributed to which wells. I do not recall the specifics of when.

Q. We'll get to that in a minute. So you agree that the case, the Woburn case, Woburn, Massachusetts, it involved TCE contamination wastes that had been dumped on the ground by different industries?

A. That is right.

Q. Just to be clear, you did discuss the Woburn case in your expert report in this case; right?

A. I mentioned the general framework of that with respect to how it compares to Camp LeJeune.

Q. So the plaintiffs in the Woburn case claim that they had developed cancer, that they had developed leukemia from drinking contaminated well water; right?

A. Yes.

Q. By the way, did you work with Dr. Pinder on the Woburn case?

A. No, I did not.

Q. Had that happened before you were there?

A. That happened before, yeah.

Q. Did you ever talk to Dr. Pinder about Woburn?

A. There were very general discussions about the Woburn case, but never a detailed one on exactly how work was done.

Q. So did you ever review Dr. Pinder's modeling work for Woburn?

A. No, I did not.

Q. Did he mention Woburn in his teaching?

A. Woburn was a very known case at the time. There was a movie I think at the time as well. But under the very general terms. We never went into details as far as I can remember.

Q. But you learned how to do groundwater modeling from Dr. Pinder; right?

A. Among others, yes.

Q. And did he teach hind casting or historical reconstruction?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure how to answer that question. Part of the things that I learned with him was how to construct the model, how to calibrate a model and use it also as a management tool.

BY MS. BAUGHMAN:

Q. Just to be clear, you're offering an opinion in this case about the differences between Woburn and Camp LeJeune; right? You've commented on that in your report?

A. The comment that I made in my report --

Q. Try to answer my question. You are comparing Woburn and Camp LeJeune in your report; right?

A. In my report I'm offering a comparison between the two with respect to the level of detail and the kind of results that we're getting from the ATSDR models in Camp LeJeune versus the different approach or results that are produced by the Woburn case model.

Q. Have you reviewed the Woburn case model?

A. I have not reviewed the model itself.

Q. Did you review Dr. Pinder's testimony in that case?

A. No, I did not.

Q. He was deposed for many days, and he testified at trial. Did you review any of that testimony?

A. No, I did not.

Q. Have you reviewed his expert report, Dr. Pinder's report in Woburn?

A. No, I did not.

Q. Do you know whether Dr. Pinder used a groundwater model to demonstrate that water contaminated with PCE reached water wells in Woburn?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Do you know whether he did that?

A. He did determine or he offered an opinion on which sources contributed contamination to which wells.

Q. Using groundwater modeling?

A. That is correct.

Q. Are you aware that there was no sampling data of groundwater or well water prior to 1979, which was when the wells had been discovered to be contaminated?

A. I do not recall the dates on when monitoring data were available.

Q. Well, let me just ask this. For Dr. Pinder's work, did he have available to him past groundwater and well water contamination data?

MR. ANWAR: Object to form.

THE WITNESS: Again, I do not recall when he had data available to construct his models.

BY MS. BAUGHMAN:

Q. So for your opinion in this case in comparing Woburn to Camp LeJeune, you don't know how the amount of data compared, like what Dr. Pinder had versus what ATSDR had; fair?

A. The comparison that I made was --

Q. I want you to answer my question. Can you tell us the difference between the past, the historical groundwater and well water contamination data, how that compared, Camp LeJeune versus Woburn?

MR. ANWAR: Object to form.

THE WITNESS: Again, I'm not sure that I can do that, but that was not the opinion I offered in my --

MR. ANWAR: Let him finish.

THE WITNESS: That is not the opinion

that I offered in my expert report. Therefore, that is somewhat irrelevant to what I said there and the comparison I made.

BY MS. BAUGHMAN:

Q. That's your opinion. I'm going to ask you questions about it. In 1979 it was discovered that the Woburn wells, two of them, were contaminated with PCE; correct?

A. That is possible. I do not recall the details. So I cannot opine on an analysis that was done for a different project with different data that were not part of what I reviewed as part of my opinions for this project.

Q. Can you tell me anything about the amount of data Dr. Pinder had available to him in terms of concentrations to do his modeling work in Woburn?

A. I cannot do that today.

BY MS. BAUGHMAN:

MR. ANWAR: Laura, whenever you're at a good place. We've been going for about an hour.

MS. BAUGHMAN: Let me try to get through this.

BY MS. BAUGHMAN:

Q. What did you review about Woburn to

offer your opinions about Woburn in this case?

A. Mr. Maslia offered a summary of the work that was done in different studies that he considered similar to the Camp LeJeune case. And there, even from that summary, it was obvious and again from additional opinions that Mr. Maslia has offered over time, that the work at Camp LeJeune was different from all of them and the fundamental part that it was all novel, complex and the level of detail in the results that it produced was something unprecedented in that sense.

So there may similarities with other work on certain aspects of the different studies or projects. But this one was unique. And that was the whole point of my opinion, that the uniqueness of the modeling work done here cannot be compared with the other studies.

The fact the Camp LeJeune models calculate monthly concentrations at the treatment plant is something that the other analysis that he provided as examples did not do and for the timeframe that that was done. So this is where my critique is primarily based on.

MS. BAUGHMAN: I'm going to object to that answer as nonresponsive.

BY MS. BAUGHMAN:

Q. The question I asked you, which I'll ask you again, what materials did you review about Woburn to offer an opinion about how Woburn compares to Camp LeJeune?

A. I reviewed the material that Mr. Maslia provided in offering that comparison between his work and the work that others have done.

Q. So you reviewed Mr. Maslia's expert report about Woburn.

A. Yes.

Q. Did you review anything else to offer your opinion about the comparison of Woburn to Camp LeJeune other than Mr. Maslia's report in this case?

A. It was not relevant for the work that I was doing. So, therefore, I did not.

Q. Just a couple more questions. Then we'll take a break.

Can you tell me how far back in time the wells at Woburn operated that Dr. Pinder offered his analysis on? In other words, how long were those wells operating?

A. I cannot do that.

Q. How far back in time did Dr. Pinder

model? From when the contaminants were disposed of until the alleged contamination, what was that timeframe?

A. You're asking me questions about a case that I did not review because it is irrelevant to the opinion that I'm offering here regarding the criticisms on this model.

Q. But you've talked about Camp LeJeune and the fact that it went back 30 or 40 years. And that's one of your criticisms, that there weren't data that far back.

So I'm just asking when you're comparing Woburn to Camp LeJeune, how far back did Woburn go in the hind casting?

A. I do not know that. But again, it is irrelevant to my criticism of Camp LeJeune because I have specific comments with respect to how the work was done for Camp LeJeune.

Q. You can't tell us today how far back Dr. Pinder modeled, can you?

A. No, I cannot.

Q. Did Dr. Pinder have concentration measurements that he could use to calibrate his model?

MR. ANWAR: Object to form.

THE WITNESS: I am not familiar with the details of that work to answer that question.

BY MS. BAUGHMAN:

Q. Did Dr. Pinder have available to him historic concentrations of the contaminant that had been dumped by any of the industries that were at issue?

MR. ANWAR: Object to form.

THE WITNESS: I do not know the details of that work to answer this question.

BY MS. BAUGHMAN:

Q. Do you know whether Dr. Pinder performed calculations and modeling to determine how long it would take the PCE to reach the water wells at issue in the Woburn case?

A. I do not recall that.

Q. You don't know. Do you know what opinions Dr. Pinder actually did reach?

MR. ANWAR: Object to form.

THE WITNESS: No. I did not remember that, the details of that, no.

BY MS. BAUGHMAN:

Q. Do you know whether Dr. Pinder used historical reconstruction to prove that individuals had been exposed to PCE?

MR. ANWAR: Object to form.

THE WITNESS: The only thing that I can -- the only opinion that I can offer with respect to that work was essentially what Mr. Maslia provided as a comparison of different cases. And for this one he illustrated the fact that the work that was done for Woburn was not same as what was done at Camp LeJeune for the level of detail that Camp LeJeune sought to provide calculations.

MS. BAUGHMAN: I'm going to object as to nonresponsive.

THE WITNESS: That's the extent of what I know about the Woburn case or the other cases.

MS. BAUGHMAN: I'll object as to nonresponsive.

BY MS. BAUGHMAN:

Q. The extent of what you know about Woburn is what you read in Mr. Maslia's expert report; fair?

MR. ANWAR: Object to form.

THE WITNESS: He was the one that provided the summary, and I commented on that summary.

BY MS. BAUGHMAN:

Q. The extent of what you know about Woburn is what you read in Mr. Maslia's expert report; is that true?

MR. ANWAR: Same objection.

THE WITNESS: Like I said, I'm not familiar with the details of the Woburn case other than what Mr. Maslia has provided in his summary.

BY MS. BAUGHMAN:

Q. You didn't read anything about Woburn for your opinion in this case other than Mr. Maslia's expert report; is that true?

MR. ANWAR: Object to form.

THE WITNESS: It was not necessary for the opinions that I offered in this case.

MS. BAUGHMAN: Object as nonresponsive.

BY MS. BAUGHMAN:

Q. You're not answering my question.

Whether you think it's necessary or not, did you read anything about Woburn to offer your opinion in this case other than Mr. Maslia's expert report?

A. I do not recall reading anything in more detail about the Woburn case.

Q. You don't know how detailed Dr. Pinder's

historical reconstruction was because you didn't review it, did you?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. You didn't review any of that modeling work, did you?

MR. ANWAR: Object to form.

THE WITNESS: I don't know how I could have reviewed their modeling work.

BY MS. BAUGHMAN:

Q. Did you read any publications about Woburn to offer your opinion?

A. What do you mean by that?

Q. Anything that's been published in the literature.

A. I have not reviewed the Woburn case at that level of detail.

Q. Mr. Maslia cited some publications about Woburn. Did you read those?

A. I did not read any publication that Mr. Maslia offered. I looked at his summary and...

Q. In his report?

A. That he provided in his report, yes.

Q. And that's it?

A. That is correct.

MS. BAUGHMAN: We can take a break now.

THE VIDEOGRAPHER: Off the record at 10:48.

(Recess from 10:48 a.m. to 11:06 a.m.)

THE VIDEOGRAPHER: On the record at 11:06.

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, have you ever worked on a project that had as its goal determining or measuring human exposure to contaminants?

A. I have not.

Q. Has anyone to your knowledge from S.S. Papadopulos worked on such a project?

A. I do not know.

Q. Have you ever worked on behalf of people who've been exposed to contaminants in water or air or soil?

A. Not that I can think of, no.

Q. We mentioned a few times your work at Hanford. Can you tell us what the Hanford site is?

A. Hanford is a federal site. That's where plutonium was enriched back in the '40s as part of the Manhattan project. There was a lot of

contamination. It's a very large site, over 500 square miles, several nuclear reactors and groundwater -- soil and groundwater contamination resulting from different activities and a large remediation site in the last few decades where cleanup operations are taking place.

Q. Are you still working on the Hanford site, on the Hanford project?

A. No, I am not.

Q. When did you last work on it?

A. As part of contracting work we did, I think it was 2021 maybe, the last year we worked as part of that project.

Q. So in your CV, you said that you were the technical lead and lead modeler for certain parts of the Hanford site; is that true?

A. That is true.

Q. And part of your work for Hanford was to develop and calibrate a groundwater flow and contaminant transport model; right?

A. Several groundwater models.

Q. You did that to evaluate the migration of hexavalent chromium and other contaminants in the groundwater; right?

A. Yes.

Q. And your modeling work to model the migration of hexavalent chromium in groundwater, you used MODFLOW and MT3DMS for that?

A. For most of the calculations we performed with respect to modeling, yes.

Q. We talked about it earlier. One of the papers you said was about fate and transport modeling is -- I'll mark it as an exhibit.

(Spiliotopoulos Exhibit 3 was marked.)

BY MS. BAUGHMAN:

Q. Our court reporter has marked as Exhibit 3 a 2010 conference paper called Groundwater Modeling in the Support of Remedial Process Optimization: Implementing a Developing Conceptual Site Model into Comparative Remedy Analyses; correct?

A. That is right.

Q. This is one of your papers that you presented at a conference on contaminant fate and transport; right?

A. Yes.

Q. And you're the author, you're lead author of Exhibit 3?

A. Yes.

Q. And Exhibit 3, your 2010 conference

paper, describes model construction calibration used to determine which remedial alternatives to use at Hanford; fair?

A. Yes.

Q. On the first page, you describe the remedial action objectives, in other words, the objectives you were trying to reach in doing the modeling; right? You were trying to protect the aquatic receptors, this first one. That means fish and aquatic organisms; is that right?

A. Yes.

Q. You were also trying to protect human health by preventing exposure to contaminants in groundwater; right?

A. These are the action objectives for the project, yes.

Q. The third was to provide information that will lead to a final remedy; right?

A. Correct.

Q. The goal there is actually -- the remedy is like to clean up the contamination in the groundwater, right, to at least to an acceptable level?

A. Contain or clean up. It depends on the situation.

Q. I'm looking at the second page, and it's not numbered, but the second page of your 2010 conference. That first full paragraph says, "Groundwater flow and contaminant transport modeling was performed to support the calculation of appropriate pumping rates for injection and extraction wells to achieve the remedial process optimization objective."

So that's what you did. You did this modeling to try to achieve remediation goals; right?

A. Yes.

Q. On page 2, it does say that MODFLOW is used for the groundwater model; right?

A. Yes. We developed -- we used MODFLOW from the groundwater flow model, yes.

Q. And also MT3DMS, it says right there on page 2, was used to simulate the contaminant plume migration; right?

A. Yes.

Q. The primary contaminant you were modeling is chromium 6?

A. Correct.

Q. And you modeled chromium 6 using monthly periods; right?

A. Monthly stress periods, yes.

Q. Forward and backward?

A. That was for model calibration, yes, and I believe, if I remember correctly -- I have to go back and see the calibration.

The model was looking at how we can develop a pump-and-treat configuration to contain the plume and clean it up to required concentration levels.

Q. So you did do predictive modeling then; right? You looked into the future to see, well, if you use this remediation versus that remediation, which one is going to be the best way to clean up and contain the contamination; right?

A. Yes.

Q. So you did do predictive forward modeling; right?

A. Correct.

Q. In monthly time steps?

A. Yes.

Q. And you did backwards in time?

A. Yes. We calibrated the model to past data.

Q. Did you have past data on chromium in the groundwater?

A. Yes.
Q. How far back?
A. More years than even the model was calibrated for.
Q. On the fourth page -- let me ask you a general question. You didn't have site time specific data for all of the parameters for this model; right?
A. Actually at Hanford, there were plenty of site-specific data to be used because there were several analyses that were done to calculate these parameters.
MS. BAUGHMAN: I'm going to object as nonresponsive.
BY MS. BAUGHMAN:
Q. You did not have site-specific data for all of the parameters that you used in your groundwater modeling in Hanford, did you?
MR. ANWAR: Object to form.
THE WITNESS: Which parameters would you refer to?
BY MS. BAUGHMAN:
Q. Let's look at their paper on page 4 where it says Parameter Values - Model Calibration. Do you see that heading?

A. Yes.

Q. The second sentence says, "In particular, values for some of the boundary conditions and aquifer parameters were estimated through a combined manual and automated calibration process."

Do you see that?

A. Yes.

Q. So you did have to estimate some parameters. You didn't have data for all of them, did you?

A. But this refers to the distribution of these parameters in the aquifer, which is part of the model calibration process based on available site-specific data. An example of that is hydraulic conductivity distribution. In any model we do not have values everywhere in the model domain, we have to estimate them. The question is whether we have available data to do so.

Q. Let's look at the next paragraph. The second sentence, you wrote, "The model was calibrated to data from throughout CY2018."

Do you see that?

A. CY2008.

Q. That means the year 2008. Okay.

Now, what data -- if you look up above at the very top of the page, that's talking about -- from previous page to that page -- it says, "The stress periods correspond to monthly average river stages representing the time varying river stage for the period January 1, 2008 through December 31, 2008. It is assumed that these conditions are representative of the typical conditions in the field and that future conditions will not vary."

Do you see that?

A. Yes.

Q. And then going down below, it says, "The model was calibrated to data from throughout CY2008."

Did you have chromium 6 concentrations or just the flow concentrations to calibrate?

A. There were water level data available, and there were chromium 6 available data. And I'm just highlighting two key inputs to the model that were used for the model calibration.

Q. The next sentence says, "No formal calibration statistics were calculated to determine the goodness of fit of the model results to the measured data."

Did I read that correctly?

A. That is correct.

Q. Is that true?

A. That's what it says there. It's 15 years ago.

Q. What's a calibration statistic?

A. Usually it's the root mean square error or something that calculates the difference between observed and simulated values.

Q. How you don't know if observed and simulated values match if you don't do calculations?

A. Well, there are different ways of looking at model calibration, and that is sometimes using the statistic and sometimes it's using visual calibration, for example, when you look at hydrographs of water levels or concentrations over time to see how well you fit the data.

Q. So looking at visuals or hydrographs to determine how well data fits for calibration, that's an appropriate methodology?

A. That's a methodology. It depends on the number of data available to do that.

Q. You used that methodology in Hanford?

A. I will have to go back. I cannot recall exactly what the specifics were, what the data we used for that one. Again, like I said, it was 15 years ago.

We have developed models for a much longer period of time with lots of data. We have calculated calibration statistics. It's in the reports that we have published for Hanford. So this is just one example where a specific calculation was performed. And that was a scoping in calculation based on limited data apparently if we're looking for one year.

Q. You then said in that same paragraph, "In addition, maps of water level contours calculated by the model were compared to contours included in published reports."

So that's another way of doing calibration, right, comparing the maps?

A. Again, that was a limited calibration process based on limited data available at the time as far as I recall. At that time the conditions in the K area were being under development. The remediation scheme was evolving. There were a few wells in place, and they were planned on adding more.

So that was a scoping calculation with respect to what we could expect for the contaminant migration to be and what it would take to capture that plume. That was a two-dimensional plume model as far as I remember. So it was in the very early stages of the design process. This was, by no means, a regress calibration of the model.

Q. So for your modeling of chromium 6 at Hanford, did you have a calibration target for the chromium?

A. You mean for this particular application?

Q. Well, the idea was that you did modeling of chromium 6 predict inned the future, right, to determine the best remediation strategy; right?

A. Yes.

Q. And you say that you calibrated the model with chromium 6 data; right?

A. Correct.

Q. What was calibration target?

A. There wasn't a single calibration target because the dataset was too small for that. This was again a visual qualitative calibration of the model because there were not enough data for us to

use for a rigorous calibration.

So again, this model was created with best information available at the time to be used as a scoping calculation for how the remediation system could be designed.

Q. Not just how it could be designed. You made recommendations to the federal government on how to design their remediation at Hanford based on this model; right?

A. Well, there are additional dimensions to this. This is only one part of the process at the time that used this modeling to estimate what the migration could be. As part of that effort, there's also recommendations for monitoring to collect additional data and see whether these predictions can be accurate so adjustment to the remediation scheme can be performed.

Q. Well, we're going to look through the paper.

You agree with me that you and your colleagues made recommendations based on this model at the time in 2010 on what to do to meet 2012 and 2020 goals on remediation. You used the model to do that then; right?

A. That was preliminary estimates that they

were developed using a scoping calculation and a model that was calibrated to limited data at the time to guide the remediation process. The recommendations that came out of this were essentially suggesting that wells could be placed at several locations to start containing the plume.

But there is a lot more that goes with it, which is monitoring program, collection of additional data and adjustments to the remediation effort, which has happened over the year since then.

Q. Turn to -- I know you don't have numbers on yours, but toward the end, there's a Results and Discussion section.

Do you see that?

A. Yes.

Q. Under Results and Discussion, you've written, "The proposed design for attainment of the 2012 and 2020 goals consist of the following as a minimum."

And you have six bullet points of recommendation of your proposed design; correct?

A. Correct.

Q. And that proposed design includes, among

other things, 40 new -- I'm sorry -- yeah, 40 new extraction/injection wells in the 100-H area and 30 new extraction/injection wells in the 100-D; correct?

A. Correct.

Q. So at least 70 new wells among other recommendations you were making at the time; correct?

A. Yes.

Q. And that based on this model that we're talking about right now with the information you had available at that time; correct?

A. That was an initial proposal, yes.

Q. And the modeling that you did to make that proposal, you just -- you didn't have a calibration target, right, for your chromium 6 model?

A. There were not sufficient data to do that. Again, this was a design effort to start the remediation process and provide a framework for developing the remediation scheme, which was further updated in years to come.

In fact, this model here was just the basis for what became a much more expensive model after that, multiple layers. There was additional

efforts in more recent years to do more focused modeling and refine the process. So this is just a snapshot of the work that was done to design the remedial scheme.

MS. BAUGHMAN: I'm going to object as nonresponsive to everything after the initial first sentence of the answer.

BY MS. BAUGHMAN:

Q. Let me go back to the page 4 and the parameter values model calibration.

When you're talking about these contours that you used --

A. I'm sorry. Can you give me a second to go back there?

Q. Talking about the water level contours that were calculated and compared to contours in published reports. Were calculations done regarding the goodness of fit of those contours?

A. No. That wouldn't be meaningful at the time because the monitoring network at the time was very limited. So there were only a few data available. On the basis of that, water level maps were created using interpolation methods, for example, as an interpretation of these data across a much larger are and the model attempted to get

as close to these water levels as possible so we can have some confidence that the model is representative to some extent to the limited data available.

Q. With respect to chromium 6 at the time, what method did you use to determine whether your predictive model values reasonably fit measured data?

A. The predicted values could not match data because there were no data available at the time. This was a predictive calculation to determine whether the limited information available at the time and dissolved chromium plume that was delineated on the basis of these limited data, where it was possible to migrate to and what would be needed to contain that plume. That was the level of effort at the time.

Q. So you didn't have data to measure what your predictions -- to say whether your predictions would be accurate; fair?

A. I could not have data from the future to evaluate whether my predictions were correct. That came afterwards, and adjustments were made to the design on the basis of these new data.

Q. So had you calibrated at this time, in

2010, your chromium 6 with past chromium data?

A. We had very limited data over a short timeframe as wells were installed, and data were collected. Those provided the basis of limited interpretation of the extent of contamination in the aquifer. On the basis of that limited interpretation we were asked to evaluate the plume migration in the future knowing, of course, that additional data would be collected in the future and those calculations would be updated.

Q. But at that time in 2010, what analysis, what method did you use to determine how -- let me ask you this: Had you done a sensitivity analysis or an uncertainty analysis with regard to your predictions of chromium 6 levels with a different remediation?

A. Well, actually an uncertainty analysis has been done.

Q. No, at this time in 2010. That's what I'm asking. Had it been done then?

A. That's what I'm providing. Yes. During that time, not presented in this paper, a sensitivity and uncertainty analysis was done to see based on the limited information available what could be possible plume migrations and what

the remediation system could do to contain that plume migration in the future based on the limited data available. And, in fact, a sophisticated uncertainty analysis was done at the time to do that again with the data available at the time.

This is a scoping calculation that is very common in what we could. Based on limited data, we're try to see what is possible to happen. We do not determine what happens. We evaluate what is possible to happen.

Q. Your testimony under oath now is that in 2010, you did an uncertainty analysis with respect to the transport model for chromium 6.

A. We did an uncertainty analysis that evaluated the uncertainty of the hydraulic conductivity fields that would impact plume migration in the aquifer under the remediation schemes.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. I'm talking about your uncertainty analysis with regard to your predictions of chromium 6 distribution.

Did you do an uncertainty analysis for

that in 2010?

A. Yes. The uncertainty analysis we did for the model looked at the uncertainty of the hydraulic conductivity fields in the groundwater flow model and the impact of that uncertainty in the predicted concentrations in the aquifer treatment system and the extraction wells.

Q. Your uncertainty analysis focused on the groundwater flow model; right?

A. The uncertainty analysis looked at the conduct activity fields and how those would impact concentrations, yes.

Q. That's the flow model, isn't it?

A. That was the flow model, yes.

Q. Not contaminant transport?

A. No. At the time, that was not the scope of that evaluation.

Q. So at the time in 2010, you had not done an uncertainty analysis regarding contaminant transport; fair?

A. We looked at the uncertainty of the transport simulations because of the variability in the hydraulic conductivity fields.

MS. BAUGHMAN: I'm going to object as nonresponsive because I don't think you're

answering the question.
BY MS. BAUGHMAN:
Q. Did you do a history matching with regard to chromium 6 concentrations for your modeling in 2010 at Hanford?
A. For this modeling it was impossible to do because we had very limited data. We have done a lot more modeling work that goes back in time and covers 10 or 15 years of available data for history matching.
MS. BAUGHMAN: Object as nonresponsive everything after "it was impossible to do."
BY MS. BAUGHMAN:
Q. I understand what you're saying, because you're saying you did it then you didn't do it.
At the time in 2010 when you made these recommendations regarding the remediation strategy model, had you done history match for chromium 6 concentrations?
A. This particular model, the only thing that we looked at was one year's worth of data for this scoping calculation. I'm only adding that there's a lot more modeling work that was done at Hanford where we included history matching over a long period of time.

MS. BAUGHMAN: Object as nonrsponsive.
BY MS. BAUGHMAN:
Q. Talking about this paper and the work presented in this paper. For what's presented in this paper, was history matching done? Had it been done for chromium 6?
A. No. There was in history matching in this model. The conditions in 2008 was used as initial conditions for the scoping calculations with respect to the model, this particular model.
MS. BAUGHMAN: I'll object as nonresponsive to everything after "no."
BY MS. BAUGHMAN:
Q. Back to the initial conditions issue in a minute. The modeling that you did that's presented in your 2010 paper, you used one year of data, like you said. That was the flow data from 2008; right?
A. Correct.
Q. And you modeled 12 years into the future; is that right?
A. Yes.
Q. On page 5, this page --
A. Yes.
Q. On number three on that page, you've got

the phrase "aquifer testing data are limited." Do you see that?

A. Yes.

Q. Do you know how many aquifer tests you had at the time?

A. I do not recall, but there were very few.

Q. I don't know how to pronounce this word. Kriging?

A. Kriging.

Q. The paper describes under item number four on this page, model calibration describes the use of kriging for your model's hydraulic conductivity; right?

A. Correct.

Q. Hydraulic conductivity, that's an important parameter when you're simulating groundwater flow; right?

A. It is an important parameter.

Q. Probably the most important one; right?

A. I wouldn't say that. It's very important parameter.

Q. My understanding is kriging is a statistical method used to estimate values at locations where data isn't directly available; is

that fair?

A. Yes. It's an interpolation technique.

Q. So you estimated initial mean values for the hydraulic conductivity using your limited aquifer test data; is that right?

A. That is correct.

Q. That's because you didn't have hydraulic conductivity data that covered the entire study area?

A. Of course.

Q. And then those values were updated in the calibration process; right?

A. Yes, some calibration again based on the limit data available at the time.

Q. Just to be clear, you adjusted hydraulic conductivity using model calibration; right?

A. Correct.

Q. And that's an appropriate methodology; right?

A. In general, yes.

Q. Adjusting model parameters during the calibration process, that's a standard practice in groundwater modeling; right?

A. We do adjust parameter values during model calibration on the basis of input data that

we have available and calibration data.

Q. The next page talks about this in the second full paragraph about effective porosity and a specific yield. Those two parameters, you determined those used model calibration as well; right?

A. Yes. That is correct.

Q. Then if you look at Contaminant Transport Model, the heading on the page we're on right now, do you do the heading Contaminant Transport Model?

A. Yes.

Q. It says, "The migration of chromium 6 in response to current and projected well operations in the 100-HR-3 area was simulated to support the remedial optimization process design for attaining the 2012 and 2020 river protection and aquifer cleanup goals."

Did I read that correctly?

A. Yes, you did.

Q. So you were using the contaminant transport model in your projections to determine the best remedial strategy; right?

A. We used the groundwater flow model and the contaminant transport model for scoping

calculations to see what kind of a design we should have based on the limited information to protect the river and provide aquifer cleanup, a projection of aquifer cleanup.

Q. So under the heading Contaminant Transport Model, then the next subheading is Initial Conditions for that Model; right?

A. That's correct.

Q. You used chromium 6 concentrations from 2008; correct?

A. Yes.

Q. And that was basically like your source or mass loading. Like that was how much is there to figure out how to decrease it; right? Initial conditions your source loading for this model; right?

A. No. There were no source loading in this model actually. This only considered the delineated chromium 6 plume based on the limited data available and being conservative with respect to the concentrations we used so we don't underestimate that plume size when we perform these calculations. That's why the maximum concentrations were used.

Q. And then it says here to attain the

initial conditions, you, in this second full paragraph, you said use a stepwide procedure. First, the quantile kriging used to obtain the contours for chromium 6, right, and that would be estimation based on your 2008 data; is that right?

A. Correct.

Q. Then it says, "The contours were digitized and manually adjusted to reflect institutional knowledge of the historical plume migration and the local conditions affecting the actual chromium 6 distribution in the aquifer."

Did I read that correctly?

A. Yes.

Q. So that means that manual adjustments to your initial conditions of how much chromium 6 was in the water were made based on professional judgment; right?

A. What we did, the data from 2008 included a number of wells that were sampled during that year. Other wells were not sampled that year. Therefore, if we only relied on the data from that particular year, we would have missed known extent of the plume from previous years through its migration since it was first introduced in the aquifer.

So we used additional data to provide a more conservative delineation of that plume so we can make sure that in our design, we don't underdesign the system and miss some of that mass.

Q. It says here you made manual adjustments to reflect institutional knowledge of the historical plume migration under local conditions; right?

A. That is correct.

Q. And those manual adjustments means you went in and you added or changed the data; right?

A. We enhanced data asset, yes.

Q. That was based on professional judgment, wasn't it?

A. Yes.

Q. Page 9, two pages forward, there's a heading called Model Assumptions and Limitations. Do you see that?

A. Yes.

Q. It's standard protocol when you write up and you present a report of a model to present the assumptions and the limitations of the model; right?

A. In general, yes.

Q. A good practice in your field is that if

you're publishing or presenting a report on the model, you would say what are the assumption of this model and what are the limitation; right?

A. Of course.

Q. It's fair to say all groundwater models include assumptions?

MR. ANWAR: Object to form.

THE WITNESS: That's a blanket statement, yes. In general, yes, that applies to every model.

BY MS. BAUGHMAN:

Q. All groundwater models have limitations?

A. That is also correct.

Q. One of your assumptions and limitations was that that second bullet point, you said that a sensitivity analysis should be performed regarding a vertical no flow boundary.

Do you see that?

A. Yes.

Q. This publication doesn't mention any sensitivity analyses that had been done. Had a sensitivity analysis been done for this model at the time?

A. This model was the springboard of the modeling work that was done over several years.

So that model evolved to a three-dimensional model eventually with additional layers and all the proper evaluations of the model sensitivity.

Q. As of 2010, had you done your sensitivity analysis?

A. No. That was not done. That's why it was included in there as an assumption and limitation.

Q. We already talked it. If you turn to two pages ahead, the Results and Discussion, that Results and Discussion presents your recommendations at the time of the remedial strategy based on your modeling; right?

A. Yes. That is correct.

Q. And you said at the bottom of that page, "Given the modeling assumptions and limitations, the calculated chromium 6 distribution at different times in the future should be considered relative estimates and not absolute predictions of the actual plume migration patterns that will prevail."

Did I read that correctly?

A. Yes, you did because, we're highlighting the fact that we didn't have enough information to say with certainty that that would be plume

migration in the future.

Q. At the time you had not done an uncertainty analysis with respect to chrome 6; right?

MR. ANWAR: Object to form.

THE WITNESS: Not as part of the work that is presented right here.

BY MS. BAUGHMAN:

Q. When you say that work that's presented here in the paper that we've marked at Exhibit 3, does it follow like proper model calibrations practices?

MR. ANWAR: Object to form.

THE WITNESS: It did follow practices that could be applied to the conditions presented herein. In other words, we did look at the comparison of water levels, measured to calculate it. We used input data available. And that calibration stopped there because we didn't have enough information to develop a very detailed model. And that's why this model was only used for scoping calculations understanding the limitations that were presented here.

BY MS. BAUGHMAN:

Q. So your opinion is that whether proper

model calibrations practices have been done depends on the case. It depends on the model.

A. It depends on the intended purpose of the model, and it also depends on what data are available to perform that calculation, and, therefore, how confident you are in the calibrated model that you have.

Q. Is it also true that -- let me ask you this: Are there published standards in your field on how to do an uncertainty analysis?

A. Standards for performing an uncertainty analysis?

Q. Yes.

A. There are various methods for performing uncertainty analysis.

Q. I mean, within your profession, is there like a guideline or a standard where it says okay this is how to do an uncertainty analysis for groundwater flow and contaminant transport modeling?

A. Not that I'm aware of.

Q. What about for sensitivity analysis, is there a standard within your field that's accepted that says this is how the sensitivity analysis should be performed for groundwater flow and

contaminant transport modeling?

A. I would have to go back and look at the standard of calibration and see if sensitivity analysis is mentioned. However, sensitivity analysis in many ways is a very standard approach with respect to how we deal with it in our profession. We all follow the same approach, I would say, to validate the sensitivity of the different parameters.

Q. But some models or some modelers might evaluate sensitivity for two parameters or five parameters or eight parameters.

Is there a guideline that says when you model the transport of contaminants, you need to or you must do a sensitivity analysis for these specific parameters in this specific way? Does that exist?

A. Not that I know of. This is something you evaluate on a case-by-case basis.

Q. Were any of your proposed design methods or alternatives implemented based on this work that's presented in Exhibit 3?

A. A lot of what is presented here in some form or shape was actually implemented as an interim remedy to initiate the containment of the

contaminant plume and start mass recovery from the well, but it was enhanced over time based on additional data that became available.

(Spiliotopoulos Exhibit 4 was marked.)

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, the court reporter has handed you Exhibit 4 to your deposition.

Is Exhibit 4 your expert report that was presented in this litigation?

A. That appears to be the case, yes.

Q. Is that your signature on the first page?

A. Yes.

Q. Did you write this report?

A. Yes, I did.

Q. Did anyone assist you other than counsel?

A. No. I wrote my report myself.

Q. We'll get to the bills or the invoices later, but I notice on the invoices from S.S. Papadopulos, there are a lot of people who worked on this project at your firm.

Are you saying no one helped you write your report?

A. No one helped me write my report.

Q. Does your report that we've marked as Exhibit 4, does that contain all of the opinions that you will testify to in this litigation?

A. Yes.

Q. And does your report contain the basis and reasons for each of your opinions that you will testify to in this litigation?

A. At a different level of detail, yes.

Q. What do you mean by "a different level of detail"?

A. Well, in many cases I provide an opinion, and I offer a reason for that. There is underlying details. None of them are listed at that level of detail in my report. There's a lot that comes with it. I provide an opinion that describes the issue at hand and the critique that I provide. It doesn't have all the data or everything I could say it. If you ask me a question, I will provide additional information.

Q. Did you purposely leave out any data or references that support any of your opinions in Exhibit 4?

A. No. I did not I just provided the description of my opinions and the critique on the model. But there's a lot that goes with it.

(Spiliotopoulos Exhibit 5 was marked.)

BY MS. BAUGHMAN:

Q. Our court reporter has marked Exhibit 5 to your deposition, which is a one-page errata sheet.

Are you familiar with that errata sheet?

A. Yes.

Q. So Other than the two corrections that are identified in Exhibit 5, your errata sheet, have you identified any other changes that you wish to make to your report?

A. Not at this time, no.

(Spiliotopoulos Exhibit 6 was marked.)

BY MS. BAUGHMAN:

Q. The court reporter has handed you what I marked as Exhibit 6 to your deposition, which is the Supplemental and Corrective Reliance List that's been provided to us with respect to your report.

Have you reviewed this document?

A. Yes. I have looked at the information that is included in this document.

Q. Did you prepare it?

A. I provided information to our secretary that was putting this stuff together. So I

provided references, yes.

Q. Does your Supplemental and Corrective Reliance List list all of the documents you've reviewed and you're relying on for your opinions in this case?

A. It includes the documents that were available to me and I reviewed a different level of detail.

Q. So to be clear, does Exhibit 6, your; Supplemental and Corrective Reliance List, include all of the materials that you considered in reaching your opinions expressed in your expert report in this case?

A. At a different level and extent, yes.

Q. So I think what you're trying to tell me is you didn't review every document in Exhibit 6 cover to cover?

A. No, I did not.

Q. Some of them you paid more attention to than others; fair?

A. That is correct.

Q. But are there any documents or data or materials that you are relying on for your opinions in this case that are not on Exhibit 6?

A. Not that I can think of at the moment

besides perhaps that came to my attention as part of the depositions that I have attended, in other words, information that was included in these depositions. I'm not sure depositions if depositions are included in here.

BY MS. BAUGHMAN:

Q. Well, I'll help you out on that. Like the second page lists the deposition of Dr. Aral and the deposition of Mr. Davis. And then on page 6, you've got the deposition of Dr. Jones and the deposition of Dr. Konikow. And I'll tell you that this was dated or provided to us on February 28, 2025.

So given that, is there any document, data or information you're relying on for your opinions that is not provided on Exhibit 6?

A. Dr. Maslia's deposition of last week is not there. That's what comes to mind. I don't think I can think of something else right now that is not there.

Q. If we added in Mr. Maslia's deposition to Exhibit 6, it would be complete; fair?

A. I would think so.

Q. You don't have anything else to add today?

A. Not off the top of my head, not at this time.

Q. Have you actually read all of the documents that are on Exhibit 6?

A. No, I did not.

Q. Is there a way for us to be able to tell which ones you read and which ones you didn't?

A. I don't think so. There are things that I may have checked in different documents. There's certainly the ATSDR documents that I read in more detail depending on the content and what was relevant to my opinions.

Q. Why would there be documents on Exhibit 6 that you haven't read? Why would those be included?

A. If they were available to us.

Q. In other words, the lawyers provided you the documents?

A. We have these documents, yes, available.

Q. So anything the DOJ lawyers said to you you included on your reliance list even if you didn't read it; is that fair?

A. It is included in here because I'm assuming that this is something I needed to disclose as being in my possession and available

to me to review.

Q. You've attended by Zoom many depositions taken in this case; right?

MR. ANWAR: Object to form.

THE WITNESS: I have attended the depositions of the people listed here including Mr. Maslia's deposition last week.

BY MS. BAUGHMAN:

Q. You've also attended Dr. Waddill's deposition, right, by Zoom?

A. No, I did not. I don't believe I did. I don't recall attending it. I could be wrong.

Q. What about Renee Suárez?

A. That's a good question. I'm not sure.

Q. Susan Martel?

A. No.

Q. Did you assist with preparing any of those individuals for the depositions?

A. No.

Q. Have you had any calls or meetings or Zooms or other communications with Dan Waddill about this case?

A. No.

Q. You refer in your report to Dan Waddill as the Navy's water modeling expert. That's on

page 8 if you want to look at it.

My question you to is: What makes Dr. Waddill an expert on modeling, groundwater modeling?

MR. ANWAR: Object to form.

THE WITNESS: That's how he has been described in different documents where his opinions are stated.

BY MS. BAUGHMAN:

Q. Are you familiar with Dr. Waddill's expertise, to the extent he has it, in groundwater modeling?

A. No.

Q. Do you know whether Dr. Waddill has ever developed a model, a groundwater model?

A. I'm not aware of his work.

Q. Do you know whether Dr. Waddill has even read a groundwater model himself?

A. I don't know. I'm not familiar with his work.

Q. Have you reviewed the rebuttal expert reports of Dr. Konikow?

A. Yes, I have.

Q. Did you review Mr. Maslia's rebuttal report?

A. Yes.
Q. And what about Dr. Jones and Mr. Davis?
A. Yes.
Q. Dr. Sabatini?
A. No.
Q. We've already talked about Dr. Konikow. Do you know any of the others personally? Do you know Mr. Maslia personally?
A. No. I only saw Mr. Maslia in 2005 during the expert panel meeting event.
Q. That's the only time you've ever seen him in person?
A. Yes.
Q. What about Dr. Jones and Jeff Davis, do you know them?
A. I've never met them in person.
Q. Dr. Sabatini?
A. No.
Q. I assume you never worked with Mr. Maslia or Dr. Jones or Mr. Davis or Dr. Sabatini?
A. No.
Q. You had heard of Mr. Maslia before this case. Had you heard of any of the others other than Dr. Konikow?

A. I know Mr. Maslia from this case only. Mr. Konikow I mentioned. The other ones, Dr. Aral I know by name, but I'm not familiar with his work. Dr. Jones, to the extent that he was involved in the development of GMS, which is a software that people use in our industry, but not Mr. Davis.

Q. What's your opinion of the professional reputation of Mr. Maslia in the groundwater -- in the hydrogeology industry?

A. I don't have an opinion because I'm not familiar with his work. I'm only familiar with work done for the ATSDR. I'm not familiar with this work otherwise.

Q. Have you reviewed any of the Mr. Maslia's publications in the peer-reviewed literature?

A. I've only looked at the Auburn case report in trying to see what kind of connection it may have, how it could compare with the work done by ATSDR for the calculation.

Q. So you read his publications on the Dova. Anything else?

A. I have not.

Q. Your report mentions on page 1 that you

reviewed interview summaries. Interviews of who?

A. I'm sorry. Where are you?

Q. So the second to last paragraph on Section 1, page 1, talks about all the different kinds of materials you've reviewed. And one of them says interview summaries.

Which interview summaries did you review?

A. I'm trying to remember if it was just the information we collected during the site visit and with the scope of people there, and they provided information on the operation of the treatment system and the components of the treatment system.

Q. I'm sorry. So you went to site. I'm going to ask you about that. So you're saying there were interview summaries made regarding your visit to Camp LeJeune?

A. As we took notes during the site visit of the information we got from people working at Camp LeJeune on past operations and knowledge of the system components.

Q. And did you do that yourself? You took notes from those site visits?

A. I do not recall if they were just my

notes or others.

Q. How many people were with you?

A. There were a large group of people including the lawyers, other experts, I believe.

Q. And when was this meeting? When was this visit?

A. May of 2024.

Q. And who did you interview, or who did you speak to about past Camp LeJeune operations?

A. I don't remember the names of the people that we met. But there were people like operators of the treatment system. I'm trying to remember the name of the person that gave us the introduction. Williams, I'm trying to remember if that's right.

Q. Scott Williams?

A. Scott Williams, yeah, because he accompanied us through the whole site visit.

Q. So you, yourself, took notes at the site visit; is that right?

A. I think I did.

Q. And when you refer to that you relied on interview notes, you also reviewed notes of other people from that site visit?

A. No. That would be my notes of people

that gave us information, but I don't recall. I can't remember the notes that I took.

Q. Are those the only interview summaries you're relying on, the notes that you took at your site visit?

A. I'm trying to remember if I had anything else that I relied on. I can recall, off the top of my head, if there was something else.

Q. So that's the only time you been at Camp LeJeune, that one time in May 2024?

A. That is correct.

Q. How long were you there?

A. One day.

Q. All day long?

A. Yes. It was a day visit, sometime in the morning.

Q. You remember Scott Williams. Do you remember anyone else that you gathered information from?

A. I don't remember their names, but there were different people involved in the operations and providing us the tour.

Q. What did you tour specifically?

A. Things that I can readily recall were the treatment systems and Tarawa Terrace and

Hadnot Point. And we stopped at different locations like the landfill area Hadnot Point. We toured by bus those two parts of the base. And then we went by bus all around the other side of the river, the other areas including the training zone as far as I remember. These are the things I can readily recall of my visit.

Q. The Tarawa Terrace treatment plant is shut down; right?

A. Yes.

Q. But you were still actually able to tour it?

A. We toured plant to see where water was coming in, where the tanks were, trying to get the lay of the land with respect to how water was coming to treatment plant and where samples were taken, for example.

Q. So it's still existing. It's just shut down, not operating?

A. I don't know its current operation.

Q. Well, when you toured the Tarawa Terrace water treatment plant, was it operating?

A. There was water there, yes.

Q. So they were treating water at the plant?

A. I do not recall what the operations were at the time.

Q. Do you know what the Tarawa Terrace water treatment plant is being used for now?

A. I don't know its current use.

Q. Tell me, is there information that you gained from your site visit at Camp LeJeune that you're relying on for your opinions?

A. Other than getting a sense of the area extent and the lay of the land, like I said, nothing else.

Q. Did you take any photographs or videos of Camp LeJeune while you were that?

A. I did not personally take pictures. I appointed the lawyers to take pictures that could be of interest in terms of remembering the lay of the land.

Q. Are the lawyers the only ones who took pictures while you were there?

A. Yes, as far as I recall.

Q. Was there video taken?

A. I do not recall.

Q. How long have you been consulting with the Department of Justice regarding Camp LeJeune?

A. As far as this litigation, I started

working maybe sometime in 2023, if I remember correctly.

Q. You said as part of this litigation. Have you done work regarding Camp LeJeune that's not part of this litigation?

A. I was on the expert panel in 2005. So that timeframe.

Q. What were you doing -- who was employing you to be at the expert panel in 2005?

A. In 2005 Gordon Bennett and Remy Hennet asked me to attend the meeting so I can see what is discussed about the development of the model at the time, the data available, and how they were considered, and just listen in and provide them with information about that.

Q. Were you working for a particular client?

A. I didn't know at the time who the client was. I was just asked by the principal, Dr. Bennett and Dr. Hennet to attend the meeting. So I didn't know the details.

Q. Did you bill your time to a specific file?

A. My time was billed on the project, yes.

Q. What project was it?

A. I don't recall the name of that.
Q. Was it for the Department of Justice?
A. Well, at the time for me, it was project the number. I believe it was part of consultation to the Department of Justice at the time.
Q. Did you take notes at the expert panel meeting?
A. I don't recall.
Q. Did you submit any kind of report or writeup or email to Mr. Gordon Bennett and Remy Hennet about what you learned?
A. I briefed them when I came back because that was the intent of my visit. So I told them what I heard, but I do not recall if there were any notes involved.
Q. Other than attending the expert panel in 2005, did you do any other work related to Camp LeJeune prior to being retained in this case in 2022?
A. I do not recall doing any work after that time. No, off the top of my head, I do not recall doing other work.
Q. Are you aware of work that Spilotopoulos -- I'm sorry -- that Papadopulos & Associates has done for the DOJ prior to 2022

regarding Camp LeJeune?

A. I know Dr. Hennet has provided services, but that's as far as I can go with what I know about the project. I don't know any other details or who else has been involved in that.

Q. Do you know what he's done before 2022 for the DOJ at Camp LeJeune?

A. Not in any detail, no.

Q. And you did not assist him with that work other than attending the one expert panel meeting?

A. That is correct.

Q. Has S.S. Papadopulos had any role regarding remediation of Camp LeJeune?

A. I'm not aware of any of that.

Q. Have you at any time recommended any testing done at Camp LeJeune?

A. No.

Q. Or any specific remediation?

A. No, I have not.

Q. Has all of your work related to Camp LeJeune been for the purpose of litigation?

A. I'm not sure how to answer that question. My participation in 2005 was part of work that SSPA or Dr. Hennet was doing at the

time.

Q. Let's separate that out to be clear. You don't know whether -- for what reason Dr. Hennet asked you to be at that expert panel meeting, whether it was for litigation or something else; right?

A. I have no idea.

Q. I'm going to set that aside.

After that, the next time you did work on this case was when you were retained for this litigation. I'm sorry. After going to the expert panel meeting, the next time you did work related to Camp LeJeune was part of this case; correct?

A. As far as I can recall, yes.

Q. So other than attending one expert panel meeting, it's fair to say that all of your work, your professional work related to Camp LeJeune has been done for the purpose of litigation; right?

A. To the best of my recollection, yes. It's 2023, so it was part of that litigation.

Q. Other than attending one expert panel meeting, you haven't done any other work related to Camp LeJeune that was not conducted for the purpose of litigation. True?

MR. ANWAR: Object to form.

THE WITNESS: Of this litigation?

BY MS. BAUGHMAN:

Q. Yes.

A. No. For this litigation is the work that is presented here in my expert report.

Q. The answer is kind of confusing because you said no, but I think you mean yes. So let me just ask it again to be clear.

Other than attending one expert panel meeting, all of your related to Camp LeJeune has been conducted for the purpose of this litigation; correct?

A. Work that I did back in 2005, that included that visit at the expert panel meeting, I do not recall. Maybe I reviewed some documents, for example, and things like that back at that time. That's all I can remember about the work that I have done with respect or related to Camp LeJeune until my involvement in this litigation.

Q. Other than attending the expert panel meeting in 2005, can you identify any work that you have done related to Camp LeJeune in your career that was not related to litigation, specifically this litigation?

A. No other work that I have done is

related to this litigation. If I understand your question correctly, I'm saying that work that I did prior to my involvement in this litigation here for which I provided an expert report, work that I did prior to that was related to my visit in Atlanta for the expert panel meeting and some review of reports and other documents at the time.

Q. Let me try it again. Let's try it this way. Other than you attending the 2005 expert panel meeting and reviewing some reports and documents at the time related to that panel meeting, other than that, can you identify any work that you have done that was not -- that was related to Camp LeJeune and not related to litigation?

A. I do not recall any other work that I have done.

Q. So it's fair to say that the vast majority of your work related to Camp LeJeune is litigation related; right?

MR. ANWAR: Object to form.

THE WITNESS: This litigation work here, yes.

BY MS. BAUGHMAN:

Q. When you attended the expert panel

meeting, you were just an observer right?

A. That is correct.

Q. And you don't know whether the DOJ paid for you to be there or not. You just know that you billed it to whatever code your boss told you to bill it to; right?

MR. ANWAR: Object to form.

THE WITNESS: Yes. I provided my expenses to our accounting.

BY MS. BAUGHMAN:

Q. Did you speak at the expert panel meeting in 2005 about Camp LeJeune?

A. No, I did not.

Q. That wasn't a very good question.

The expert panel meeting in 2005, it was about the water modeling for Camp LeJeune; right?

A. Yes.

Q. Did you speak at that meeting?

A. No, I did not.

Q. And the panel was presenting methodologies -- to be clear let -- me back up.

That expert panel had ATSDR scientists presenting to the panel their methodologies that they were using to model groundwater flow and contaminant transport at Camp LeJeune; right?

A. At the time, yes, they presented methodologies and I believe some preliminary approaches to performing groundwater flow modeling. I believe they had some draft results of discussions revolved around how this model was constructed. The panel experts provided comments. And there were some discussion of the next steps, I believe, that would include transport modeling as well.

Q. And the focus at that time at that 2005 expert panel meeting was about Tarawa Terrace; fair?

A. That is correct.

Q. The subject of your expert report in this case, Exhibit 4, is a critique of some of those methodologies that were presented at that meeting; right?

A. It's a critique of the implementation of the methodologies for reconstructing contamination history at Tarawa Terrace.

Q. Did you raise any of the concerns you about ATSDR's modeling methodology or implementation of it with the panel when the observers at the meeting were given an opportunity to speak?

MR. ANWAR: Object to form.

THE WITNESS: I don't think I was in a position to offer an opinion at the time. I was just listening to what they were presenting as an approach. I didn't have an opinion at the time.

BY MS. BAUGHMAN:

Q. You said you had reviewed some documents; right?

A. Documents that I reviewed at the time, I think they were general about groundwater modeling, hydrogeology, something to give me some understanding of the setting at Camp LeJeune as far as I recall.

Q. So when you listened to the ATSDR present regarding their methodologies and their preliminary results, at that time, you didn't have any critique to provide them?

A. No.

Q. You didn't have any criticisms to voice?

A. I didn't know enough about it, and I was not familiar with that work at all. So I was just listening in to provide information to Dr. Hennet and Dr. Bennett on what was discussed. That was the extent of my involvement at the time.

Q. Just to be clear, based on your review

of documents and your attendance at that 2005 meeting, you did not make any recommendations to the ATSDR regarding the methodologies that they were using for groundwater flow and contaminant transport or how to implement them? You did not make any recommendations; right?

A. I did not.

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. You did not?

A. I did make any recommendations. I was not familiar enough with the project to do that.

Q. So you didn't make any recommendations to ATSDR; right?

A. I did not.

Q. You didn't make any comment at the meeting to the expert panel right?

MR. ANWAR: Object to form.

THE WITNESS: No, I did not make any recommendations.

BY MS. BAUGHMAN:

Q. Did you report back to Gordon Bennett and Remy Hennet regarding your thoughts on how the ATSDR should do anything differently than what they were doing?

A. Like I said, I was not familiar enough to provide critique, opinions or anything to that effect. I only provided a briefing on what I heard that ATSDR was doing and some of the comments and thoughts that I heard from the panel experts to the extent that I could fully assess them and understand them within the context of this project and my very short involvement in it.

Q. The ATSDR modeling project went on, as you know, for several years; right?

A. Yes.

Q. To your knowledge, did you or anyone else from S.S. Papadopulos make any recommendation to ATSDR about the methodologies they were using for groundwater flow and contaminant transport or the implementation of them or anything they should do differently?

MR. ANWAR: Object to form.

THE WITNESS: I'm not aware of anything like that.

BY MS. BAUGHMAN:

Q. Dr. Hennet, he was involved in a more detailed and a higher level of detail working at the DOJ at that time than you; right?

MR. ANWAR: Object to form. Foundation.

THE WITNESS: I do not know what his involvement was.

BY MS. BAUGHMAN:

Q. To your knowledge, did Dr. Hennet ever make a recommendation to the ATSDR that they should do anything differently with respect to their groundwater modeling project for Camp LeJeune?

A. I do not know.

MR. ANWAR: When you're at a good place, we're coming close to 12:30. It might be a good time for a lunch break.

MS. BAUGHMAN: Sure. We can take a lunch break.

THE VIDEOGRAPHER: Off the record at 12:27.

(Recess from 12:27 p.m. to 1:35 p.m.)

THE VIDEOGRAPHER: On the record at 1335.

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, you know you're still under oath?

A. Yes.

Q. Did you talk to the DOJ counsel about any of your substantive testimony during the lunch

break?

A. No, I did not.

Q. Earlier today we had a discussion about your interview notes, in particular notes that you and perhaps others took when you visited Camp LeJeune in approximately May, 2024. I'll make a formal request that you produce those notes.

Do you have any problem with producing them?

MR. ANWAR: I will just jump in. We'll discuss, but we object. We served our objections on the basis of work product privilege as that was -- all of that work was conducted in anticipation of litigation or in litigation.

So our view is that is work product privilege. But we'll note your request. That's protected by the work product privilege, but we'll note your request. I'm happy to meet and confer with you on it.

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, you're relying in part on your visit to Camp LeJeune for your opinions in this case; right?

A. With respect to the opinions that I provided here, I do not think that anything that I

saw during the visit form the basis for my opinions.

MR. ANWAR: I'm sorry to interrupt you. You're asking about the 2005 notes or the site visit notes? I'm sorry if I confused the issue.

MS. BAUGHMAN: I think it was 2004.

MR. ANWAR: 2004?

MS. BAUGHMAN: Yeah.

THE WITNESS: 2024 site visit.

MR. ANWAR: I'm assuming you're referring to that one; right?

BY MS. BAUGHMAN:

Q. May 2025 hasn't happened yet. You said May 2024 is when you went there?

A. Yes, last year.

Q. That's the one I'm talking about. You went to Camp LeJeune, and you testified that you took notes; right?

A. I believe I took some notes, yes.

Q. Right. And is it your testimony you're not relying for your opinions in this case on anything that you learned during your suit visit at Camp LeJeune?

A. No. The things that I heard about and people described to us did not help me form my

opinions.

Q. So when you testify, you're not going to tell the court that you have like increased knowledge compared to someone else because you actually visited the site and talked to to the people and you learned something there. That's not relevant. Your site visit isn't relevant at to your opinions; is that true?

MR. ANWAR: Object to form.

For the opinions I provide regarding the modeling work, the things I learned at the site there did not help me in any way.

BY MS. BAUGHMAN:

Q. So on page 1 of your report, you talk about what you did and what you reviewed and what you're relying on for your opinions, and you listed your interview summaries as some of the materials that you reviewed. But you're saying even though you reviewed the interview summaries, your not relying on them for any opinion?

A. I'm saying that the notes that I took with respect to what I saw there and the information that I got during my visit helped me understand the lay of the land, where things are, where the treatment plants are, the Tarawa Terrace

residential area, for example. But that's to form a visual context of the area.

The opinions that I provide here are based -- rely on -- I'm looking at the model implementation. So I have them in my mind, but I don't think that there's something in those notes that I took directly and used them here. I considered them. I remember what I saw. That's why I'm listing it there for completeness. But I don't think there was anything that I took from those notes used them in my analysis.

MR. ANWAR: I just want to clarify my objection earlier. I misunderstood and thought you were requesting any notes that exist from the 2005 panel, 2005 expert panel you had that asked questions about earlier.

To the extent there were notes taken related to the site visit along with photographs and things of the like, that stuff, I believe, has been produced. We're happy to go back and check and meet and confer with you about it. The work product objection that I made was with respect to the 2005 expert panel.

MS. BAUGHMAN: So just to be clear, I'm asking for any notes that Dr. Spilotopoulos

reviewed or took, either took himself or others related to the 2024 Camp LeJeune site visit. But I'm also, now that you bring it up, requesting notes that you took regarding the 2005 expert panel meeting. You say you have those notes. We request that you produce them.

MR. ANWAR: I'll note for the record we served our objections in response to that request, and I believe anything we believe is not protected by the work product doctrine has been produced.

MS. BAUGHMAN: So we'll meet and confer about that after the deposition.

MR. ANWAR: Sure.

(Spiliotopoulos Exhibit 7 was marked.)

BY MS. BAUGHMAN:

Q. I've handed you marked as Exhibit 7 to the deposition, and that is a series of invoices from S.S. Papadopulos to the DOJ that were produced to us. And those are Bates-stamped CLJA_SSPA_INVOICES 1 through 442.

Have you reviewed these documents before?

A. I have seen the document. I haven't reviewed it in detail. This is something that the accounting department has produced.

Q. So you see these are in date order, and page 1 starts for services rendered through August 31, 2022. Do you see that?

A. Yes.

Q. Is that when your work began in this litigation?

A. It is possible. I don't recall the exact date when I started working on this.

Q. So these bills don't identify you by name, but are you the senior hydrologist on the case? In other words, if I wanted to know which of these hours were your work, how would I figure that out based on these invoices?

A. I'm not sure there are other senior hydrologists involved. It could be me, but I do not recall.

Q. What is your title?

A. I'm a senior associate, senior hydrogeologist.

Q. Has that been your title since August of 2022?

A. Probably around that time is when I became a senior hydrogeologist. I'm not the only one, but it sounds right. I don't recall the exact date I got the last promotion.

Q. Who are the other members of your team, people at S.S. Papadopulos who are billing the DOJ for the Camp LeJeune work? Obviously, Dr. Hennet and yourself. Who else?

A. There are several people that I've worked with. I'm not sure this is something to disclose. I have to ask attorneys if this is something that I can disclose.

Q. He didn't object, so you can answer.

A. That's fine. The names that I can recall are Keir Soderberg, Chris Muffels, Zdravka Karanovic. Off the top of my head, these are people that I can think of.

Q. So the first one is Soderberg. How do you spell that?

A. S-O-D-E-R-B-E-R-G.

Q. What's that person's job title?

A. He is a senior geochemist, but I don't know if that falls in this category here with the same title, a generic title for the rank in our company.

Q. Next one you said Muffles?

A. Chris Muffels.

Q. How do you spell the last name?

A. M-U-F-F-E-L-S.

Q. What the job title?
A. I do not recall his -- senior project scientist or senior scientist. I don't recall.
Q. What's the next person?
A. Zdravka Karanovic; K-A-C-A-N-O-V-I-C, same senior project, I think.
Q. Senior project scientist?
A. Yes, I think.
Q. Have you worked with anyone else on this case?
A. I'm not sure I recall other names, off the top of my head, right now.
Q. That would be invoices for work that you've done related to Camp LeJeune that aren't included here, right, because that would be from 2005?
MR. ANWAR: Object to form.
THE WITNESS: This only reflects my work after, whatever, August 2022. To the extent I'm included in the early ones, I don't recall the exact time I start working on this. But it wouldn't include any work prior to that.
BY MS. BAUGHMAN:
Q. But you did have work related to Camp LeJeune prior to August 2022; right?

A. I said before what my involvement in the work related to Camp LeJeune was in the 2005 period as far as I recall.

Q. So that would be invoices for that work; right? They would exist somewhere?

A. I don't know what the accounting practice is for maintaining records. Possibly. I don't know.

Q. You said that you went to -- let's try to find the invoice for the trip to you said in May 2024?

A. If I'm not mistaken. I want to say it was May of 2024. Yes, that looks about right, yep.

Q. So if you look at the invoice with the last number 28, there are employee expenses right related to a rental car and meals.

Do you see that?

A. Yep.

Q. So we can date this that your trip was on May 21 and 22, 2024; correct?

A. Yes, around those dates 21 to 24 perhaps, yes.

Q. So if we go to the end, I see a few. At least since August of 2022, it appears based on

page 42 of Exhibit 7 that it says S.S. Papadopulos billed the DOJ $2,004,131.67; correct?

A. If I'm reading this right, I believe, yes.

Q. And that last bill, if you look at the second to last page, that's for services rendered through January 21, 2025; right?

A. That's what it says.

Q. But you've done a significant amount of work in February and March 2025, haven't you?

MR. ANWAR: Object to form.

THE WITNESS: I do not recall how much work I've done during that time. So I wouldn't be able to characterize that as significant.

BY MS. BAUGHMAN:

Q. Well, we know that you've attended via Zoom the depositions of Dr. Aral, Mr. Davis, Dr. Jones and Mr. Maslia; right?

A. Yes.

Q. And you've prepared for your deposition?

A. Correct.

Q. Did you have anything to do with working on going back to the site in February and then doing new calculations regarding volatilization in response to Dr. Sabatini's report? Were you

involved in that work?

A. No. I was actually out of the country on a different project.

Q. So can you tell me how much time you've billed in February or March 2025 for this case?

A. Not off the top of my head.

Q. Do you keep track of your time?

A. We have an accounting system that we use to register our working hours every week.

Q. So you keep track of it. Do you keep track of it yourself weekly or daily? How do you do it?

A. Daily.

Q. Do you write it down on paper, input it somewhere? How does that work?

A. We have a software system where we log our hours on a daily basis.

Q. When you log your hours, you obviously say who client is that should be billed, right, in the log so they know who to bill?

A. They're billed to a particular project number.

Q. Do you say what you did?

A. It depends. Not always.

Q. Like, for example, if you logged hours

for today, will you say, this was my time being deposed, or would you just put the hours in with no explanation?

A. I would probably put in the deposition or some general description of the work that is done, but not always. It's not required.

Q. Where is that information stored on what you did on a day-to-day basis for the DOJ?

A. That's within our accounting system.

Q. And does S.S. Papadopulos send bills to DOJ that include a log of the tasks that were performed?

A. I'm not aware of this information because I do not handle that.

Q. Well, the file name for the document that was sent to us with this was called 1817 Invoices through January 31, 2025, 013125, without backup.pdf.

Do you know, what does the without backup refer to?

A. I don't know what accounting describes as such. I'm assuming that there will be additional information on the project work, but I don't know what that would be, notes for other.

Q. So you don't know whether DOJ, in

addition to a bill like this, gets some kind of backup that says, for example, what you did for this certain amount of time in that month?

A. I do not recall what the files were that were sent to DOJ and what they contained.

MS. BAUGHMAN: So I'm going to request on the record that we be provided with the backup information and the time tracking that tells us what each person did on a day-to-day basis that backs up the more than $2 million of bills that have been sent.

MR. ANWAR: I'm just going to note for the record we responded to your request for production. I believe we've produced rat required under rule, but we're happy to meet and confer about it.

THE WITNESS: Just to make sure I provide a complete answer on this, that our system has notes. I just do not recall what was produced for this and what is entailed in the other one. Maybe there's more information. I will have to go back and check as well.

BY MS. BAUGHMAN:

Q. In other words, internally at S.S. Papadopulos, there is information about the tasks

that you've performed for the DOJ beyond how many hours you billed in a given month; right?

A. In our system we provide notes, not necessarily always, and I don't know to what detail. It all depends.

Q. Does it depend on the client?

A. Or how general the description is, for example. Sometimes it's not because it's work on something that is a continuous task, for example, so it's not necessary to log every day specific details. I've never been told that there's specific requirements for producing note like that. This is usually for our internal purposes and keeping track of the work that we do sometimes, not always.

(Spiliotopoulos Exhibit 8 was marked.)

BY MS. BAUGHMAN:

Q. I'm handing you what I've marked as Exhibit 8 to your deposition. Exhibit 8 is the notice of your deposition, and then attached to that is a subpoena, and then attached to that is an Exhibit A that has a list of 16 different types of documents that we had requested that you produce to us.

Have you reviewed this and in particular

reviewed Exhibit A?

A. I have reviewed this with the lawyers.

MR. ANWAR: For the record, we provided a written response to each and every one of the document requests.

BY MS. BAUGHMAN:

Q. I want to ask you some questions about what kind of documents you might have in your possession. So if you look at the request No. 2, it ask abs materials in your possession and it lists all different kinds of documents, emails, memoranda, et cetera, in any way related to work performed by you related in any way to Camp LeJeune since 2004 to the present.

Do you have a working file of documents that you've reviewed and you're relying on for this case, for this litigation?

A. As part of this particular litigation, I have the material that is mentioned in my expert report. So I have the backup of that. I have the model files.

Q. Anything else?

A. Potentially, yes, in the project folders.

Q. What else would be in the project

folders?

A. Notes, input files for the models, things of that sort.

Q. Your notes?

A. By notes, I mean whatever goes into the model, for example, for the different calculations or the parameters to be used in our tests and calculations as part of what is presented in this expert report.

Q. Have you had any communications with anyone, current or former employees, of the Department of the Navy to form the basis of your opinions?

A. The Department of the Navy?

Q. Yes.

A. No, I don't think so.

Q. Or any Marines or anyone who had worked at Camp LeJeune, any communications with them?

A. Not that I can recall, no.

Q. Other than your in-person meetings?

A. That's the only thing I can think of.

Q. Number 14 asks for photographs and videos taken by you or S.S. Papadopulos related to Camp LeJeune.

Do you have any photographs or

videotapes in your possession, meaning at your office or wherever it is that you work?

A. No. I recall receiving the photographs in communication with the lawyers.

Q. So that means you do have them in your possession?

A. I received them, yes.

Q. Did you rely photographs for your work?

A. For my opinions presented herein, no.

Q. Do you have any video of Camp LeJeune?

A. I don't believe so. I didn't take any video. I don't know if that was any video included there. I cannot recall.

MR. ANWAR: For the record, photographs and to the extent there are videos, that's been produced.

BY MS. BAUGHMAN:

Q. Other than the expert panel meeting in 2005, did you attend any other meeting related to Camp LeJeune prior to being retained as an expert witness for this litigation regarding Camp LeJeune?

A. What type of meetings do you mean?

Q. Any kind of meeting related to Camp LeJeune. So at some point in 2022 or 2023, you

were retained as an expert in this case; right?

A. I do not recall the exact time I was retained as an expert. I was first involved in the work for Camp LeJeune for this site. I do not recall the date when I was actually retained to be an expert and provide an expert report on this.

Q. Prior to your work in 2022 or 2023 regarding this litigation, prior to that, did you attend any other meetings related to Camp LeJeune other than the 2005 expert panel?

A. But again that's a very general question. No, I don't believe so.

Q. Number 16 asks about letters, emails, other communications you sent or received related to the National Research Council, NRC, report related to Camp LeJeune, including who would be on that panel and any draft of the reports.

Do you have any communications about that?

A. No, I do not.

Q. What role did you have, if any, regarding the NRC report about Camp LeJeune?

A. Role.

Q. Role. What role?

MR. ANWAR: Object to form.

THE WITNESS: I was not involved.
BY MS. BAUGHMAN:
Q. Did you assist with identifying anyone who would be on the NRC panel?
A. No, I did not.
Q. Did you assist with drafting any part of the NRC report?
A. No.
Q. To your knowledge, did anyone from S.S. Papadopulos have a role in drafting the NRC report?
A. I do not know.
Q. How many experts in water modeling or geohydrology in your field were on NRC panel that published the report about Camp LeJeune?
MR. ANWAR: Object to form.
THE WITNESS: I do not recall.
BY MS. BAUGHMAN:
Q. Dr. Clement is in your field; right?
A. Yes.
Q. Is there anyone else on the NRC panel who has expertise in groundwater modeling or geohydrology?
A. Not that I can recall, no.
Q. You had a statement in your report.

It's on page 21, if you want to look at it. But it said Dr. Clement's article you're referring to the 2011 published article published in Groundwater on complexities in hind cast models. You said, "Dr. Clement's article echoed NRC's concerns."

Isn't that really Dr. Clement repeating his own concerns?

MR. ANWAR: Object to form.

THE WITNESS: I looked at the two separately. The NRC report was a document that I looked at. And Dr. Clement's paper was another piece of information that I looked at. And I drew that conclusion. I didn't look at the time who was participating in the NRC group that provided that report.

BY MS. BAUGHMAN:

Q. But as you sit here now, you recognize that the only water modeling expert on NRC's panel was Dr. Clement; right?

A. That is correct.

Q. That NRC report from 2009 was limited to critiquing Tarawa Terrace; right?

A. That's my recollection, yes.

Q. It doesn't critique the model for Hadnot

Point Holcomb Boulevard because that hadn't been completed yet; right?

A. Yes.

Q. On page 21 of your report, you quote from NRC, and you say that, "Per the NRC regarding ATSDR using computer codes and modeling techniques" --

A. I'm sorry. Can you point exactly where you're looking at just to make sure I'm following. You said page 21?

Q. Page 21 on the second bullet point.

A. Some of the modeling approaches, is that correct, is that what you're looking at it?

Q. No. You say that, "Some of the modeling approaches used by ATSDR were cutting edge, meaning that they used computer codes and modeling techniques that are still in the research stage."

Which computer codes and modeling techniques are you referring to there?

A. First of all, that's a quote; right.

Q. Sure. In your opinion, which computer codes and modeling techniques of ATSDR were still in the research stage that they used for their modeling of Tarawa Terrace?

MR. ANWAR: Object to form.

THE WITNESS: I believe that's something for the NRC to articulate.

BY MS. BAUGHMAN:

Q. Can you identify any today?

A. That's not part of the opinions that I provide. So I don't have an opinion on that.

Q. You chose to put that quote in your report though; right?

A. Well, it's a big quote. It involves other things in there as well. So contextually it contains what report was saying, but there's a lot in there.

Q. But you're the one who chose to put the quote in there; true?

A. Yes.

Q. Have you communicated with Dr. Clement regarding Camp LeJeune?

A. No, I have not.

Q. Turn to page 18 of your report. I want to focus on a statement that you have on page 18 toward the top of the page where you say, "ATSDR's reports indicated that the Tarawa Terrace reports indicated that the water modeling was intended to support an epidemiological study, not for the purpose of making exposure assessments in

individuals."

Do you see that?

A. Yes.

Q. I want to then focus on the second bullet point underneath that. In that bullet point, you have a long quote from ATSDR Tarawa Terrace Chapter A report.

Do you see that?

A. Yes.

Q. What you wrote there or what you quoted in support of this statement you've made that these modeling was for the purpose of making exposure -- not for the purpose of making exposure assessments in individuals, you quote, "ATSDR is using water modeling techniques to provide the epidemiological study with quantitative estimates of monthly contaminant concentrations in finished water because contaminant concentration data and exposure information are limited. Results obtained by using water modeling techniques along with information from the mother on her water use can be used by the epidemiological study to estimate the level and duration of exposures to the mother during her pregnancy and to the infant up to one year of age."

Did I read that correctly?

A. Yes.

Q. So the ATSDR stated that its water modeling results can be used in combination with information from the mother on her water use to estimate the level and duration of her exposure to these contaminants; right?

MR. ANWAR: Object to form.

THE WITNESS: No. It clearly says it was to be used by the epidemiological study to estimate the level and duration of exposures to the mother. But there are caveats with respect to that.

BY MS. BAUGHMAN:

Q. Is that a caveat right there?

A. This is not the only quote in my opinions regarding what that did. This is just one piece. You cannot take it out of context.

Q. Does this not say that the ATSDR's work, the monthly mean concentrations can be used by the epidemiological study to estimate the level and duration of exposures to the mother? It says that; right?

MR. ANWAR: Object to form.

THE WITNESS: Even though that is said

there, Mr. Maslia has also provided responses to the expert panel, for example, with respect to how the results of these analyses will be used or the level of detail that would be required. Then, in fact, he said things like medium, high, medium, low rather than actual values, detailed concentrations.

So there is a caveat here with respect to how that should be interpreted.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Let me ask you this: Have you reviewed the published epidemiology studies regarding Camp LeJeune?

A. I have not.

Q. Do you know whether in any of the published epidemiology studies they document that the epidemiologist used the modeling in order to calculate the level and duration of exposure to contaminants?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Do you know whether it says that in the published studies?

A. No. I have not read those studies.

Q. Do you know if the ATSDR epidemiologists actually used ATSDR modeling of the historical concentration -- strike that.

Do you know if ATSDR epidemiologists had used the mean monthly levels of contaminants predicted by ATSDR's models to calculate the cumulative exposure for any individuals who lived at Camp LeJeune?

MR. ANWAR: Object to form.

THE WITNESS: I do not know that. I'm not familiar with the epidemiological studies at Camp LeJeune.

BY MS. BAUGHMAN:

Q. So if the modeling was sent to support the epidemiology studies and the epidemiologists used the modeling to calculate cumulative exposer to individuals, you don't know that; right?

MR. ANWAR: Object to form, foundation.

THE WITNESS: My work here is only to critique the quality of the modeling work and outcome of that modeling.

BY MS. BAUGHMAN:

Q. So you don't know whether ATSDR's work was used for the purpose of making exposure

assessments in individuals? You don't know either way, do you?

MR. ANWAR: Object to form and foundation.

BY MS. BAUGHMAN:

Q. By the ATSDR epidemiologists. Do you know?

A. This is irrelevant to my opinions on this matter.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Page 23 of your report, you chose to put in your report a statement about this work being to support and epidemiologic study and not for purpose of making exposure assessments in individuals. You included that in your report; right?

A. I included that in my report because it provides context with respect to how this work was done, what it was intended to do, what the timeframe of that was and, therefore, support my work in looking at whether the modeling work that was done provided good results to rely on and support such evaluations.

Q. Can you tell me whether or not the ATSDR epidemiologist used the ATSDR's mean monthly concentrations from the modeling in order to make exposure assessments in individuals? Do you know whether they did that? Yes or no.

MR. ANWAR: Object to form and foundation.

THE WITNESS: I do not know that, but it's not relevant to work that I did and the opinions that I provide.

MS. BAUGHMAN: I'll object as nonresponsive to everything after "I do not know that."

BY MS. BAUGHMAN:

Q. Did you do any research to determine how ATSDR's modeling studies were used by the epidemiologists?

A. That was not my role in this case.

Q. Your report at 25 on a similar subject here, the last sentence on the first paragraph, you've written, "ATSDR further acknowledged this uncertainty by stating," quote, "'ATSDR's exposure assessment cannot be used to determine whether you or your family suffered any health effects as a result of past exposures to contaminated water at

Camp LeJeune.'"

You put that quote in your report; right?

A. Yes.

Q. And you're citing there two documents including ATSDR had Hadnot Point Chapter A; right?

A. Looks about right.

Q. Yes?

A. Yes.

(Spiliotopoulos Exhibit 9 was marked.)

BY MS. BAUGHMAN:

Q. I'm handing you what's marked as Exhibit 9 to your deposition, which is Chapter A, Summary and Findings from Hadnot Point. That's the document that you cited there; correct?

A. Yes.

Q. Let's turn to the page you cited page A182. The very first sentence under the bolded statement is your quote, right, what you quoted? But you left out a word, didn't you? What the ATSDR wrote was "ATSDR's exposure estimates cannot be used alone to determine whether you or your family suffered any health effects as a result of past exposure to TCE contaminated drinking water at U.S. Military Base Camp LeJeune." Right?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. That's what it says in the document right? Is that true?

Did I read that correctly?

A. This is correct, yes. That was --

Q. Cannot be used alone.

A. Yeah. That's what's in there, that is correct.

Q. In your report, you have that quote, but you left out the word "alone," didn't you?

A. That was an omission on my part. Yes, I didn't realize that.

MR. ANWAR: Object to form. There are two documents cited there.

THE WITNESS: Exactly. The first one where I took the quote from was the Tarawa Terrace one. And in looking at that and in looking at this, it seemed to me like it was exactly the same statement.

BY MS. BAUGHMAN:

Q. It's a misrepresentation to leave out the word "alone," isn't it?

MR. ANWAR: Object to form.

THE WITNESS: Well, in the first

statement, that word was not there. In the statement Tarawa Terrace modeling was not there.

BY MS. BAUGHMAN:

Q. You had sent a letter to us saying that we should limit objections to "Objection. Form." Your last objection was a statement and coaching of the witness. Don't do it again or we'll write a letter back and we'll bring it up with the judge.

MR. ANWAR: Noted.

MS. BAUGHMAN: You cannot tell him about two statements or if it's in another document. That's coaching the witness. You just coached the witness on record.

MR. ANWAR: I'm not coaching the witness.

MS. BAUGHMAN: Don't do it again.

MR. ANWAR: I'm not.

THE WITNESS: This is an exhibit?

BY MS. BAUGHMAN:

Q. Yes. It goes in the pile.

You're aware that the Tarawa Terrace and the Hadnot Point Holcomb Boulevard models have been peer reviewed; right?

MR. ANWAR: Object to form.

THE WITNESS: The Tarawa Terrace model has been reviewed. I don't believe that the Hadnot Point model has been reviewed.

BY MS. BAUGHMAN:

Q. We're talking about peer review, not just review. So you're saying only Tarawa Terrace has been peer reviewed; is that right?

A. I do not recall seeing a peer review of the Hadnot Point model, but you can show me where that is.

Q. We're going to get back to it. Let me go back to something else. I forgot one thing. Let's go back to page 26 of your report.

We were talking about what Mr. Maslia said or didn't say about -- I'm sorry -- not your report.

(Spiliotopoulos Exhibit 10 was marked.)

BY MS. BAUGHMAN:

Q. I'm marking as Exhibit 10 the expert report of Morris Maslia from October of 2024.

You've reviewed that document; right?

A. Yes. I've read it.

Q. And you said that when you -- part of the reason you included these statements in your report about what the intent was of doing the

modeling or how it was going to be used is you were relying on what Mr. Maslia had said about that; right? You had mentioned something about that?

A. I mentioned that there are several quotes by Mr. Maslia at different times including his depositions, the ATSDR reports, his expert report and so on, regarding this subject.

Q. Turn to page 26 of Mr. Maslia's October 2024 expert report under the heading 7.3, Water Modeling and Study Objectives. Do you see that?

A. Yes.

Q. And Mr. Maslia says there, "When ATSDR health study epidemiologists requested scientific and technical support from the exposure dose program, they presented a list of the five objectives and questions that they wanted to achieve an answer."

So the epidemiologists presented this list to Mr. Maslia and his team; correct?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Is that right?

A. That's what it says.

Q. It says that that these five objectives and questions were originally presented at a meeting held on October 28, 2023 at ATSDR's headquarters in Chamblee, Georgia with attendance by ATSDR, Department of the Navy, Naval Facilities Engineering command staff, and the ATSDR university partner and contractors.

I left out some parentheticals, but that's what it says; correct?

A. Correct.

Q. Then it lists the five study objectives and questions that the epidemiologists asked ATSDR to address; correct?

A. Yes.

Q. And those include what were the mean monthly drinking water concentrations; correct?

A. Yes.

Q. That's the third one. But the first one is what chemical compounds contaminated the drinking water and where did they come from. Right?

A. Correct.

Q. The second one is when did contaminated groundwater reach water supply wells and what was the duration of the contamination. Correct?

A. Correct.

Q. Let me ask you a question about that. You've done a lot of work, and you've written a report that's about a hundred pages on this subject matter; correct?

A. Yes.

Q. Do you have an opinion about when any contaminant reached a water supply well at Tarawa Terrace or Hadnot Point? Had you offered those opinions?

A. My opinions critiqued the estimates provided by ATSDR on the basis of poor calibration, poor model construction, and lots of assumptions that cannot be tested as well as the accuracy of the model results.

MS. BAUGHMAN: I'll object as nonresponsive.

BY MS. BAUGHMAN:

Q. Try answering my question. If the answers is no, that's fine.

Do you have an opinion for the court, for the four judges in this case, about when any contaminant in groundwater reached any water supply well at Tarawa Terrace or Hadnot Point?

A. I did not offer an opinion that would

pinpoint a date or a timeframe for that to happen.

Q. Do you have an opinion that you can provide to any of the judges that are addressing this case on when any contaminant in groundwater -- strike that.

Do you have an opinion that you can provide the court in this case about the duration of contamination for any contaminant that contaminated a water supply well at Tarawa Terrace or Hadnot Point? In other words, how long did it contaminate the well?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Do you have any opinions like that?

A. My opinions actually suggest that it is not possible with any kind of certainty to answer that question.

Q. So you don't have an answer?

A. I only know what the data suggests with respect to when we know the contamination was there, but with respect to when it arrived there or at what level, I don't think it's possible to provide that answer with any kind of certainty.

Q. With any kind of certainty. Okay.

The next question that Mr. Maslia

addresses is what were mean monthly drinking water concentrations? Do you have an opinion for the court in this case as to what a mean monthly drinking water concentration was for any contaminant at Tarawa Terrace or Hadnot Point water treatment plant at any point in time?

A. Prior to the dates for which data are available, it is not possible to do that at all. And even within the timeframe for which data were available, and I'm talking about the period up to 1985 for starters, this is also not possible to be done with any kind of certainty estimates.

Q. So you're not going to offer in this case to the court an opinion as to what the mean monthly drinking water concentration was for any month or at any point in time at the Tarawa Terrace or Hadnot Point water treatment plant; right? You're not offering those opinions, are you?

A. The only opinion that I'm offering is that we have data for the months for which we can say what kind of contamination we had in the treatment system, but for the other months, I'm saying that we cannot know with any kind of certainty.

Q. Have you performed modeling to try to answer the question yourself?

A. I've only performed modeling to test the ATSDR models for their accuracy.

Q. You haven't tried to do it yourself?

A. No. In fact, my opinion suggests with the data available, it is not possible to do that.

Q. So let's go back to the peer review. There were two expert peer-review panels, right, that were conducted regarding ATSDR's modeling work; right?

A. Yes.

Q. You attended one of them; right?

A. Correct.

Q. Why didn't you attend the other one?

A. I was not asked to do at the time, something like that. I was not involved in the project otherwise.

Q. Just to guide our discussion, if you could turn to Mr. Maslia's report, which we've marked as Exhibit 10, on page 99 there is a section in his report called Peer Review of ATSDR Analyses, Results and Reports.

Do you see that?

A. Yes.

Q. So I want to talk about five different kinds of peer review. First, there were two expert peer-review panels that looked at the modeling work of ATSDR and reviewed it in 2005 and in 2009; correct?

A. In 2005 the expert panel reviewed the preliminary work and approaches that ATSDR offered for doing this work. In 2009, I believe there were some discussion with respect to the findings based on the model, the ATSDR model for Tarawa Terrace. I think the discussion after that was for the approaches proposed for the Hadnot Point model. At the time, they didn't review the Hadnot Point model.

Q. So in 2005, they discussed methodology and approaches being used for the model of Tarawa Terrace; right?

A. That is correct.

Q. And the experts provided feedback, and ATSDR considered that feedback and, in fact, wrote a report about the panel and what they were going to do as a result; correct?

MR. ANWAR: Object to form and foundation.

THE WITNESS: They offered comments and

opinions on what was preliminary work at the time, and I believe it was primarily or mostly related to the groundwater flow model, not the transport model because it was not available at the time. They discussed in 2005 approaches on how to go about performing the transport modeling.

BY MS. BAUGHMAN:

Q. ATSDR took that advice under advisement and wrote a report about that panel meeting; right?

A. It was a report that summarized the discussions, comments and recommendations.

Q. And then four years later. ATSDR got another panel, expert panel together and talked more about their methodologies and their approaches, presented Tawara Terrace results and talked about their approach for Hadnot Point; right?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure at the time what the panel reviewed with respect to the work that was done in terms of reports, model files and things like that. So I'm not sure what exactly they looked at.

BY MS. BAUGHMAN:

Q. Just to be clear, you weren't at the 2009 panel; right?

A. No, I was not.

Q. Did you read those two days of testimony, of remarks?

A. I reviewed some of that, but not in detail word by word.

Q. Did you review the report that was written about the two-day meeting in 2009?

A. Again, I reviewed that to some extent, yes.

Q. Not all the way through?

A. I can't recall if I reviewed every -- because it involved many different things, some of which were not within the scope of the work that I was doing.

Q. So Mr. Maslia wrote in the middle of that first paragraph on page 99, he said, "The panels were composed of nationally and internationally recognized experts with professional backgrounds in government, academia and the private sector."

Do you agree with that?

MR. ANWAR: Object to form.

THE WITNESS: That's his opinion on the status of the person.

BY MS. BAUGHMAN:

Q. What's your opinion?

A. I do not have one.

Q. You don't know the reputations of the experts that were on those two panels?

MR. ANWAR: Object to form and foundation.

THE WITNESS: I know of them, but I don't think I can form an opinion on how that they are, their work in general. I know some of them or all of them, but that's as far as I would go.

BY MS. BAUGHMAN:

Q. So as part of your work on this case, you didn't say it was important to look at who was on these expert panels and whether they were qualified to provide opinions to ATSDR on the methodologies?

MR. ANWAR: Object to form and foundation.

BY MS. BAUGHMAN:

Q. That wasn't part of your work?

MR. ANWAR: Same objection.

THE WITNESS: I think what is important

to know is what they reviewed and how. I'm not even sure that they went into the detail of the review that I performed on this modeling work to offer my opinions on this.

MS. BAUGHMAN: Let me start with I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Did you as part of your work on this case look into the qualifications and backgrounds of the panelists who were on the two expert peer-review panels for ATSDR?

A. I know a few of the people on those panels, and I respect their reputation in the field. But, like I said, I do not know what they reviewed to come to their conclusions and recommendations or comments.

Q. So you know a few of the people in the field and you respect them, but you didn't look at the qualifications of all of the expert panelists; is that fair?

MR. ANWAR: Object to form.

THE WITNESS: I don't think that it's relevant to the work that I'm doing here with respect to the level of detail that I looked into these models. Like I said, unless I knew what

exactly they looked at and we could have a conversation face to face on these issues, I cannot offer an opinion on what kind of comments they produced.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Whether you think something is relevant or not actually doesn't matter. You're required to answer my questions whether you think it's relevant or not.

So let me ask this question again. Did you look into the qualifications and background of each of the expert panelists that were on the 2005 and 2009 panels for ATSDR? Did you do it or not?

MR. ANWAR: Object to form.

THE WITNESS: I know most of the people there as members of the scientific community in our field, and I know their reputation and their qualifications.

BY MS. BAUGHMAN:

Q. And they're qualified, aren't they?

MR. ANWAR: Object to form and foundation.

THE WITNESS: This is a very general

description to provide. I think they're good practitioners or researchers in the field. But this is not relevant to whether they formed an opinion based on facts similar to those that I looked at. So that's important with respect to the opinion they provided there.

BY MS. BAUGHMAN:

Q. What materials did ATSDR provide to the panelists in advance of the 2005 panel?

A. I do not know.

Q. What materials did ATSDR provide to the panelists in advance of the 2009 panel?

A. I do not know.

Q. You know it's documented in the reports what they were provided. You just didn't look, did you?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure I recall, but I do not think that the actual model files and especially the final model files were provided, but I can't be sure. And I don't know to what level of detail the panel looked at these files and formed opinions.

BY MS. BAUGHMAN:

Q. Did you attempt to find out what the

panelist members reviewed prior to meeting in 2005 or 2009?

MR. ANWAR: Object to form.

THE WITNESS: I'm sorry. Can you repeat the question?

BY MS. BAUGHMAN:

Q. Did you do any research or did you read any documents to try to determine what the panelists were provided to review prior to the 2005 and 2009 meetings?

MR. ANWAR: Same objection.

THE WITNESS: No, because it was not relevant to the work that I was doing. It's performed an independent evaluation.

MS. BAUGHMAN: I'm going to object as nonresponsive to everything after "no."

BY MS. BAUGHMAN:

Q. Now, let's go to the next level of review. The second paragraph of Mr. Maslia's report says under the section of peer review on page 99, says "In addition to the expert panels and implementing their recommendations, ATSDR sought out independent external peer review for every chapter report for the Tawara Terrace, Hadnot Point, Holcomb Boulevard reports. These

peer reviewers were subject matter experts in all topics covered by the ATSDR historical reconstruction analysis reports."

Did I read that correctly?

A. You read that correctly, yes.

Q. Now, were you aware that each chapter of Tawara Terrace and Hadnot Point, Holcomb Boulevard received independent external peer review?

A. I don't see any reference here as to who these people were and what work they did. So I don't know.

Q. Were you aware -- this is my question -- that each chapter was independently externally peer reviewed? Were you aware of that?

A. Not other than what I'm reading here.

Q. Are you aware that as part of the file that's been produced in this case actually by the Department of Justice, there are documents documenting the peer review and the comments and the responses regarding every chapter? Did you review those documents?

MR. ANWAR: Object to form.

THE WITNESS: I only performed an independent evaluation of the work done by the ATSDR.

MS. BAUGHMAN: I object as nonresponsive.

BY MS. BAUGHMAN:

Q. Here's my question. Did you review the documents regarding the external peer review of the every chapter of the Tawara Terrace and Hadnot Point, Holcomb Boulevard reports? Did you review those peer-review comments and responses?

MR. ANWAR: Object to form.

THE WITNESS: You will have to present me with these documents, and I can tell you if I reviewed them or not. I cannot recall, off the top of my head, if something I reviewed was relevant to your question.

BY MS. BAUGHMAN:

Q. Do you recall at this point having reviewed the peer-review comments of the chapters at Hadnot Point and Holcomb Boulevard and Tawara Terrace from the independent external peer review?

Do you recall reviewing those documents?

MR. ANWAR: Object to form.

THE WITNESS: You're referring to the external peer review mentioned in that paragraph?

BY MS. BAUGHMAN:

Q. Yes.

A. I do not recall off the top of my head.
Q. You don't. Okay.
Do you know whether the individuals who did that independent external peer review of each chapter, do you know whether they were subject matter experts in the topics covered by the ATSDR historical reconstruction reports?
A. You will have to tell me who these people were so I can tell you more about it.
Q. You did review Mr. Maslia's report; right?
A. Yes.
Q. And you saw that he said that each chapter is externally peer reviewed; right?
A. Yes.
Q. Did you look into that any further?
A. It was not necessary.
Q. So let's talk about the third level of peer review. You're aware that Mr. Maslia and his colleagues published in peer-reviewed journals articles regarding the modeling of both Tawara Terrace and Hadnot Point; right?
MR. ANWAR: Object to form.
THE WITNESS: I have seen publications to that effect, yes.

BY MS. BAUGHMAN:

Q. So in 2009 in the journal Water Quality Exposure and Health, Mr. Maslia published an article about his modeling of Tarawa Terrace called Reconstructing Historical Exposures to Volatile Organic Compound Contaminated Drinking Water at a U.S. Military Base. Correct?

A. Yes.

Q. That's a peer-reviewed journal?

A. Yes.

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Then in 2016, Mr. Maslia published in the journal Water regarding Hadnot Point and Holcomb Boulevard in an article entitled "Reconstructing Historical VOC Concentrations in Drinking Water for Epidemiologic Studies at a Military Base: Summary of Results." Correct?

A. It appears so, yes.

Q. That's also a peer-reviewed journal; right?

MR. ANWAR: Object to form.

THE WITNESS: Well, peer review is with respect to what the paper states and the approaches and results. But unless you look at

how the calculations are performed and the details of how the analysis is done, I don't know that you can offer an opinion to that effect.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. There's a peer-review process for publishing articles in literature; right?

A. That does not include necessarily look at the actual model files and looking in details on what is presented in the papers.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. I didn't ask you that. That's not what I asked you.

There is a peer-review process. There is a process to publish in the peer-reviewed literature; right?

MR. ANWAR: Object to form.

THE WITNESS: My response to your question is yes, but that peer review rarely, if not ever, includes reviewing the actual calculations and the context of those calculations. It looks at the methods and the

results.

MS. BAUGHMAN: I'm going to object as nonresponsive to everything after "yes."

BY MS. BAUGHMAN:

Q. So you've published in your career a total of two articles in the peer-reviewed literature; right?

MR. ANWAR: Object to form.

THE WITNESS: Yes.

BY MS. BAUGHMAN:

Q. You've never been asked to be a peer reviewer of anyone else's article in the peer-reviewed literature; right?

A. I have 20 years in the field working on very complex problems.

Q. How many articles were you asked to peer review in the literature in your field, how many?

A. I'm not sure how that is relevant to anything.

Q. What's the answer to the question?

A. I believe you said before it's two articles I have in peer review.

Q. No. How many times have you been asked to review someone else's before it's published in the peer-reviewed literature?

A. I have not been involved in that process.

Q. I didn't think so.

So you don't know what the peer reviewers of Mr. Maslia's two published peer-reviewed articles looked at in order to agree that those articles should be published? You don't know that, do you?

MR. ANWAR: Object to form.

THE WITNESS: You're asking me whether they have reviewed model files and things like that?

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, I'm asking you: You don't know what they did or didn't review, do you?

A. I am familiar with the review process in peer-reviewed journals. And to my experience and knowledge, almost I would say never, but I want to reserve the right to maybe be wrong in some cases, but that is never done.

MS. BAUGHMAN: I object as nonresponsive.

BY MS. BAUGHMAN:

Q. I didn't ask about a specific type of document. I'm asking: Do you know what the peer

reviewers reviewed before agreeing that Mr. Maslia's article on Hadnot Point modeling could be published in Water in 2016? Do you know what they reviewed?

MR. ANWAR: Object to form.

THE WITNESS: I don't know what they reviewed, but it would still not impact my opinion.

MS. BAUGHMAN: I'm going to object as nonresponsive to everything after "I don't know what they reviewed."

BY MS. BAUGHMAN:

Q. Fourth, Mr. Maslia and his peers have presented their modeling work at multiple professional conferences, haven't they? Are you aware of that?

A. That seems right. I don't know what the actual number is, but, yes, they have done that.

Q. Just like you've gone to conferences and, for example, talked about their Hanford work, they've gone to work and presented their work regarding modeling methodologies; right?

A. That is correct.

Q. And you view that as a form of peer review. You told me that earlier; right?

A. These conferences and presentations provide a forum for people to present their work, and it stimulates conversation regarding that work. Peer review for the conferences that I have participated, similar to those that you referred to regarding Mr. Maslia and the ATSDR group, they review the paper that you provide if that's necessary and required. In many cases it's a presentation that is not even reviewed. But where it is reviewed, the paper itself is reviewed with respect to how it presents the work, not necessarily what goes behind the calculations that are presented there, whether they're correct or not.

This is part of the conversation that the paper and presentations stimulate in the presentation.

Q. And what you just said applies to each of the conferences where you've presented your work to; right?

A. That is correct.

Q. It's not really a true peer review, is it?

MR. ANWAR: Object to form.

THE WITNESS: It's the type of peer

review that I just described.
BY MS. BAUGHMAN:
Q. You didn't cite either of Mr. Maslia's published peer-reviewed articles regarding the modeling work for Tawara Terrace or Hadnot Point in your report, did you?
MR. ANWAR: Object to form.
THE WITNESS: I'm not sure. I have to check.
BY MS. BAUGHMAN:
Q. We just checked. It's not cited in your footnotes, and it's not in your up-to-date Supplemental and Corrected Reliance List. It's not on either one. Does that surprise you?
A. In what sense? I'm not sure I'm following your question.
Q. Is there a reason why the two published peer-reviewed articles of Mr. Maslia from 2009 and 2016 regarding his work at Camp LeJeune are not cited in your report or in your Supplemental and Amended Reliance List?
A. Because the work that I did relied on the modeling files provided in support of the ATSDR reports. That's all I needed to look at.
Q. Did you actually review what Mr. Maslia

published in 2009 and 2016 regarding his modeling?

A. I'm not sure that I did. I do not recall.

Q. You don't recall reading those articles?

A. Off the top of my head, I'm not sure that I did.

Q. If you had read them, you would have included them on your Supplemental and Amended Reliance List, right, as something you considered?

A. I would think so.

Q. So you didn't consider them?

A. I'm saying that I do not recall them and, therefore, they were not there. But I'm not sure even that I did, and I don't think that I would forget to include them there.

Q. Right. So based on what you know about your methodology, have you reviewed Mr. Maslia's two published peer-reviewed articles on the modeling done for Tawara Terrace and Hadnot Point, you would have put it on your Supplemental and Amended Reliance List; right?

MR. ANWAR: Object to form.

THE WITNESS: I'm sorry. You mentioned in the beginning of your question based on my methodology?

BY MS. BAUGHMAN:

Q. Yeah. Based on your ordinary practice, if you review something, you put it on the list; right? Isn't that what you did?

A. Hopefully without forgetting to include something just because it slipped my mind.

Q. You told me if you were provided something by the lawyers, you'd put it on your list even if you didn't review it; right?

A. That would be the case in general, yes.

Q. So I guess the lawyers didn't provide you with Mr. Maslia's peer-reviewed articles, and you didn't go out and find them, and you didn't review them for your work on this case; right?

MR. ANWAR: Object to form and foundation.

THE WITNESS: I'm not sure if they were provided, if I reviewed them. That I certainly don't recall. But again for my work, they were not necessary.

BY MS. BAUGHMAN:

Q. So based on your sworn testimony today, you do not recall ever having reviewed Mr. Maslia's 2009 or 2016 published peer-reviewed articles regarding his modeling at Tawara Terrace

and Hadnot Point; right?

MR. ANWAR: Object to form and foundation.

THE WITNESS: Again, I do not recall. I honestly do not recall.

BY MS. BAUGHMAN:

Q. You can't recall having reviewed them; right?

A. I cannot recall.

Q. Are you saying you can't either way, or you don't recall having reviewed them?

A. I do not recall having reviewed them. Whether I did or not, like I said, I do not recall.

Q. And to the extent you did review them, you have no explanation for me as to why they're not on your Supplemental and Amended Reliance List; right?

A. I think I was very clear. I do not recall if I did. If I did and they wouldn't be there, would that be omission? I don't know. I do not recall.

Q. Did you purposely leave Mr. Maslia's two published peer-reviewed articles on his modeling at Tawara Terrace and Hadnot Point off of your

list? Did you do that on purpose?

MR. ANWAR: Object to form.

THE WITNESS: I'm telling you I do not even recall reviewing them. So I don't understand how I could have intentionally omitted them.

BY MS. BAUGHMAN:

Q. The last thing I want to point out, are you aware that ATSDR's modeling team received an award from the American Academy of Environmental Engineers and Scientists for their modeling work regarding Camp LeJeune? Are you aware of that?

A. I am aware of that.

Q. In 2015 they received the Excellence in Environmental Engineering Award, grand prize, for the research category from the American Academy of Environmental Engineers and Scientists; correct?

A. Yes. I do know that. But like I said before, I don't know whether that was on the merit of developing a novel approach to doing things versus whether the applicability of that method is reliable for the purposes, the intended purposes of this study. These are two different things.

Q. You're aware they got the grand prize award in 2015; right?

A. Yes.

Q. Have you ever gotten a grand prize award for any of your work?

MR. ANWAR: Object to form.

THE WITNESS: No, I have not.

BY MS. BAUGHMAN:

Q. Do you know what the criteria were for receiving the grand prize award from the American Academy of Environmental Engineers and Scientists?

THE WITNESS: I do not.

BY MS. BAUGHMAN:

Q. Did you look into it?

A. No, I did not.

Q. Are you a member of that organization?

A. I am not.

Excuse me, ma'am. How long have we been going on in this session? I don't know if it's time for a short break.

Q. If you want a break, we can take a break.

A. Five minutes.

THE VIDEOGRAPHER: Off the record at 1447.

(Recess from 2:47 p.m. to 3:00 p.m.)

THE VIDEOGRAPHER: On the record at 1500.

THE WITNESS: Before we begin, I would like to go back to your question. I believe you asked me whether I can or will offer an opinion regarding the timing of contamination reaching the wells in Tawara Terrace or Hadnot Point.

My complete answer to that is I do not believe that the current model can do this, but I can have an opinion on the likelihood for contamination to reach in those wells without having a certain date, but certainly a timeframe.

BY MS. BAUGHMAN:

Q. In your expert report, is there an opinion that states when a contamination, any contamination would reach any well at Tawara Terrace or Hadnot Point?

A. My expert report focused solely on the critiquing the model. So it was only focused on that.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. I'm asking you in your expert report, is there an opinion that tells us the timing of when contamination of any contaminant reached or would reach any well at Tawara Terrace or Hadnot Point?

Is that opinion in your report?

A. I do not have a formal opinion in that respect.

Q. You didn't cover that in your expert report; right?

A. Explicitly, no.

Q. Or even implicitly. I mean, if you can show me where in your report you provided the opinion on the timing of when contamination would reach any well at Tawara Terrace or Hadnot Point, I want to see where that is.

A. I do not have an explicit opinion like that. I state facts and data, but there is additional things that I have thought and considered during this process of depositions and other things that I looked at that can help me form another opinion potentially on that.

Q. Understood. But you understand that the process in federal court is that if you have an opinion you're going that offer the court, it's supposed to be in your expert report; right?

A. That is correct, although I never had the benefit of rebuttal of -- the rebuttals of the plaintiffs' expert. Therefore, I'm a little shortchanged in that respect.

Q. I asked you about the water wells. I want to ask you about the water treatment plants. In your report, you haven't offered any opinion as to when contamination reached the water treatment plant initially for Tawara Terrace or Hadnot Point water treatment plants, have you?

A. No. That falls squarely in what I said before about the wells and the treatment plant. So that's an opinion I can offer.

Q. That is not in your report?

A. That is not currently explicitly in my report.

Q. Well, you say explicitly in your report. It's not implicitly report either; right? When I say that, if it's in your report, I want you to show me what page it is where you've offered the opinion where any contamination reached any well or the water treatment plant?

A. By implicity I mean I provide opinions and facts regarding when contamination was found, what data suggests that, for example, nondetections were there and the model, for example, falsely ignored them and provided elevated concentrations at the same time. So all this can inform an opinion as to when

contamination could have arrived.

Q. But that opinion is not stated in your report; fair?

A. That is correct.

Q. We talked about this in Mr. Maslia's report about those five questions that the epidemiologist posed to him and his team on page 26 and 27 of his report.

My question is: Do you have any basis that disagree with Mr. Maslia that, in fact, these were five objects and questions presented by the epidemiologist to the team?

MR. ANWAR: Object to form.

THE WITNESS: That's what it's stated there as being the objectives. My question and critique on whether the work that ATSDR did could actually answer those questions with any kind of accuracy or certainty.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Here's my question. Do you have any basis to disagree that at this meeting in October of 2003, the epidemiologist presented these five study objectives and questions to Mr. Maslia and

his team? Do you have to any reason to disagree that that occurred?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure. I don't know what happened at that meeting. That's a statement that Mr. Maslia is providing. I haven't read anything in support of this to say that it's true or not.

BY MS. BAUGHMAN:

Q. So you think it's possible that Mr. Maslia is not telling the truth here, is that what you're saying?

MR. ANWAR: Object to form.

THE WITNESS: I'm saying that I don't know the facts. So I'm taking this at face value at this point.

BY MS. BAUGHMAN:

Q. You have some statements in your report, one of them is on page 30, where you say toward the bottom of the page, "ATSDR ignored any contaminant losses that would occur during treatment."

I want to just ask you about that. I know Dr. Hennet has offered some opinions on volatilization. So my question for you is: Have

you, yourself, performed any calculations regarding alleged volatilization losses at the water treatment plants?

A. No, I have not, my calculations and at the treatment plant.

Q. So are you relying on the calculations and the opinions of Dr. Hennet regarding the quantification of any alleged VOC losses at the water treatment plants?

A. Yes, I do.

Q. So I want to talk about something different. In your report, I've counted this up, you've used the word "arbitrary" 16 times to describe ATSDR's estimates or expert judgments regarding parameter values and other assumptions.

You're familiar with that, right, your use of the word "arbitrary"?

A. I do not recall the number of times, but you've used the word "arbitrary."

Q. What do you mean by "arbitrary"?

A. Well, I guess we have to go to the specific. Can you give me an example so I can talk about it? I don't know if the context across the entire document is the same.

Q. Can you give me a definition of

"arbitrary"?

MR. ANWAR: Object to form.

THE WITNESS: Again, I would like to see the actual statement and tell you on that statement what my opinion is.

BY MS. BAUGHMAN:

Q. Okay. Let's go to page 84.

A. 84 you said?

Q. Yep. By the way, so your testimony is your definition of "arbitrary" might change in each time you use it?

MR. ANWAR: Object to form.

THE WITNESS: No. I'm saying I would like to see the statement and make sure that the context is correct.

BY MS. BAUGHMAN:

Q. So the last sentence of the second full paragraph under 4.2.5.1.1 says, "The empirical data for undergrounds storage releases may or may not be applicable to the USTs installed at Camp LeJeune and, therefore, assignment of timing and magnitude for these sources is arbitrary and uncertain."

What's the word "arbitrary" mean?

A. It basically means that ATSDR looked at

the analysis of 12,000 something leak incidents across the United States, considered the timeframe indicated in that report regarding when leaks might have occurred, and within that timeframe, they selected the mean value that was, if I remember correctly, nine years.

The problem is that what happens across the United States that doesn't mean that happened in North Carolina. It certainly that doesn't mean that we know what happened in each and every one of those tanks at Camp LeJeune. So the assumption is absolutely arbitrary because it's not informed by any kind of site-specific data. It's an average over the entire United States. To me, that's the definition of arbitrary.

(Spiliotopoulos Exhibits 11 - 12 were marked.)

BY MS. BAUGHMAN:

Q. I'm going to hand you what I've marked as Exhibits 11 and 12. And these are definitions from the Oxford Dictionary and from the Miriam Dictionary. Oxford is 11 and Miriam is 12 on the definition of the word "arbitrary."

Exhibit 11, in Oxford, the first definition is: Based on random choice or personal whim rather than any reason or system. An

arbitrary decision. So random choice.

The second definition on Miriam is: Existing or coming about seemingly at random or by chance or as a capricious and unreasonable act of will.

Do you see those definitions?

A. I also see the second one there based on or determined by individual preference or convenience rather than by necessity or the intrinsic nature of something. That's another one there.

I would call very much of that semantics in the sense that still ATSDR had no idea when these tanks leaked. There's a fact that they leaked.

Q. They did leak; right?

A. Yes, they did. But the problem is when. And ATSDR proceeded one step further to take the mean value and consider that the starting date. When ATSDR did a sensitivity analysis, it considered plus or minus nine years, which actually suggests that there was no foundation in the selection of values in their models, and the uncertainty is so extreme that, yes, to me at that point, it's arbitrary.

MS. BAUGHMAN: I'll object to that whole speech as nonresponsive to any question pending.

BY MS. BAUGHMAN:

Q. Now, let's go to Section 4.2.5.1.1 of your report on page 84. That's where you describe --

A. One second, please.

Q. That's where we just were.

A. Yes, but I closed it to see your other exhibit.

Q. Page 84.

A. Okay.

Q. Page 84, you describe this EPA report from 1986. Leaking around storage tanks that ATSDR relied upon; right?

A. Yes.

Q. And that report from the EPA was based on records of more than 12,500 reported leak incidents; right?

A. Yes.

Q. And the ATSDR used the median value of nine years after installation to assign release dates to the leaks; correct?

A. Yes.

Q. And you call that assignment arbitrary;

right?

A. Yes, I do because we have no idea when they leaked. And this is a critical parameter that goes into the model because it determines when contamination started entering the aquifer.

Q. Are you aware of any other study that's been performed regarding leaking underground storage tanks in the United States that's considered more data than what the EPA considered in this 1986 study?

A. I'm not sure, but that's absolutely relevant because what happens in a mean sense across United States has nothing to do with what happened at that site. And when the purpose of this analysis is to determine monthly concentrations over a period of time, we better get right the starting time for that.

MS. BAUGHMAN: Object as nonresponsive.

BY MS. BAUGHMAN:

Q. The deposition -- I'm going to ask for more time if you don't start answering my questions instead of giving speeches.

MR. ANWAR: Please don't threaten the witness. You can direct that to me.

MS. BAUGHMAN: You just make "Objection.

Form."

MR. ANWAR: Don't threaten me either.

MS. BAUGHMAN: That's the second example I'm going to give the court for you.

BY MS. BAUGHMAN:

Q. Now, Dr. Spilotopoulos, what research did you do for your report regarding what's been published regarding how long it takes for underground storage tanks to leak? Did you look at any other studies or data in addition to the 1986 EPA report?

MR. ANWAR: Object to form.

THE WITNESS: I did not have to.

BY MS. BAUGHMAN:

Q. Did you look at any?

A. No.

Q. Did you actually read the EPA's report from 1986 on leaking underground storage tanks?

A. I reviewed the report which is why actually I corrected the number of leaks that was in the ATSDR report.

Q. Now, is there any reason that you can identify as to why EPA's empirical data on the 12,000 underground storage tanks would not apply to the USTs installed at Camp LeJeune?

MR. ANWAR: Object to form.

THE WITNESS: Because the empirical data look at different conditions in different places, and, therefore, an average value of those has nothing to do with what happened in Camp LeJeune in each and every one of those tanks.

BY MS. BAUGHMAN:

Q. Why would the storage tanks leak at a different time in Camp LeJeune? In other words, is there something about the tanks that were used at Camp LeJeune, their materials, how they were installed, that's different from the tanks that the EPA studied that you can identify?

A. Because corrosion occurs differently in different parts of the country or even within the same state close or far from the shoreline. There are different geochemical and environmental conditions. There are issues with installation, good or bad installation. There's a number of reasons why tanks would fail.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. I'm focused first on the kind of tanks that were installed at Camp LeJeune. Is there

something about those tanks, about their materials or how they were installed that makes them different from what the EPA studied in the 12,000 tanks? Can you identify anything different about the tanks themselves?

A. The EPA study looked at a number of different types of tanks across the United States. So they didn't perform a study on the particular type that was installed at Camp LeJeune to provide any kind of confidence in their estimates. This is across the board for all types of.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. Tell me what's different about the tanks specifically at Camp LeJeune as compared to what the EPA studied, the difference in the material, the construction, the installation. Tell me what's different.

MR. ANWAR: Objection to form to foundation.

BY MS. BAUGHMAN:

Q. If you know.

A. I think I responded that the EPA report looks at a number of different types and does not

focus on the types of tanks that we encounter at Camp LeJeune. And even if they did, the fact that that is a range of failure time suggest that we can't really tell when the tank will corrode and, therefore, start leaking.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. Can you tell me what type of tank, what type of underground storage tanks were installed at Camp LeJeune?

A. I do not know.

Q. What were they made off? What were the materials?

A. I believe they were steel tanks, but I'm not sure about the specifics.

Q. Who manufactured them?

A. I don't know.

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. What years, what are the range of years that the underground storage tanks were installed?

A. I'm sorry. Can you repeat that question?

Q. Yeah. When were the underground storage

tanks installed at Hadnot Point?

A. I don't recall the installation time for each tank.

Q. Did the EPA study include the type of tanks that were installed at Camp LeJeune in the study?

A. I don't even know if that were the case or how close they would come to the exact type.

Q. Do you know whether the EPA study included the type of environmental conditions that the underground storage tanks would find at Camp LeJeune as part of the type as part of their study? Let's just say this. Were there -- strike that.

Did the EPA study include tanks that had been installed in North Carolina?

A. I do not know, but it would still be irrelevant. It doesn't answer question as to when the specific ones leaked.

Q. How many of the 12,000 tanks that the EPA studied had similar geochemical and environmental conditions as the tanks at Camp LeJeune?

MR. ANWAR: Object to form. Foundation.

THE WITNESS: I do not know. I do know,

however, that ATSDR looked at that and actually looked at the sensitivity of 18 years of possible release time. So that speaks volumes about what ATSDR considered about the time.

MS. BAUGHMAN: Object as nonresponsive to everything after "I do not know."

BY MS. BAUGHMAN:

Q. You also believe that the source release timeframe of seven years for the landfill area is arbitrary; right?

A. I don't see how we could have known what the time was.

Q. So let's talk about the landfill for a minute. You went to the landfill when you had your site visit, right, last year at Camp LeJeune?

A. We went by the landfill. We saw that at some distance. We didn't actually walk on it.

Q. So Hadnot Point began operations in 1942; right?

A. Yes. That's my understanding.

Q. When were materials -- when that did waste begin to be disposed at the landfill at Hadnot Point?

A. I don't think we have a good understanding of what types of materials and the

timing of the disposal occurred at the landfill. We have some general ideas. I don't even know that we know exactly where they started being disposed of and the progression of the landfill coverage, that it's fully understood.

Q. I'm not asking about "we." I'm asking about you, what you know. When you say "we," I don't know who you're talking about. So just to be clear, when I ask questions, I'm asking about your knowledge. Okay?

When Hadnot Point opened in late 1941 and 1942, where were wastes disposed? Was there another landfill used, or was it always this landfill?

MR. ANWAR: Object to form and foundations.

THE WITNESS: I think that was the case where things were disposed, but I'm not a hundred percent sure. In my analysis I worked with the sources identified by ATSDR. So I took those for granted in terms of the analysis.

BY MS. BAUGHMAN:

Q. Turn to page 14 of your report. The first sentence on page 14, you wrote, "Historical based operations and waste disposal practices have

been identified as being responsible for the contamination of groundwater and finished water supply to the Hadnot Point and Holcomb Boulevard area." Correct?

A. Yes.

Q. Do you agree that those were the sources of contamination at Hadnot Point?

A. I'm just stating what I have read in timelines and reports about Hadnot Point. I do not have any personal knowledge on this.

Q. You agree that industrial wastes were disposed of at the Hadnot Point landfill?

A. Possibly, yes, I think so. But I'm not a hundred percent sure.

Q. Do you know what was disposed of at that landfill?

A. I do not recall the details. Like I said, I took ATSDR's assumptions regarding the source location and type as the starting point of my analysis.

Q. Was the landfill lined at Hadnot Point?

MR. ANWAR: Object to form and foundation.

BY MS. BAUGHMAN:

Q. If you know.

A. I'm not sure. I don't think so, but I'm not sure.

Q. So when waste was disposed of there, was it disposed of in containers, or was it just dumped on the ground?

A. I think there were different types of products that were disposed and different packaging of the disposed material. So there were tanks, but there was other material that was loose. That's my understanding in general terms, but I do not know in detail how material was disposed there.

Q. You said there were tanks. Are you referring to underground storage tanks?

A. No. I'm sorry. I misspoke. I think of drums perhaps, but I don't know. I'm just speculating again on the types of materials that were disposed.

Q. So what precautions were taken in the 1940s to make sure that the waste that was dumped at the Hadnot Point did not leach into the groundwater? Are you aware of any?

MR. ANWAR: Object to form and foundation.

THE WITNESS: I'm not offering an

opinion on that. I'm not in a position to answer that question.

BY MS. BAUGHMAN:

Q. You don't know, do you?

A. I do not know.

Q. So if the landfill began accepting industrial waste dumped on the ground without liners and containers in 1942, why would it be arbitrary to assume that the contaminant releases began seven years later? Why is that arbitrary?

MR. ANWAR: Objection.

THE WITNESS: Because there are no data on which calculations can be based to determine that.

BY MS. BAUGHMAN:

Q. What timeframe -- I want you to assume with me that it's opened in 1942 and the waste begins to be dumped there, and they aren't taking precautions because that wasn't done at the time to make sure that these wastes did not leak in the groundwater.

How long do you think it would take for the release to start?

MR. ANWAR: Object to form.

THE WITNESS: I have no data to offer an

opinion on that.

BY MS. BAUGHMAN:

Q. Did you look into it?

A. No, I did not. I could not, anyways.

(Spiliotopoulos Exhibit 13 was marked.)

BY MS. BAUGHMAN:

Q. I'm handing you what I've marked as Exhibit 13 to your deposition, and that is Chapter F, Simulation of the Fate and Transport of PCE from Tawara Terrace.

I'm going to ask you some questions, but first I wanted to ask you: Do you agree that the water supply well that was the largest contributor of PCE to the Tawara Terrace water treatment plant was well TT-26?

A. I agree.

Q. Let's look at page F34. And I want to ask you some questions about the Figure F16. Okay?

Now, do you see that there's a short timeframe where there were five observed values of PCE that vary from about 1600 micrograms per liter to about 100 micrograms per liter?

A. I can above the one, but, yes, that's range approximately, yes.

Q. And you can see that the simulated value at that time produced by the Tawara Terrace water model of ATSDR shows approximately 800 micrograms per liter when those five values were measured; right?

A. Actually, if I recall correctly, that 800 was a little before that. It was a little less than that during the time when those measurements were available. But roughly, yes.

Q. One question I have for you is looking at -- this is TT-26, right, that we're looking at, the simulation and the measured values; right?

A. Yes.

Q. Can you explain to me why, if you believe it, why this result would show an indication of the model results being biased high?

A. First things first. This is a graph of the historical reconstruction at well TT-26 for which data are available to test its accuracy are only from December '84, January '85, like that critical inflection point, at which point the well is turned off. Then there's another datapoint in 1991.

When I look at this graph, the first thing that I see is when we look at what happens

in 1991, the model calculates practically double the concentration that is measured in the aquifer at that time. So that's a bias high. With respect to what happens prior to that date, this is not the only graph to look at to arrive to that conclusion.

You have to look at all of them from F13 to F17. And all of them are showing that the model overestimates the concentrations, the measured concentrations at the wells at all times.

Q. The other three are not about TT-26; right?

A. No. From RW to near the source to TT23, 25 and 54.

Q. Would you agree the PCE values observed at Tawara Terrace showed a high degree of variance?

A. I'm sorry. Repeat that again.

Q. Do you agree that the PCE values observed at Tawara Terrace show a high degree of variance?

A. Well, the variance that we see in these results is expected given the timeframe that they represent if you collect data within a few days from each other. Of course, you can have the kind

of variability. The problem here is that you have no historical data to test whether the variability you see in '85 is similar to what you see in the previous year and what the trends are historically. So we're only looking at a point in time.

MS. BAUGHMAN: I'll object as nonresponsive to everything starting with "the problem here" and going from there.

BY MS. BAUGHMAN:

Q. When you're calibrating a transport model to observations with a high degree of variance, is it realistic to expect that the simulated concentrations would match the observed concentrations with a high degree of precision?

A. Precision or accuracy?

Q. I asked precision first.

A. Precision is something that is difficult to get. You have to have a great model to do that. You have to have an accurate model, nonetheless, that comes close to the observed values.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. If you're calibrating a transport model to observation to high degree of variance, is it realistic to expect that the simulated concentrations would match the observed concentrations with a high degree of precision?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure I can answer this question in a different way. If I only answer with respect to precision, I'm taking things out of context here.

The critical issue in the model calibration is that the model is, first of all, accurate. So it comes close to the real value. How close is determined by precision. That's a different thing.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Would you expect the model results to match each of the five observed values at TT-26 with a high degree of precision?

MR. ANWAR: Object to form.

THE WITNESS: Of course, not, because the model simulates monthly concentrations, and

these are daily values.

(Spiliotopoulos Exhibit 14 was marked.)

BY MS. BAUGHMAN:

Q. Let me ask you. I'm going to mark as Exhibit 14. I have one copy, but it's just a blowup of Figure 26 -- F16.

I've handed you Exhibit 14, which you can compare, if you want to, to Exhibit 13, page, F34. You see it is Figure F16 from Tawara Terrace Chapter F; right?

A. Yes, it looks like it.

Q. So what I'm going to ask you to do -- I'll hand you a Sharpie. If the simulated value was to be precise and to precisely match up to with a high degree of precision the measured numbers, show me what that simulation would look like. Here's on the marker.

Can you graph that for me what that would look like?

A. But again, we have different values measured over a number of days, and the model calculate a monthly average value. There's no precision here. There's accuracy. What kind of precision can we have if we have different measured concentration over different days and the

model calculates a monthly average value? The model is not constructed to calculate daily values.

Q. Would it be reasonable to assume that the model simulated concentrations would vary as much as the data shown in F16 over that short period of time?

MR. ANWAR: Object to form.

THE WITNESS: I'm sorry. Can you repeat that question, make sure I understand it.

BY MS. BAUGHMAN:

Q. Would it be reasonable to expect the called simulated concentrations to vary the way it's shown in F16 over that period of time?

MR. ANWAR: Object to form.

THE WITNESS: Actually, based on the approximations in the model from the cell size loading and plume size and the variability, I would expect it not to change unless the model had daily pumping rates that would reflect the actual operation of the wells during those days, because what you see at the well is directly related to the pumping rate for that date.

Here the model assumes a monthly average flow rate and calculates a monthly concentration.

BY MS. BAUGHMAN:

Q. Can you draw for me on what we've marked as Exhibit 14 what the simulation would look like if it was accurate with respect to the values shown on F16?

A. You mean with respect to the monthly average concentration that it calculate?

Q. Yes.

A. It would probably be somewhere very close to that.

Q. Close to what's shown in F16 right now?

A. Yes, maybe a little higher or a little lower. To me they would all be acceptable. Given the range of observations, something within that range would be accurate enough.

Q. Thank you.

A. That doesn't say anything about the history of contamination at that well, nonetheless.

MS. BAUGHMAN: Object as nonresponsive to everything after "accurate enough."

BY MS. BAUGHMAN:

Q. If you could turn in your report to page 36. Just to be clear about F14, what you just told me is -- I asked you to draw on F16, Figure

F16 where the simulation would be if you were trying to show accuracy with respect to those datapoints that are almost at the same timeframe. And you said you can't draw anything better than what's on F16 now; is that right?

A. No. What I said is that a model would predict a value that would be somewhere within that range and we would preferably like it to be somewhere within that range, maybe a little higher or a little lower in by itself.

Q. Show me what you think would be accurate. If the model were accurate for F16, where would it be? Here's the marker.

A. Hold on a sec. I would like to answer your question, but I have to answer it in a way that makes sense.

What I said is that the model provides a approximation of the measured concentrations at that time. The problem here is that in the absence of historical concentrations prior to that, whether a value is a little higher or a little lower cannot be evaluated even by itself.

In other words, you can have a model that maybe at that date, it can show a higher concentration than what this one says. But prior

data would show what the trend is like to get there. And looking at all the data, we would make a determination as scientists whether that's an accurate model. Having only data for one month and trying to see if the model is accurate on that date, it's not necessarily meaningful because, like I said, maybe the model would give us something lower than that, maybe something that's 700, maybe something that's 900.

You have to look at the history and not just one datapoint and determine whether it's accurate or not.

MR. ANWAR: Object as nonresponsive.

BY MS. BAUGHMAN:

Q. That is not what I asked you. I asked you to draw if you don't think that's an accurate representation of the values at that time, at that timeframe where those five were taken. If that doesn't represent accuracy in your definition of accurate, show me what would be accurate. I want you to draw it. I don't want an explanation. I just want you to draw. What would be more accurate?

MR. ANWAR: I'm just going to note you don't need to draw anything if it's not possible

to.

THE WITNESS: I'm answering the question. I think you changed the question. But nonetheless, I'm trying to answer your question.

An accurate solution within this range of values is this one. It can be a little, a higher a little lower. What I'm trying to say that and in by itself with one essentially datapoint with just over one month, you cannot opine on the accuracy of the model because the accuracy of the model cannot be determined on the basis of one point.

If you were to take the average of these values and compare the average to that simulated value, you can come as close as 10 micrograms per liter, 20, 50, a hundred. Any of those would be fine provided that you have enough information to determine that getting there is acceptable. Otherwise, with just one point, you cannot answer that question.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. Can you come up with a number or can you mark it on there what would be more accurate than

what's simulated on F16 at that point. I'm not asking before or after. I'm asking you for that point right there. Is there a more accurate number or a more accurate point than what we see there in F16? If there is, I would like you to draw it for me.

A. And I'm saying there are many values here that can be considered accurate with respect to comparing them to the measured values. There's a range here that is fine. But there's no single value that is more or less accurate. This is a relative term.

Q. So what is modeled in F16 is within the range of accuracy for that point in time; right?

MR. ANWAR: Object to form, foundation.

THE WITNESS: And again to provide context to that answer, I'm saying that if we're to look only at that value, we'd say that's close enough. But that's not enough to say anything about the calibration of the model.

MS. BAUGHMAN: Object as nonresponsive to everything after "that's close enough."

BY MS. BAUGHMAN:

Q. Let's go to page 36 of your report. Under Section 4.1.2.1, your first sentence is:

"In its contaminant transport model, ATSDR represented the PCE contamination source at Tawara Terrace as ABC One-Hour Cleaners."

Do you see that?

A. Yes.

Q. Do you disagree with ATSDR's conclusion that ABC Cleaners was the source of the PCE contamination at Tawara Terrace?

A. That's my understanding of what the source of contamination there is.

Q. You haven't identified any other source; right?

A. No, I have not, or to be more precise, I have not looked at any other sources. I took this as the source of contamination.

Q. So in terms of determining the mass loading rate at Tawara Terrace, you'd agree that ATSDR looked at the available data and began with a mass loading rate of approximately 200 grams per day; right?

A. I'm sorry. You're referring to something that I said here?

Q. No, I'm not. I'm just referring. Do you remember?

A. Off the top of my head, no. If you can

point me to the document, I can...

Q. You agree with me ATSDR adjusted the mass loading for Tawara Terrace in its calibration process?

A. That I agree on, yeah.

Q. Isn't that a generally-accepted methodology?

MR. ANWAR: Object to form.

THE WITNESS: In general, yes. But in order to do that, you have to have several datapoints to be able to calibrate to that. Otherwise, it's an assumption that cannot be verified or tested.

BY MS. BAUGHMAN:

Q. In your modeling efforts in fate and transport of contaminants, have you ever adjusted the source mass loading rate as part of the calibration process?

A. Of course, following the steps I just described using data to calibrate the model to that.

Q. In your opinion at the bottom of page 36 is that ATSDR start date for the PCE source release at ABC One-Hour Cleaners was incorrect; right?

A. Yes.

Q. And what was your methodology that you used to determine the correct start date?

A. I believe Dr. Brigham provides the foundation for supporting this argument.

Q. So you reviewed their report of defense expert Dr. Brigham; right?

A. Yes, I did.

Q. Did you do anything else to determine what the alleged correct start date is at ABC One-Hour Cleaners other than review Dr. Brigham's work?

A. I looked at documents myself, but his expert report provides all the supporting material for that opinion.

Q. Did you review any documents other than those cited by Dr. Brigham?

A. No, I don't believe so.

Q. Are you aware of that ATSDR relied on the sworn testimony of Victor Metz, owner of the ABC One-Hour Cleaners for the 1953 start date?

A. That is true. Dr. Brigham brings a lot more information to that subject.

MS. BAUGHMAN: Object as nonresponsive to everything after that is true.

BY MS. BAUGHMAN:

Q. Is it your opinion that relying on sworn testimony is improper?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure I can answer that question. I'm just saying that I don't think that the information provided there was correct based on all the information and material that Dr. Brigham provided.

BY MS. BAUGHMAN:

Q. Did you review the deposition of Victor Meltz?

A. I think I read the portion where he mentioned -- I think he responded to questions about the starting date.

Q. The deposition of Victor Meltz is not on your Supplemental and Amended Reliance List, Exhibit 6. Is there a reason it's not on there if you reviewed it?

A. That's a good question. I would have to check.

Q. Do you actually remember reading the deposition?

A. I'm trying to remember if I read the deposition itself or if it's Dr. Brigham's text

that referred to that. I'm not clear at the moment. I'm thinking of the deposition and what Mr. Meltz said. But I don't recall if it was in Dr. Brigham's report. I do not recall.

Q. As you sit here today, you don't know whether you read Victor Meltz' deposition; is that fair?

A. That's a good question. I'm not sure. I know that Dr. Brigham provided information on that, and maybe I'm thinking what I read there is as if I was reading his report, his deposition. I'm not sure.

MR. ANWAR: Just for the record to clarify something you said, Laura, it's identified by Bates-stamped on his reliance list.

MS. BAUGHMAN: Where do we look?

MR. ANWAR: It's COW_WATERMODELING_09-0000650741.

MS. BAUGHMAN: In the future, if you're going to deal with something like that, I want you to deal with it with the witness outside the room because that is a form of coaching. That's the third time that you've done it. If you want to point that out, we'll take a break. He can leave and you can tell me. Or you obviously can ask him

questions at the end, but doing that now is improper.

MR. ANWAR: I'll note that for the next deposition.

BY MS. BAUGHMAN:

Q. Can you tell me what Victor Meltz said in his deposition about when he began operating ABC One-Hour cleaners?

A. I do not recall verbatim, but I think he said that the business started in '53 perhaps or at least that's -- and I don't recall if that's what he said or what I read in the report, the ATSDR report referring to that source.

I'm not clear as to what the source of my recollection is, but my understanding is that ATSDR suggested that, based on Mr. Meltz' deposition, the starting date was 1953.

Q. I just want to know what do you remember. Assuming you reviewed Victor Meltz' deposition, what did he say? What do you know about what he said. If you don't know, just tell me that.

A. I do not remember verbatim. Like I said --

Q. I'm not having verbatim. What year did

he say he started his business? What year did Victor Meltz say he started his dry cleaning business, ABC One-Hour Cleaners?

A. I'm not sure. I remember it is possible that he said 1953, but I'm not a hundred percent sure if that's what it is or what I remember from the ATSDR report stating that date and attributing that to Mr. Meltz' deposition.

Q. So in any event, the impact on using a start date of July 1954 instead of January 1953 is limited to the early 1950s; right? That's what you wrote in your report?

A. I'm just stating the fact that it's incorrect and to a great extent conservative because even if the business started operation in 1953, for ATSDR to choose January 1, 1953 as the starting date for the source of mass loading is a conservative assumption and certainly wrong.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. That's not what I asked you. I'm going to start counting now. This is number two. I'm going to keep counting them because you're wasting my time. Try to answer my questions.

MR. ANWAR: Please speak to the witness respectfully.

BY MS. BAUGHMAN:

Q. At the bottom of page 36 of your report, you wrote, "This incorrect assumption resulted an estimate monthly contaminant concentrations that were conservative and biased high in the early 1950s."

Isn't it true that you're saying the impact of having a start date of July 1954 instead of January 1953, the impact of that is limited to the early 1950s? It didn't affect the modeling results beyond that, did it?

A. With respect to the starting date, no, it had an impact on that start of contamination in the aquifer by a certain amount of time, yes.

Q. It impacted the early 1950s only; correct?

MR. ANWAR: Object to form.

THE WITNESS: In terms of introducing mass in the aquifer, yes.

BY MS. BAUGHMAN:

Q. EPA placed both Camp LeJeune and ABC One-Hour Cleaners on the National Priorities List in 1989; right?

A. I will have to check the timeline for the correct date.

Q. Page 16 of your report.

A. Yes.

Q. Why is it important that both Camp LeJeune and ABC One-Hour Cleaners were placed on the National Priorities List?

A. I'm not sure I understand the question.

Q. You put it in your timeline. What does it mean? What's the National Priorities List?

A. The National Priorities List is when a site is contaminated and EPA considers that requiring attention in terms of remediation and protection of recipients -- I'm sorry -- receptors of contaminated water.

Q. It's on the National Priorities List also, that's because it's a Superfund list; right? It's a Superfund site; right?

A. That is correct.

Q. Both ABC One-Hour Cleaners and Camp LeJeune are on the Superfund list.

A. Yes. In 1989 they were placed on the list.

Q. What's a receptor of a contaminated water? It's a phrase you just used. Is that a

person?

A. It depends. A person, natural environment.

Q. You agree that the water delivered to residents in Tawara Terrace from the Tawara Terrace water treatment plant was for some period of time between 1954 and 1987 contaminated with PCE?

MR. ANWAR: Object to form.

THE WITNESS: You're talking about the Tawara Terrace treatment plant; is that correct?

BY MS. BAUGHMAN:

Q. Yes.

A. For some time, yes.

Q. And you haven't identified that timeframe in your report; right?

A. No, I have not.

Q. We talked about this. You haven't identified when the contaminated groundwater at Tawara Terrace first reached any water supply well by TT-26-26 or any of the others; right?

A. I think we have -- we have data in 1982 and in '85 and beyond that. We also have a composite sample from 1980 that showed no contamination. It's one datapoint, but it is a

datapoint that suggests there was no contamination there in 1980.

MS. BAUGHMAN: I object as nonresponsive.

BY MS. BAUGHMAN:

Q. In your report have you identified the date when contaminated groundwater first reached any water supply well at Tawara Terrace?

A. No, I have not done that in my report.

Q. In your report have you identified the timeframe when contaminated water first reached the Tawara Terrace water treatment plant?

A. No, I have not.

Q. On page 3 of your report, opinion 6, you say that "ATSDR's dose reconstruction groundwater model for drinking water in Tawara Terrace estimated monthly contaminant concentrations that were conservative and biased high, not reflecting observed data that indicated absence of contamination in the aquifer."

What data are you referring about that indicate absence of contamination?

A. I would refer to the figures you showed me earlier from the extraction wells. So I don't know how we can go back to that figure. That's

Exhibit 13, page 34. For example, Figure F15 shows well TT-25, we had a nondetect value. The model calculates a much higher value. If you look at TT-54, it shows a nondetect as observations, but the model calculates higher values than that.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. I'm asking you not if the model didn't reflect the data. I'm asking you what data indicates absence of contamination? What's the data you're relying on for absence of contamination of the aquifer at Tawara Terrace?

A. I'm just pointed at them in these figures.

Q. So when there's a nondetect value, in your mind that proves that the aquifer is not contaminated?

A. Well, in Tawara Terrace, where we have samples, for example, where the lab analysis showed that there is trace of contamination below the detection limit, they marked that with a J. Where there was not case, it was just a nondetect.

So the lab was capable of detecting traces of contaminations in wells. When it

didn't, it gave a nondetect. My sense is that in most of those cases and especially when you have multiple samples that show nondetect, it's highly unlikely that there is contamination there. It's certainly much lower than what the model calculates.

Q. I'm talking about absence of contamination in the aquifer. That's the phrase that you used. So you're saying that one nondetect sample means the entire aquifer is not contaminated?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Is that what you're saying?

A. I'm saying that the only information we have about contamination -- sorry. You're talking about contamination in the aquifer or wells?

Q. You used the phrase aquifer. You used the phrase absence of contamination in the aquifer. So I'm asking you if there is a nondetect found, does that indicate that the aquifer is not contaminated?

A. I'm saying that it is indication that there is no contamination where samples are taken and, therefore, we have to look a different way on

determining how much contamination is in the aquifer, where and when. I'm looking at just the data. In the absence of data, I'm just making estimates.

Q. Do you agree that the water delivered to residents at Hadnot Point from the Hadnot Point water treatment plant was for some period of time between 1954 and 1987 contaminated with TCE and PCE?

A. For some period of time, yes.

Q. Same for the BTEX compounds?

A. I do not have an opinion on that. I have not looked at BTEX.

Q. What about vinyl chloride?

A. I only looked at the modeling work for Hadnot Point. But there was probably some vinyl chloride, but I did not focus my analysis on that to tell you how much was there and whether that would be considered as contamination above some level.

Q. So you haven't identified the period of time in your report when the Hadnot Point water treatment plant water was contaminated with TCE and PCE; right?

A. For Hadnot Point you're saying?

Q. Yes.
A. I think it's impossible to answer that question with the data available.
Q. It's not in your report, is it?
A. No. If it's not highlighted the reason why, we cannot answer that question.
Q. You haven't identified in your report when contaminated groundwater first reached any water supply at Hadnot Point; right?
A. No. I don't think that's possible.
Q. And you haven't identified in your report when contaminated water at Hadnot Point first reached the Hadnot Point water treatment plant; right?
A. In my report I have not, but -- I will stop there.
Q. Do you agree that prior to December 1954, the level of PCE in the water at the Tawara Terrace water treatment plant was zero?
MR. ANWAR: Object to form.
THE WITNESS: You're talking about the aquifer or well? You're saying in the aquifer, there's no PCE in the aquifer, is that what you asked me?

BY MS. BAUGHMAN:

Q. Well, I didn't ask you about the aquifer. I asked you about the PCE in the Tawara Terrace water treatment plant.

A. It was not contaminated with PCE at that time.

Q. So prior to December 1954, you agree that there was not PCE in the water at the Tawara Terrace water treatment plant. The levels were zero; right?

A. I would be confident about that considering the one source being ABC One-Hour Cleaners.

Q. So level of PCE in the groundwater was zero, you agree, prior to ABC starting its operations; right?

A. Yes. Assuming that's the only source of contamination in the aquifer, yes.

Q. And you don't have any information about any other source?

A. I only looked at that based on ATSDR's assumptions.

Q. So we know the initial conditions, right, at Tawara Terrace in the aquifer for PCE. We know the initial condition was zero; right?

A. Yes.

Q. Do you agree that prior to December 1951, the level of PCE and TCE in the water at the Hadnot Point treatment plant was zero?

A. '51 you said?

Q. Yeah.

A. For Hadnot Point we have no idea when contamination was not there on the basis of the assumptions by ATSDR. I had my assumption that it would be much later than that actually.

MS. BAUGHMAN: So then I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. So do you believe that prior to December 1951, the levels of PCE and TCE in the water at the Hadnot Point watered treatment plant were zero?

MR. ANWAR: Object to form.

THE WITNESS: Based on the data that I have seen, I believe there was no contamination at that time.

BY MS. BAUGHMAN:

Q. So again for Hadnot Point, we know what the initial conditions were; right? They were

zero.

MR. ANWAR: Object to form.

THE WITNESS: The initial condition used in the model is the assumed timing of start of mass releases, and those are different times. That's the starting addition.

BY MS. BAUGHMAN:

Q. Before --

A. So we have a lead source and see when contamination was introduced in the aquifer based on the model assumptions.

Q. Let me say it this way. Before 1942 when they built the Hadnot Point water treatment plant and Hadnot Point itself, was there any contamination in the aquifer?

A. I don't believe there was there, no.

Q. So it started out at zero; right?

A. In 1942 you said?

Q. Right.

A. Not any other date.

Q. And then we went all the way to December 1951. And you would agree that even as of December 1951, the water in the water treatment plant at Hadnot Point would be zero; right?

A. Again, that's an arbitrary number. I

don't know where you're coming up with this number. You have to explain to me where that number is coming from.

Q. I'm asking you. Do you think water is contaminated at the Hadnot Point water treatment plant in December 1951 with TCE or PCE?

A. I don't know when contamination reached the groundwater at Hadnot Point. What I'm saying is that we have no idea of knowing what happened at Hadnot Point. ATSDR showed exactly that in its sensitivity analysis.

MR. ANWAR: Whenever you're at a good spot, we've been going for about an hour.

MS. BAUGHMAN: Sure. We can take a break.

THE VIDEOGRAPHER: Off the record at 1508.

(Recess from 4:08 p.m. to 4:22 p.m.)

THE VIDEOGRAPHER: On the record at 1622.

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, do you agree that the lack of a high reading at one sampling location in an aquifer does not mean that the aquifer is not contaminated in other locations?

MR. ANWAR: Object to form.

THE WITNESS: You're talking about the sample in one location?

BY MS. BAUGHMAN:

Q. Yes.

A. Yes. It's not representative of what's happening in the entire aquifer. It's about what it shows at that location. But other inferences can be made.

Q. Can you turn to page 10 of your report please.

A. Yes.

Q. Under 3.1.8, Concluding Remarks, in the middle of that first paragraph, you have a sentence where you state, "In all cases, a model is required to reasonably fit the measured data to reliably tell us what happens when data are not available."

Did I read that correctly?

A. Yes.

Q. And that's your opinion; right?

A. Yes.

Q. Can you define what "reasonably fit" means?

A. It depends on the case. There's no

single metric to that.

Q. I think you answered this question, but is there a -- can it be quantified. In other words, is there a test or a numerical value that would qualify or be defined as a reasonable fit?

A. We use metrics to calculate that. And depending on the number of points we have, for example, those metrics can take a different meaning if we have many points versus few things points and things like that. So everything is relevant and it has to be looked at case by case.

Q. Somewhere is there a definition of reasonable fit in your industry, like a standard that I could look to?

A. No.

Q. ASTM or other kind of standard that this is what reasonable fit means.

A. No. Like I said, it's a case-by-case situation and it's relative.

Q. Is it also subjective?

A. It can be subjective. There are considerations that go into it.

Q. I want to ask you for a minute about calibration targets.

Are there established standards or

guidelines in the fate and transport modeling community for determining and applying specific calibration targets?

A. No. We try to stay very close to the measured data and have as many data as possible so we can have a reliable calibration.

MS. BAUGHMAN: I'm going to object as nonresponsive to everything after "no."

BY MS. BAUGHMAN:

Q. So there are no standards or guidelines in your field for determining or applying calibration targets; right?

A. There's no single standard, no.

Q. Have you used calibration targets for your models?

A. Yes, I have.

Q. Did you use one for Hanford?

A. Many times.

Q. For chromium 6 concentrations?

A. I have to remember. Yes, I think so.

Q. What was it? What was your calibration target?

A. Well, it depends. It was relative to the values that we had. So it's not a single number. It was a range, but I think it was

also -- I'm trying to remember the actual publication to remember what range was, but we're trying to stay as close as possible. So it was a subjective number. I don't think it was the --

Q. It was subjective, is that what you said?

A. It is a subjective number.

Q. So is it your testimony that calibration targets are subjective by definition?

A. Calibration targets look at how close we get to the data. So we'll look at many different things. We're looking at the type of gradient to see how close they are. We're looking at well levels, how close they are. We look at the concentration trends and we try to get as close to them as possible. There's no single way of quantifying what is close and what is not. We all look at it from different standpoints making sure that we have a good fit. And that's subjective.

Q. If you could turn to page 31. You wrote under Section 4.1, Tawara Terrace, the third full paragraph, you wrote, "Based on my professional judgment, there were insufficient data to conduct reliable model calibration and uncertainty analysis."

Did I read that correctly?

A. Yes.

Q. Can you identify any textbook or published literature that you are relying on for your opinion that there were insufficient data to conduct reliable model calibration and uncertainty analysis?

A. I don't believe there's a document that will give you a number of datapoints.

Q. What about a published standard in the field, is there a published standard in the field you're relying on for your professional judgment and opinion that there were insufficient data to conduct a reliable model calibration and uncertainty analysis?

A. No. This is something we judge based on professional judgment and experience.

Q. Can you tell me what your method was to reach your opinion that there were insufficient data?

A. I don't think it's a matter of method. It's with respect to all my observations with respect to how the model was constructed and calibrated.

Q. What amount of data would have been

sufficient at Tarawa Terrace to conduct a reliable model calibration and uncertainty analysis?

MR. ANWAR: Object to form.

THE WITNESS: I'm afraid it's hard to answer that question because almost everything in the modeling that ATSDR did was based on assumptions and not data. Please do not take that literally. I mean, there were data, but the type of data, the quality of the data, the frequency of the data, the location of the data, these are all important things with respect to the flow model.

When it comes to the transport model, we had little to nothing especially for the period of interest up to 1985 or '87. It was as if it was like one or two datapoints and nothing to give us a sense of the history that we can calibrate to.

MS. BAUGHMAN: I object as nonresponsive.

BY MS. BAUGHMAN:

Q. Let's start with the flow model. What amount of data would have been sufficient, in your opinion, to conduct a reliable model calibration and uncertainty analysis for the groundwater flow data at Tawara Terrace?

MR. ANWAR: Object to form.

THE WITNESS: I'm afraid I cannot answer your question with a single number. I can provide a qualitative answer if you'd like. I do have an answer, but...

BY MS. BAUGHMAN:

Q. Can you tell me the amount of data that would be sufficient for the groundwater flow data at Tawara Terrace to conduct a reliable model calibration and uncertainty analysis?

A. There's not a number that would answer your question. It's about the quality of the data.

Q. If you look at page 69 of your report. By the way, when you talk about the quality of the data, are you relying on any textbook or published literature or standard for your professional judgment regarding the quality of the data at Tawara Terrace?

A. I'm referring to what is very well known in our field as to the kind of data we need for a transient model simulation and calibration. And I think most people would agree on that.

Q. Is that published somewhere?

A. I have provided information in my report regarding certain references, but otherwise, this

is very much common knowledge. I'm not ready to give you a reference. But it's one of those things in our field we consider it self evident at this point.

MS. BAUGHMAN: I'll object as nonresponsive.

BY MS. BAUGHMAN:

Q. Turn to page 69. In the second full paragraph, you say you have a similar opinion as what we just talked about, but here it's for Hadnot Point. You wrote, "Based on my professional judgment, there was insufficient data to conduct groundwater flow and contaminant transport model calibration and uncertainty analysis."

Correct? That's your opinion?

A. That is correct.

Q. If I ask you the same questions, like can you identify a textbook or published literature that you're relying on for this opinion, you're going to give me the same answers; right?

MR. ANWAR: Object to form.

THE WITNESS: Actually, I would refer to you ATSDR statements about the availability of

data to conduct the calibration and uncertainty analysis.

BY MS. BAUGHMAN:

Q. Can you cite me to a textbook or literature that you're relying on with regard to how much data is sufficient to conduct a groundwater flow and contaminant transport model?

A. I don't believe there's a number anywhere published or not.

Q. You did not cite the published literature for this opinion; right?

A. No. I'm stating a fact in our industry.

Q. Similar to what we just looked at, if you look at page 32 and then kind of put your finger there and page 70, you have headings for Tawara Terrace and for Hadnot Point that both say "Available data are limited or nonexistent." Do you see that?

A. One second. Yes.

Q. Let's look at the -- right after you say Available data are limited or nonexistent for Tawara Terrace, you say that there were horizontal hydraulic conductivities from 36 aquifer test analyses at Tawara Terrace and adjacent areas; right?

A. Correct.
Q. On page 70 you note that there were more than 200 aquifer and slope test analyses; correct?
A. Correct.
Q. That's lot of data, isn't it?
MR. ANWAR: Object to form.
THE WITNESS: Depends on the context.
BY MS. BAUGHMAN:
Q. Aquifer tests are time consuming and expensive, aren't they?
MR. ANWAR: Object to form.
THE WITNESS: Usually I believe for most of these here, they're done routinely when that a model well is installed.
BY MS. BAUGHMAN:
Q. I remember for Hanford, you said that you had -- your aquifer tests were limited there; right?
A. At the time, yes.
Q. Because they hadn't been done in the past; right?
A. Some were done. This was still an evaluation of the site. We're still under a site characterization in many ways.
Q. Would you agree that ATSDR based its

hydraulic properties for its models on site-specific data?

MR. ANWAR: Object to form.

THE WITNESS: There are site-specific data with respect to that, but again, I have to provide context to my answer. I cannot just say yes or no. Otherwise, I'm misrepresenting my answer. Would you like to hear my answer?

BY MS. BAUGHMAN:

Q. I just want to know if you agree ATSDR based its hydraulic properties for its models on site-specific data. They used site-specific data, didn't they?

A. They used these site-specific data, yes. They considered them, yes.

Q. The flow model for Hadnot Point used more than 700 water level measurements; right?

A. The number again is irrelevant. ATSDR offered a statement on the quality of the available data to perform the calibration, and they indicated that it was not sufficient to calibrate the model.

Q. You're saying that ATSDR said they had insufficient data to calibrate their flow model?

A. They said that the calibration was

limited because there were no data available beyond two wells to calibrate the transient model. I have a statement in my report on that. I believe I quoted what ATSDR said in their report.

Q. Let's talk about the steady-state model. They calibrated using that using more than 700 water measurement levels; right?

A. Yes, but very little water level data as well. The model calibration is a complex process that involves development of special distributions or parameter. So the fact that you have some data somewhere, it all depends on where you have them, how many you have, how many water levels data you have.

I can go on and on about the data available at the time. You're giving me a number. But I'm just saying that there are things that were not available and that were important.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. On page 77 of your report, under Section 4.2.3.1, you have a sentence where you state --

A. I'm sorry. Say that again. Which one?

Q. Page 77.

A. 77. You're taking me to another page. Give me a second to get that. Yes.

Q. Under 4.2.3.1, second sentences, "The steady-state model" -- this is for Tawara Terrace -- "constructed for simulating predevelopment condition, i.e., ambient groundwater flow in the absence of pumping, was calibrated using more than 700 water level measurements."

Correct? That's what you wrote?

A. That is correct, but, like I said, I have to provide context on that. Otherwise, I'm not sure the message gets across.

Q. Was the 700 water level measurement used for the steady-state model an insufficient amount of data for that calibration?

A. They were not even predevelopment data because they were not available. They used data over a long period of time at the times when the wells were turned off, for example, during remediation when there was no pumping.

So they compiled a large dataset from different times. In the absence of predevelopment data, they called that predevelopment to get some sense of steady-state conditions in the aquifer.

So right there that's one thing to consider.

Q. So your opinion that the 700 datapoints used by ATSDR to calibrate the steady-state model is an insufficient amount of data?

A. I'm not saying that. I'm saying the data available provided some measurement. They were not development, referring to period prior to 1942. They compiled data from different times. But then I'm just stating that, because the most important part in this model is the transient state model, which reflects the aquifer response to pumping.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. You're doing it again. It's like here you go again. You're not answering my questions. Try to answer my questions.

You wrote in your report that the steady-state model was calibrated using more than 700 water level measurements. I want to know for that model was that an insufficient amount of data, in your opinion?

MR. ANWAR: Object to form.

THE WITNESS: I cannot answer this

question like that. I have to provide context. If allow me, I can. Otherwise, I can just confirm that what you read is correct.

BY MS. BAUGHMAN:

Q. I want to know whether the 700 datapoints used for the steady-state model was an insufficient amount of data, in your opinion?

MR. ANWAR: Object to form.

THE WITNESS: I'm saying that where they're coming from is important because they mix and match different times. I have to give context to my answer. Otherwise, I cannot answer question.

BY MS. BAUGHMAN:

Q. Wherever they came from, I'm not saying that they were predevelopment data. I'm not saying that they were from last year. You wrote in your report there were 700 datapoints.

Was that an insufficient amount of data to calibrate the steady-state flow model?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. What is your opinion?

MR. ANWAR: Same objection.

THE WITNESS: I'm not sure they were

sufficient. I have reservations about the time they were collected. But in any event, that's fine. The important part is the transient state model.

MS. BAUGHMAN: Objection. Nonresponsive regarding transient state.

BY MS. BAUGHMAN:

Q. So your opinion on whether the 700 datapoints and whether those were sufficient to calibrate the steady-state model, your answer is you're not sure if that was sufficient; is that right?

A. I don't have a particular opinion about that.

Q. If you could turn to Exhibit 4, which is the Chapter A from Tawara Terrace.

A. One second, please.

MR. ANWAR: Four I think is his report.

THE WITNESS: Are you referring to my report?

BY MS. BAUGHMAN:

Q. Time out. No. Exhibit 4. Wait. Hold on. I've got it. I have it misnumbered.

MR. ANWAR: Exhibit 9.

BY MS. BAUGHMAN:

Q. Chapter A for Hadnot Point is what I'm talking about, which is I guess Exhibit 9.

A. Exhibit 9?

Q. Yeah.

A. Okay.

Q. Turn to page A10.

A. Okay.

Q. Table A2 has the number and type of data extracted from information sources and reviewed for historical reconstruction analysis for Hadnot Point Holcomb Boulevard and Tawara Terrace study areas.

Do you see that?

A. Yes.

Q. Did you consider this table in your opinions?

A. It refers to different sources and different purposes. So I'm not sure how to answer your question.

Q. So this chart tells us number and the type of data that were extracted from information sources and reviewed by the ATSDR team for its historical reconstruction analysis; correct?

A. They were considered by ATSDR, yes.

Q. Any reason to disagree with the numbers set forth in Table A2?

A. It's probably right. I'm assuming it's accurate. I'm not sure. I haven't looked at them one by one.

Q. For example, ATSDR reports here that for its modeling analysis at Hadnot Point and Holcomb Boulevard, they reviewed 13,133 water level measurements; correct?

A. You read the number correctly there.

Q. And they also reviewed for Tawara Terrace 789 water level measurements; right?

A. Correct.

Q. And for Hadnot Point and Holcomb Boulevard, they had groundwater samples analyzed for chlorinated solvents. There were 4,104 samples; correct?

A. All types of samples, yes.

Q. For chlorinated solvents.

A. That's what they're stating and that's correct.

Q. And 192 for Tarawa Terrace; right?

A. Yes.

Q. And wells hydropunch points and boreholes, for Hadnot Point and Holcomb Boulevard,

they reviewed 1,979 different data values; correct?

A. That's what the table says.

Q. For Tawara Terrace 222; correct?

A. The approximate number of data values it says there, yes, I agree.

Q. For Hadnot Point and Holcomb Boulevard, they had 264 datapoints for supply well and monitor well aquifer and slug tests; right?

A. That's what it's stated in the table; correct.

Q. For Tawara Terrace, 33; right?

A. That's what the table says; correct.

Q. Did you review all of this data that I've just talked about? Did you actually pull up the data and review, for example, the 13,833 water level measurements for Hadnot Point?

A. No.

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. ATSDR used a test analysis for prior estimation for Hadnot Point; right?

A. For calibrating the full model I believe, yes.

Q. Well, didn't they use a test to calibrate the predevelopment model for Hadnot Point?

A. Yes.

Q. Are you aware that John Doherty assisted them with that analysis?

A. I don't know how he assisted them or whether he provided instructions. My understanding is that he provided a short course on how to use PEST. That was my understanding.

Q. Were you aware that he visited with the ATSDR people for a week and assisted them with this PEST analyses for Hadnot Point?

A. I don't know if he assisted them.

Q. You don't know? John Doherty is the man who developed PEST; is that right?

A. Yes. I know him personally.

Q. Is he associated with Papadopulos & Associates?

A. He has been under different forms and shapes, yes.

Q. Is he now?

A. I'm not sure actually.

Q. You've used PEST; right?

A. Extensively.

Q. What is it? Just in short form, what is PEST?

A. It's a computational method of considering the model structure and using calibration data or targets, adjust model parameters, properties so that the model can match to the extent possible the observed data.

Q. Have you reviewed the PEST analysis that was done by ATSDR at Hadnot Point?

A. The analysis itself you mean?

Q. Yes.

A. No, I have not.

Q. Do you know which parameter of values ATSDR calibrated using PEST for Hadnot Point?

A. I don't recall which parameters, but I would assume hydraulic conductivity.

Q. Would you agree using PEST to calibrate hydraulic conductivity is a reliable methodology?

MR. ANWAR: Object to form.

THE WITNESS: PEST is a reliable tool to be used for analysis, the analysis performed by a hydrogeologist, and the data to be used or judged accordingly.

BY MS. BAUGHMAN:

Q. Do you have an opinion on whether ATSDR

used PEST reliably in calibrating hydraulic conductivity at Hadnot Point?

A. For the predevelopment model?

Q. Yes.

A. No. I don't know.

Q. You don't know, is that what you said?

A. I'm not familiar with the work they did. I did not review their calibration.

Q. So as you sit here today, do you have any criticisms of ATSDR's use of PEST at Hadnot Point?

A. That's a very general statement. I'm saying that the importance there is on the transient model, and for that the ATSDR said that they had practically no data to calibrate the model, and that's the model that was used for the calculation. So what the predevelopment model does --

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. As you sit here today, do you have any criticisms of how ATSDR used PEST at Hadnot Point?

MR. ANWAR: Object to form.

THE WITNESS: Again, I don't have an

opinion on how they used PEST.

BY MS. BAUGHMAN:

Q. Is it your opinion that ATSDR had limited data regarding the geologic representations at Hadnot Point?

A. I'm sorry. Could you repeat the question?

Q. Is it your opinion that ATSDR had limited data regarding geologic representations at Hadnot Point?

A. What do you mean by representations? What was built into the model? I'm not sure I understand the question.

Q. The hydrogeologic framework.

A. There were several assumptions that were made with respect to hydrogeologic framework based on the data, and ATSDR discusses that especially with respect to the model construction.

Q. Do you agree that ATSDR had 931 datapoints available to describe the hydrogeologic framework?

A. Where do you see that number?

Q. Do you know how many they had?

A. I don't remember the number by heart.

Q. Do you agree that for Hadnot Point for

the level three calibration, ATSDR included data from the 1990s and also from 2000 to 2008?

MR. ANWAR: Object to form.

THE WITNESS: Where do you see that just to make sure that I concur to the right numbers?

BY MS. BAUGHMAN:

Q. Let's look at page 77 of Mr. Maslia's report. That's Exhibit 10.

A. What page was that?

Q. 77.

A. Hold on a second. 77 you said. I see page 76. 77 is this statement. Okay. Where is that number again?

Q. So --

A. I don't see that number.

Q. There were four remediation extraction wells that were installed over a decade after HP651 was decommissioned, do you see that, to cleanup the groundwater?

A. Excuse me one second. Can I find that on the page. You said page 77 of his expert report.

Q. That's right. The second paragraph.

A. Where are you looking at?

Q. The additional panels in Figure 7.12

represent four remediation extraction wells.

A. Yes.

Q. 7.21 is on the next page if you need to see it. That were installed over a decade after HP651 was decommissioned to clean up the groundwater during USEPA installation/restoration program.

Do you agree with me that for the level 3 calibration for Hadnot Point, ATSDR used both the data in the early 1980s that it had and it used data from these four remediation wells from the 2000 to 2008 timeframe?

A. Your statement is correct.

Q. Is it your opinion that these two sets of data from the '80s and then from 2000 to 2008 were an insufficient amount of data to calibrate in level 3 for Hadnot Point?

A. Yes.

(Spiliotopoulos Exhibit 15 was marked.)

BY MS. BAUGHMAN:

Q. Let's turn to Tawara Terrace, Chapter A.

So Exhibit 15, Chapter A: Summary Findings from Tawara Terrace; correct?

A. Yes.

Q. If you could turn to page A26.

A. Okay.

Q. Page A26 provides a Table 8A, provides a summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tawara Terrace and vicinity; correct?

A. Yes.

Q. So to calibrate level one, the predevelopment groundwater flow model, ATSDR had 59 separate paired datapoints; correct?

MR. ANWAR: Object to the form.

THE WITNESS: That's what the table says.

BY MS. BAUGHMAN:

Q. Is that not true? Do you have a reason to believe that's not correct?

A. I don't think so. I'm just stating the fact this is what the table says.

Q. Calibration level two, for Tawara Terrace, ATSDR had 263 transient groundwater flow monitor well paired datapoint and 561 transient groundwater flow supply well paired datapoints; correct?

A. Correct.

Q. For the fate and transport level three,

they had 36 paired datapoints; correct?

A. Correct.

Q. And for level four at the treatment plant, they had 25 paired datapoints; correct?

A. That's what the table says, yes.

Q. Did you review all of these pair datapoints as part of your work on the case?

MR. ANWAR: Object to form.

THE WITNESS: I looked at the tables that ATSDR provided for looking at these differences. I looked at the timing of the data available. And I also considered ATSDR's own statements about the number of data available and the quality of those data.

BY MS. BAUGHMAN:

Q. So you said you considered the timing of the data available. For the groundwater flow model, the transient flow model for Tawara Terrace, they had four decades of data available for that calibration; right?

MR. ANWAR: Object to form.

THE WITNESS: Actually, that is not correct and I can look at where -- there are that you remember data that span a long period, but the majority of the data are coming from 1978 or so,

if I remember correctly, for the pumping wells. And ATSDR provided some graphs to compare the observed and simulated values for those wells.

BY MS. BAUGHMAN:

Q. Let's go to Mr. Maslia's report and look at page 50.

A. Yes.

Q. If you flip to page 49, we can see what he's talking about here is level two calibration, right, transient conditions; correct?

A. Yes.

Q. Turn to the next page. He says input parameter are calibrated to minimize deviations between simulations and observed calibrations. He says, "It should be noted that four decades of data were available for this calibration, from 1951 to 1994."

Now, is that correct ATSDR had four decades of data available for that transient flow calibration?

MR. ANWAR: Object to form.

THE WITNESS: They had data from that timeframe, yes.

BY MS. BAUGHMAN:

Q. Let's flip back again. We were just

looking at Exhibit 15, Chapter A from Tawara Terrace, Table A8.

A. Table A8.

Q. On page A26, the one we were just looking at.

A. Okay.

Q. Is it your opinion that the 59 paired datapoints that ATSDR had available to calibrate its predevelopment groundwater model, that that was an insufficient amount of data to perform that calibration?

A. I believe that the number of datapoints is somewhat irrelevant when we look at this model and its calibration. There are additional considerations before we answer that question.

Q. Is it your opinion that there were insufficient data for the ATSDR to calibrate its predevelopment groundwater flow model for Tawara Terrace?

A. I believe so, yes.

Q. And how much data would have been necessary to calibrate that groundwater, predevelopment groundwater flow model?

MR. ANWAR: Object to form.

THE WITNESS: There's not an answer to

your question that comes with a particular number.

BY MS. BAUGHMAN:

Q. So what is your criticism of the 59 paired datapoints used by ATSDR to calibrate the predevelopment groundwater flow model?

A. First of all, they're not true predevelopment data for starters. They're coming from different times within a very long period of time, from I want to say the '50s if there is a one there, and everything else it's much, much later over the actual period through '85 and beyond during the remediation period. So it comes from decades.

Q. What's the other criticism?

A. Well, in and by itself, this is not predevelopment to begin with. So it doesn't necessarily reflect the conditions.

Q. Do you have another criticism?

A. In terms of the number of datapoints?

Q. In terms of why you I think datapoints were insufficient?

A. The location of these datapoints.

Q. What's the problem with the location?

A. Well, I'm not sure that they cover the entire area of interest. This is a very big

model.

Q. Did you map that out to see?

A. I believe I looked at those on the map, yes.

Q. Anything else?

A. For the predevelopment?

Q. Yeah.

A. No. Basically this is what I have for that.

Q. For the transient groundwater flow model for Tawara Terrace, why do you believe that the 263 transient groundwater flow monitoring well paired datapoints and the 526 transient groundwater for a supply well paired datapoints, is it your opinion that's insufficient data to calibrate that model?

A. That comes hand in hand with all the other information that goes into the model. The model is calculating water levels on a monthly basis. These transient water level values do not capture the variability in aquifer response to pumping at different times. It just gives us snapshots at water levels at different locations.

So for the frequency of model output and the level of detail that this model is intended

for, this is not sufficient information. We should have continuous data at certain locations to see how aquifer responds to pumping. So this is definitely not enough.

Q. How much data would have been needed?

A. Again, it's not about the number of data. It's the location and the type of data.

Q. So where were the locations of these more than 800 datapoints that they used for paired? What locations were missing?

A. The groundwater flow supply wells, again the well itself is not -- a water supply well, you turn it off and you get a measurement. You don't have continuous data there to give you --

Q. I'm asking about location now.

A. I'm saying that there should be, first of all, monitoring wells across the domain. That would be preferable. So there's a level of uncertainty there. And the data we use were coming primarily from supply wells, which were turned off at some point and a measurement was taken.

So we have no idea what the variability of water levels in the aquifer was near those wells or in the graded area.

Q. There were also 263 paired data the monitoring wells. What's your criticism of that?

A. Because the number of stress periods that we have is much bigger than that in the model. And so by no means do these datapoints capture the variability of pumping in the aquifer. That is constructed in the -- that is incorporated in the model which is monthly output.

Q. So how many datapoints would have been needed?

A. Many more than that and at different locations and over continuous periods of time to allow the modeler to calibrate the model to the aquifer response because we're pumping on a monthly basis.

Q. Can you give me a number?

A. No.

Q. Can you give me a citation to literature that supports your opinion that data -- that there were insufficient paired datapoints for the predevelopment or transient groundwater flow models for Tarawa Terrace? What literature are you relying on?

A. I don't believe that there's any literature source that would give you that answer.

Q. What standard in your field are you relying on?

A. It's common practice in our field that that to calibrate a phantom model, they need transient data.

Q. Do you have an ASTM standard or some other standard that you're relying on for your opinions regarding insufficiency of data?

A. I do not remember whether that's even stated there, but again, that's common practice in our field. And I believe -- I probably have to go back to even Anderson and Wuzner to find something to that effect.

Q. As you sit here today, can you cite a standard in your field that ATSDR violated regarding the sufficiency of data used to calibrate the Tawara Terrace model?

MR. ANWAR: Object to form.

THE WITNESS: Off the top of my head, I cannot.

BY MS. BAUGHMAN:

Q. Is it in your report?

A. We'll have to see where something like that would have been stated. I will have to check.

Q. You can't identify it as you sit here today?

MR. ANWAR: Object to form.

THE WITNESS: Again, I would say that any hydrogeologist would agree on that.

BY MS. BAUGHMAN:

Q. Page 32 of your report.

A. What page again?

Q. 32. You wrote in the middle of the page, "To construct the contaminant transport model, ATSDR used model parameters that were based on a literature review and the professional judgment of the modelers."

Do you see that?

A. Yes.

Q. You have a similar statement on page 70 regarding Hadnot Point. My question is you're basing model parameters on published literature and improper methodology in your field?

MR. ANWAR: Object to form.

THE WITNESS: It's usually the starting point in our analysis.

BY MS. BAUGHMAN:

Q. Then calibration after that; right?

A. Considering site-specific data.

Q. What is your basis for criticizing the use of published literature to inform model parameters?

MR. ANWAR: Object to form.

THE WITNESS: Literature sources is a good starting point as a reality check with respect to the values we're using. But again, site-specific data are the way to go in terms of testing whether the values we're using are appropriate for the particular conditions that we're trying to model.

MS. BAUGHMAN: Object to the nonresponsive portion.

BY MS. BAUGHMAN:

Q. Are there any standards outlining the parameters that can and cannot be based on literature in your field?

A. I'm not sure I understand your question.

Q. Are there any standards in your field that say which parameters can and cannot be based on literature?

A. I'm not sure how to answer this question. No, there's nothing that says that you can or cannot. Literature sources provide a basis when you look at conditions that you have at hand

with similar conditions from literature. And then site-specific data confirm how far or close we are to those values. And then model calibration refines that estimate.

Q. So you didn't cite any textbook or literature or anything else for your opinion that supporting ATSDR should not have used literature review and professional judgment with respect to model parameters; correct?

A. That's not what I said in my report. I said that's the only thing they relied on and they did not consider site-specific data.

Q. You're saying ATSDR didn't consider any site-specific data at all in establishing any parameter for Tawara Terrace; is that true? Is that what you're saying?

MR. ANWAR: Object to form.

THE WITNESS: No, that's not what I said.

BY MS. BAUGHMAN:

Q. So which parameters did they not use site-specific data for?

A. For the transport parameters, the value of Kd.

Q. Anything else?

A. Porosity, bulk density. The reaction rate was based on the pair of values. So certainly not enough to calibrate the model. These are the ones that come to mind right off the bat.

Q. Anything else?

A. That's all I can think right now.

Q. Are there any standards in your field that say one cannot use professional judgment to set model parameters?

MR. ANWAR: Object to form.

THE WITNESS: Of course, we use professional judgment all the time.

BY MS. BAUGHMAN:

Q. Professional judgment is used all the time to calibrate groundwater models; right?

A. That's an incomplete statement. We use professional judgment, and then we rely on site-specific data and observations to calibrate a model.

Q. Are there any standards outlining the parameters that can and cannot be based on an engineer's professional judgment in your field?

MR. ANWAR: Object to form.

THE WITNESS: Again, it's not about what

can or cannot be used. It's how our assumptions and inputs into the model are checked against observed data or site-specific data to begin with to determine whether our calibration is good enough.

MR. ANWAR: Whenever you're at a good spot to take a break, there are people in the waiting room as well. We've been going for about an hour.

MS. BAUGHMAN: We can take a break.

THE VIDEOGRAPHER: Off the record 1711.

(Recess from 5:11 p.m. to 5:17 p.m.)

THE VIDEOGRAPHER: On the record at 1717.

BY MS. BAUGHMAN:

Q. Dr. Spilotopoulos, can you identify any site-specific data for Tawara Terrace or Hadnot Point that you believe ATSDR should have considered and didn't in its modeling?

A. The most obvious one was the Kd, the distribution coefficient. There were data available. They were not considered and as a result, ATSDR used professional judgment, but also made some errors that resulted in low values.

Q. Anything other than that?

A. Bulk density was another mistake that was made, and it was later corrected as far as I understand. But it was an error that impacted the uncertainty analysis.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Let's focus on the question. Is there site-specific data that was available that ATSDR, in your opinion, should have used in its modeling and didn't use? Can you identify that data?

A. I believe the coefficient is one of them, Kd, yes.

Q. Anything else?

A. I don't know that that I know if others were available.

Q. Can you identify any other site-specific data that was available to ATSDR and that they did not use or should have used, in your opinion?

A. Possibly not, but I'm not sure. I haven't exhaustively checked that.

Q. If you turn to page 16 of your report.

A. Yes.

Q. The last paragraph right before Section 3.3, in the second sentence, you wrote, "However

assumptions and/or parameter values used by ATSDR in constructing these models were incorrect or inconsistent with site-specific data."

Do you see that?

A. Yes.

Q. Can you identify the assumptions and the parameter values that you believe were incorrect or inconsistent with site-specific data? Please tell me which ones.

A. And we're talking about the Tawara Terrace model; correct?

Q. Either one, both.

A. Assumptions and parameters that I consider incorrect or inconsistent with site-specific data, you would like a list?

Q. Right.

A. For Tawara Terrace, the start of mass loading in the aquifer; the Kd value. Let me think about this, make sure I provide a correct answer. The assumption that there were no losses at the treatment system, although this was not part of the model itself. It was part of the calculation of what went to the customer. The bulk density value that was used for Tawara Terrace and, hence, the retardation factor. I

would stop at that.

Q. So just going back, this was the list of the assumptions and parameter values that were incorrect and inconsistent with site-specific data; right?

A. Yes.

Q. So what was the site-specific data that was inconsistent or incorrect with respect to the start of the mass loading rate?

A. The fact that we have -- I consider the information we have on when we believe that actually operations started and, therefore, potential contamination into the ground commenced.

Q. So the site-specific data you're talking about there is what was in the other expert's report?

A. Yes.

Q. And the site-specific data on the VOC loss, is that what you're referring to that's in Dr. Hennet's report?

A. Correct.

Q. On page 69 of your report, you have a sentence regarding Hadnot Point.

A. I'm sorry to amend my previous answer. I think site-specific data would also apply to the

pumping rates of the wells as applied in both models.

Q. So what was the site-specific data on the pumping?

A. Well, ATSDR developed a scheme where it assigned flow rates to each well for every stress period of the model every month. Very little to nothing was known about the majority of time for the operation of those wells. So that was an assumption.

Q. What site-specific data is that inconsistent with?

A. Well, that would be actual information about the operation of those wells. I'm suggesting that that was an assumption.

Q. But is that assumption inconsistent with site-specific data that you have available to you or that ATSDR had available to it?

A. Well, that's what I'm -- the context of my answer there is that there are some data, and then ATSDR developed a technique to take out of bulk value specific flow rates for the wells. And so --

Q. But is what ATSDR did inconsistent with existing site-specific data for pumping?

A. Not to the extent that there are available data for those times and those were not used. It's more about how they were developed with respect to available site-specific data.

Q. ATSDR used all of the available data regarding pumping that it had available to it; right? It didn't ignore data, did it?

A. I don't believe that they did.

Q. If you turn to page 69, that's what we were just talking about, in the third full paragraph it starts, "Given the fact..." Do you see that?

A. Um-hum.

Q. I'm going to ask you about the second sentence. You wrote, "ATSDR's sensitivity and uncertainty analysis evaluated a range parameters values, some of which when compared to site specific value did not reflect the site conditions."

Which of the parameter values when compared to site-specific data did not reflect the site conditions?

A. Well, I believe that I have a table where I'm indicating the kind of values that ATSDR used for the sensitivity analysis that were way

outside the range of values that were developed either based on site-specific data or what they considered otherwise as the mean values as reasonable for the site.

For example, I will have to go to the actual page. I have that there. I'm actually providing some numbers here, and I'm saying that for the hydraulic conductivity, they used values equals to .1 or 10 times the calibrated value. That was way outside a reasonable range of values across the model.

Q. Inconsistent with site-specific data?

A. Well, for the distribution of those values across the entire aquifer, yes.

Q. What page are you on there?

A. Page 87. In fact, I believe that ATSDR indicated that the values would range somewhere between 1 and 50 feet per day, and I have a reference for that period. We can look at it. They use values 0.1 or 500 feet per day.

Q. Go to page 36 of your report. You wrote right above Section 4.1.2.1, you have this statement. "In this section I focus on certain assumptions and parameters due to their significant impact on the model results. It

should be noted that this discussion is not intended to be inclusive of all assumptions or parameters I believe were inappropriately selected."

Are there any others that you can identify today that you left out of your report that you intend to testify about at a hearing or at the trial of this matter?

A. I'm not sure I'm ready to offer an opinion on that. I will focus on the ones that I provided in my report.

Q. You understand that when you wrote the expert report, you were supposed to include all of your opinions and the basis for your opinions in the report; right?

A. Yes.

Q. Flip to page 92 of your report.

A. Okay.

Q. You wrote toward the bottom of the first paragraph under Concluding Remarks, you wrote, "Similarly to Tawara Terrace, there is no observed system behavior, i.e., historical data from the entire period of interest to support a reasonable and accurate model calibration."

Do you see that?

A. Yes.

Q. Are you saying here that historical data from the entire period of interest is required in order to have a reasonable and accurate model calibration?

A. I'm saying the data from the historical period are necessary to test the accuracy of the model results, some data. I'm not offering an opinion as to how many or when, but certainly within that timeframe, it would need more data.

Q. So you didn't cite any textbook or manual or authority for that opinion; right?

A. I'm not sure there is even one out there. I'm not that I'm aware of. But again, this is common knowledge.

Q. Is it your opinion that to reconstruct -- to do a historical reconstruction, it's required to have concentration data for the entire historical period?

A. I'm saying we should have some site-specific data to rely upon and not assume their values. There should be some observation data so we can test the concentration levels over time, something to that effect, because in this particular case, I think I demonstrated by just

tweaking one parameter value, we get a completely different calibrated model that is equally plausible, and it was not within the uncertainty range that ATSDR produced that gave me less confidence in the model.

Q. So the citations in your report, the textbooks you rely upon, they recognize historical reconstruction as being valid. It's a valid methodology; right?

MR. ANWAR: Object to form.

THE WITNESS: That's a very vague statement. Yes, historical reconstruction can be done, has been done, yes.

BY MS. BAUGHMAN:

Q. Is there any reference you can cite to that says you have to have concentration data from the entire historical period to do a historical reconstruction?

A. No. I'm demonstrating in this particular case, that was not done properly because I could demonstrate that. I could get a completely different answer.

Q. So what you're saying there is that -- you're talking about nonuniqueness; right?

A. Yes.

Q. Isn't it always true that water models are nonunique?

A. That's a very general statement, and that is true.

Q. In other words, nonuniqueness is not limited to or unique to ATSDR's Camp LeJeune models; right?

A. I can provide an answer with respect to the particular model. A blanket statement otherwise might misconstrue my opinion.

MS. BAUGHMAN: What? I'll object as nonresponsive.

BY MS. BAUGHMAN:

Q. You wrote on page 41 of your opinion, the very last sentence on page 41, you wrote, "While professional judgment is essential in model construction, it cannot guarantee model accuracy absent these data." Right?

A. I'm sorry. Can you point me again. The last paragraph?

Q. The last paragraph, the last sentence.

A. Yes.

Q. Cannot guarantee model accuracy.

Is there any model that can guarantee accuracy, any groundwater model?

A. There are different levels of accuracy that we can evaluate.

Q. Which level of accuracy that's required in this case, do you know?

A. What I showed is that by just tweaking one parameter, I get a completely different calibration. So I cannot even test the accuracy of the model to say whether it's good or not.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. What you're saying is the model is not unique; right?

MR. ANWAR: Object to form.

THE WITNESS: Models are not unique, that's correct.

BY MS. BAUGHMAN:

Q. No models are unique, are they?

MR. ANWAR: Object to form.

THE WITNESS: Again, very vague, general statement. Yes.

BY MS. BAUGHMAN:

Q. But it's true, isn't it?

A. Yes. Models are nonunique, of course.

Q. Now, let's go back. You're talking

about guaranteeing model accuracy. Have you ever guaranteed to any of your clients that your model is accurate?

A. What I provide to my clients is models where the accuracy can be tested with respect to data, and I illustrate the kind of accuracy that they provide. Here I cannot provide any such statement.

Q. So the Hanford model, the one that we marked as an exhibit, that paper we talked about, you didn't guarantee the accuracy of your chromium 6 concentrations; right?

A. Of course, not. That was not in the scope of that calculation. It's was not expected.

Q. What's the standard if court is to judge ATSDR's model? How accurate is it supposed to be, do you know?

MR. ANWAR: Object to form, foundation.

THE WITNESS: I'm looking at the accuracy of this model, and I say I cannot even test it. So it's not a matter of providing a level of accuracy.

MS. BAUGHMAN: Object as nonresponsive.

BY MS. BAUGHMAN:

Q. Do you know what the standard is in this

case for accuracy?

MR. ANWAR: Same objection.

THE WITNESS: My understanding is that the ATSDR model is supposed to provide monthly concentrations over a long period of time. And ATSDR also calculates the uncertainty range of that, therefore, suggesting that the potential values of contamination in any month, in any given month is within that range. And I'm saying with respect to that, I can prove that there are so many other models that can actually produce very different results outside that range. Therefore, the accuracy of the model cannot be tested, especially in the absence of any data to test that.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. Let's turn to Morris Maslia's report, Exhibit 10, at page 59. I want to ask you about a couple statements that Mr. Maslia made. I'm looking at the past paragraph on page 59 in the sending sentence. He wrote, "The observed data used for calibration included all available geologic data, supply well characteristics and

observed well contaminant values."

Do you know whether that's true, that he used all the available data for calibration at Tawara Terrace?

A. All available is a blanket statement. I would tend to think they considered the data available. I'm fine with the statement.

Q. You're fine with that. Okay.

A. Although having said that, I'm saying -- hold on a sec. That ignores site-specific data that I pointed out, for example, the distribution coefficient that was not considered. So I don't know if that falls in the category of everything you looked at there.

Q. And he's referring to Figure 7.13, which is on page 55 if you need to look at it, but he says, "The observed values at Figure 7.13 represent the measured concentration statement about the Tawara Terrace water treatment plant and at other locations in Tawara Terrace water distribution system."

But then he says, "It is important to note these observed values were not used in the calibration process and, therefore, represent an additional set of observed field data by which to

assess the goodness and fit of the four-level hierarchical calibration process."

I want to ask you about that. Is it your understanding that the values at the water treatment plant for Tawara Terrace were not used in the calibration process. Is that true?

A. That's my understanding.

Q. Instead, ATSDR used those values as an additional set of data to assess the goodness of fit; right?

A. That's what Mr. Maslia said.

Q. And did the same thing. Same process was used for Hadnot Point; right?

A. That is true.

Q. Different subject. There is a criticism that you and/or Mr. Hennet have made about TT-26-26 and when it was and wasn't operating.

Do you recall that?

A. I don't think I made a statement about the operation of TT-26.

Q. In your report, if we can turn to page 38 and 39.

A. Yes.

Q. You in your summary of opinions 2 and 3 at the bottom of the page, you say, "Parameter

values in the Tawara Terrace model were different than those in the Hadnot Point model -- you started in this page and go to the next page -- even though both models stimulated similar hydrogeologic conditions."

Do you see that?

A. Yes.

Q. It your opinion that Tawara Terrace and Hadnot Point had the exact same hydrogeologic conditions?

A. Very similar conditions.

Q. Did you review the hydraulic conductivity measurements from the two sites?

A. I looked at the values, yes, and some distributions depending on the layer, yes.

Q. Did the hydraulic conductivity measurements indicate differences in aquifer for material properties for the two sites?

A. It depends on the layer and the location. Range-wise they appeared very similar.

Q. But there were differences, weren't there?

A. There are always different. Especially we see that in the Tawara Terrace model itself.

Q. Are you aware of any textbook or

literature that supports calibrating two separate models for two different sites with the same parameter values just because they're adjacent to each other?

MR. ANWAR: Object to form.

THE WITNESS: I don't think there is any document that would suggest something like that.

BY MS. BAUGHMAN:

Q. For Hanford, didn't parameter values vary at different parts of the site even when they were contiguous?

A. Of course.

Q. Did you read the rebuttal report of Dr. Konikow?

A. Yes.

Q. If you could turn to page 10 of Dr. Konikow's report, if you look at the large paragraph in the middle, toward the bottom there, it states In Summary. It says, "In summary, the two specific possible errors cited by Dr. Spilotopoulos for both density and the distribution co-efficient largely offset each other and have a minimal or a negligible impact on the final results."

Do you see that?

A. Yes.
Q. Do you disagree with Dr. Konikow?
A. Yes.
Q. On what basis?
A. Because even though those two numbers offset each other in the calculation of the retardation factor, there were both used with their erroneous values in the uncertainty analysis and distributions of values for each one of those that were considered in that analysis.
So the errors in those values actually had an impact on the calculation of the uncertainty range.
Q. You reviewed the uncertainty analysis to check that?
A. Yes.
Q. Are you saying that for Tawara Terrace and Hadnot Point?
A. This is for Tawara Terrace. That statement here is for Tawara Terrace.
Q. All right. Dr. Konikow also says that the retardation factor of 2.9, if you look toward the middle of that page, he says, it is very consistent with values in other fields -- field studies reported in the literature, e.g. Rogers

1992 and Krepp 2019 for aquifers. And this is regarding aquifers having similar geologic features.

Do you disagree with Dr. Konikow's observation that 2.9 is a retardation factor that's similar to aquifers having similar geologic features?

A. I don't know that that statement -- what exactly that means. Yes, it is possible. It's also inconsistent with the value used right next door, and especially the value here is based on no site-specific data, but just model calibrations. So there's a lot of discussion to be made about this.

MS. BAUGHMAN: I'll object as nonresponsive.

BY MS. BAUGHMAN:

Q. Did you look up any literature regarding retardation factors?

A. I have been looked --

Q. I'm sorry. Let me ask it differently.

Did you look up literature regarding retardation for aquifers having similar geologic features?

A. I believe that the ones Dr. Konikow even

mentions here are good. But again, the calculation of retardation factors is something that comes from site-specific data and model calibration.

MS. BAUGHMAN: Object as nonresponsive everything after "good."

BY MS. BAUGHMAN:

Q. Do you agree that the retardation factors is and should be a transport parameter that is tested and adjusted during calibration of the model?

A. Of course.

Q. And the retardation factors, the parameters that the transport model -- strike that.

Do you agree that retardation factor is the parameter in the transport model that is used in the governing equation?

A. I'm sorry. Can you repeat that question? I missed something there.

Q. Do you agree that the retardation factor is the parameter in the transport model used in the governing equation?

A. It is a parameter used in governing equation, that's right.

Q. Do you agree that the same value of retardation factor can be attained with different values of Kd and bulk density that are varied in a balanced way?

A. Yes, provided that the values are consistent with site-specific data conditions.

MS. BAUGHMAN: Object to nonresponsive, everything after "yes."

BY MS. BAUGHMAN:

Q. Do you agree that an error in bulk density value can and will be compensated by a balancing error in the value of Kd and can still yield the best fit to the data?

A. What do you mean best fit? I missed that.

Q. I'll withdraw that one.

Do you agree with EPA and numerous other authors that the fraction of organic carbon should not be used to estimate Kd if the organic carbon content is less than .001?

A. I believe Dr. Hannet would be most appropriate to answer that question. But in general, I would agree that there is consideration that, yes.

Q. 43 percent of the Camp LeJeune samples

tested for FOC, fraction of organic carbon, had values less than .001; right?

A. I didn't do the math on the list, but that's probably right.

Q. In your report at page 38 you opine regarding what the model would have done if a retardation factor 6.44 had been used.

What is the site-specific data basis to choose a retardation factor of 6.44?

A. I'm not sure why this was misunderstood in the rebuttals that I saw. What I said in my statement there was that using the starting values that ATSDR indicated that they selected for the model calibration, the resulting retardation factor would be 6. something based on the values that ATSDR indicate in their report that they used to start the calibration.

That's what I said. And the model results based on that would be very different than those that they ended up with during calibration.

Q. Are you saying that there is site-specific data that supports the use of 6.44 as a retardation factor at Camp LeJeune?

A. I'm not opining on that. I just said this is what ATSDR used. I have not done the

calculation to see how we can come up with a value like that based on the site-specific data.

I have not performed the calculation to answer that question for you.

Q. So you can't identify any site-specific data that would justify using a retardation factor of 6.44, can you?

MR. ANWAR: Object to form.

THE WITNESS: No. I think it's possible that using a starting value of the Kd based on the range that we see and a value of the bulk density and the porosity, it is possible to calculate a number like that from site-specific data at Tawara Terrace.

MS. BAUGHMAN: I'm going to object as nonresponsive.

BY MS. BAUGHMAN:

Q. Did you use site-specific data to calculate a retardation factor of 6.44?

A. I said that what I used was the starting values. I indicated in my report that when ATSDR started their model calibration, the starting values they used for the parameter of Kd, bulk density and porosity based on their reported values, would end up with a retardation factor of

6. something.

Q. Were those three numbers based on site-specific data?

A. You mean that ATSDR considered?

Q. Starting values that you used for your calculation, were those based on site-specific data?

A. I'm not sure how to answer your question better. I said these are the values that ATSDR used.

MS. BAUGHMAN: I'm going to object as nonresponsive and note for the record that you're refusing to answer the question. I'm going to move on because I don't have time for you to not answer my question so many times.

MR. ANWAR: We disagree with that. But let's move on.

BY MS. BAUGHMAN:

Q. If you turn to your report at page 52.

MR. ANWAR: What is time?

THE VIDEOGRAPHER: We will be at 6:30 in four minutes.

BY MS. BAUGHMAN:

Q. So I want to talk about your criticism the Tawara Terrace uncertainty analysis. And if

you look at the bottom of page 52, the paragraph that begins bottom of page 52, you wrote, "ATSDR selected a range of acceptable values for key parameters, such as Kd, for their uncertainty analysis based solely on professional judgment and literature sources."

Do you see that?

A. Yes.

Q. Selecting that range of acceptable values based on professional judgment and literature sources, is that a correct methodology?

MR. ANWAR: Object to form.

THE WITNESS: This is taken out of context. If I say yes, it's fine. Yes, as a starting point, that's fine, but there's a lot of caveats to that.

BY MS. BAUGHMAN:

Q. What was the range of values for Kd used by ATSDR for the Tawara Terrace uncertainty analysis, do you know?

A. Do you want me to recall the exact numbers that they used?

Q. I don't know if it's in your report. I didn't see it. You're very critical of the range they used. Can you tell me what the range was?

A. I'm saying that -- well, one second. Let me answer that properly.

They used a range of values based on professional judgment. They did not look at site-specific data and see how they should vary that value. Had they considered such site-specific data, they would have used a larger range. But even the range that they said that they considered was not fully explored because they applied the statistics on how to calculate a distribution around that value that narrowed that range even more.

Q. Have you cited any support in the literature for your criticism of the range of much values used for the uncertainty analysis for Tawara Terrace?

MR. ANWAR: Object to form.

THE WITNESS: I don't understand how I should cite something for that, why I should cite something for that.

BY MS. BAUGHMAN:

Q. Well, you have a very specific criticism of how an uncertainty analysis was done for Tawara Terrace based on the range of values that they used.

Is there any discussion of that in any textbook or peer-reviewed study or ASTM method that you can point to that supports your opinion on how they should have selected the range of values?

MR. ANWAR: Object to form.

THE WITNESS: The point that I'm making is that they did not consider any site-specific data. So their starting point is off. And that they considered a tight range around it that doesn't even consider higher values based on a range they indicated as reasonable for that value.

That's all I'm suggesting. They provided the range of reasonable values, and they did not explore even that range. They explored a subset of that range.

MS. BAUGHMAN: Objection. Nonresponsive.

BY MS. BAUGHMAN:

Q. Can you cite any discussion in the literature, textbooks, standards that supports your criticism of how ATSDR did its uncertainty analysis for Tawara Terrace?

MR. ANWAR: Object to form.

THE WITNESS: I have cited references

with respect to how the uncertainty analysis is supposed to be conducted, but it includes various aspects of it. I'm not sure you want me to --

BY MS. BAUGHMAN:

Q. I want to know about this range issue. Where is the citation for your criticism about them not using the correct range of parameter values? Where is that discussed in the literature or the textbooks?

MR. ANWAR: Object to form.

THE WITNESS: I did not say that it was an incorrect range. I said that they indicated a reasonable range of values, and they only selected a part of it. And given the value that they started with, that was a very narrow range. They didn't explore even the range that they consider as reasonable for these soils.

BY MS. BAUGHMAN:

Q. Did you cite any peer-reviewed literature in support of that criticism?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Or a textbook or any kind of standard in your field?

MR. ANWAR: Object to form.

THE WITNESS: I can't think of something that would support that because there would be a literature source to answer your question.

BY MS. BAUGHMAN:

Q. I'm trying to understand the basis for your opinions. You're not citing any literature or a textbook or standard for the basis of your criticism regarding how ATSDR did its uncertainty analysis; right?

A. I think I explained very clearly what my objections are with respect to how ATSDR selected the range of values in their uncertainty analysis.

Q. Uncertainty analysis done for Tarawa Terrace by ATSDR was done using Monte Carlo simulations; right?

A. That is correct.

Q. And they used a probability density function for the range of the parameter values; right?

A. Correct.

Q. That is a recognized methodology in your field to do an uncertainty analysis; correct?

A. I cannot answer your question with a "yes" or "no." There are caveats to it. I have to provide context.

Q. You would agree that using the probability density function for a Monte Carlo simulation is a methodology that is accepted in your field?

MR. ANWAR: Object to form.

THE WITNESS: That's only an element of how we perform uncertainty analysis. There are other considerations that are very important in applying that.

BY MS. BAUGHMAN:

Q. And those other considerations that you're relying on, you haven't cited any textbook or standard or literature for those other considerations that are so important to you; right?

MR. ANWAR: Object to form.

THE WITNESS: I stated actually reasoning for that that had to do with how the model calibration is done, how the calibrated model in this case is used as the truth in the absence of data to test its accuracy. Therefore, I have provided both reasoning and references with respect to that.

BY MS. BAUGHMAN:

Q. References in the literature or

textbooks or standards, publications? Where is that reference?

A. I provided references for how the uncertainty analysis is done, how it's supposed to be done, and what are the deficiencies here with respect to performing the uncertainty analysis.

Q. So if you turn to page 87 of your report.

A. Just one second. Yes.

Q. At the bottom paragraph on page 87, you wrote, "To understand the importance of this assumption, recall that for the Tawara Terrace uncertainty analysis, ATSDR defined reasonable ranges for the calibrated parameter values." Right?

A. Well, I'm making a distinction between how the uncertainty analysis was done here versus how it was done in Tawara Terrace. But the term reasonable ranges here indicates that there was a process for selecting these ranges in Tawara Terrace, unlike Hadnot Point. I'm not qualifying them as correct.

Q. So your opinion here is the ATSDR parameter values for the uncertainty analysis were reasonable; right? They had a reasonable range?

MR. ANWAR: Object to form.

THE WITNESS: I'm just explaining the context of my response here.

BY MS. BAUGHMAN:

Q. So now you're saying they're not reasonable ranges?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. Are you taking this back?

A. I'm saying that the reasonable ranges that were developed by ATSDR for Tawara Terrace were based on mean values coming out of a calibrated model that I don't believe was even accurately calibrated. So there's a convoluted process here.

I'm not sure I have that I have all the words in there to describe that. But I'm explaining to you exactly what I mean.

Q. You wrote, "ATSDR defined reasonable ranges for the calibrated parameter values with respect to the Tawara Terrace uncertainty analysis."

That's what you wrote here; right?

A. And I'm explaining the context of that to the extent that this is not transparent as to

what the means.

Q. Do you agree that for the Tawara Terrace uncertainty analysis, ATSDR defined reasonable ranges for the calibrates parameter values?

MR. ANWAR: Object to form.

THE WITNESS: Again, I'm saying that the reasonableness with respect to how that distribution was defined mathematically, but I don't think that the actual ranges were correct. I'm just saying there was a method for developing that unlike how it was done in Hadnot Point.

BY MS. BAUGHMAN:

Q. For Tawara Terrace, you criticized ATSDR's uncertainty analysis because it did not evaluate a wider range of the parameter values; right?

A. I made the point that the values that they selected through their model calibrations were not necessarily correct. They were low in the case of Kd. And even though they indicated reasonable ranges, they explored only a tiny portion of them just because they had no data to calibrate the model properly and define a mean value that would make sense.

MS. BAUGHMAN: Objection.

Nonresponsive.

BY MS. BAUGHMAN:

Q. Turn to page 55 of your report. In the second paragraph, you wrote, "ATSDR's uncertainty analysis did not evaluate a wider range of possible retardation factor."

Did I read that right?

A. Yes.

Q. So you're criticizing ATSDR on the one hand for not evaluating a wider range of factors; right? That's what you did here; correct?

A. I'm saying that it was not wider with respect to the values that they considered at Tawara Terrace.

Q. Then for Hadnot Point, you criticize ATSDR because they used too wide of a range of parameter values; right?

MR. ANWAR: Object to form.

BY MS. BAUGHMAN:

Q. It was extreme what you said; right?

A. It was unreasonable.

Q. Are your criticisms of ATSDR's uncertainty analysis based on your professional judgment?

A. Are you talking about the Tawara Terrace

model or the Hadnot Point model?

Q. Both.

A. There are different reasons why I have opinions against how it was done, but --

Q. Are you relying on your professional judgment?

A. And I'm referencing literature sources where a discussion is made about how the --

Q. Show me where the literature in your -- specifically where you're criticizing the uncertainty analysis in your report, what's the literature source for that?

A. I'm sorry. Which part of the criticism that I provided?

Q. Where you're criticizing uncertainty analysis, what's your literature source for that?

A. I believe -- let me just go and check. One aspect is, for example, the value of that prediction should --

Q. What -- I'm sorry?

A. Page 92.

Q. Tell me -- what I want is the citation to a textbook or a standard in your field or a published document. Is that what you're telling me cited to?

A. Yes, 294, yes.
Q. What page?
A. 92.
Q. So Doherty --
A. That's one that I can --
Q. Is this about the uncertainty analysis?
A. Yes.
Q. The page 52. Anything else?
A. And 35, that's Section 315.
Q. What page?
A. Page 8.
Q. What source are you relying on here?
A. Hill and Tiedeman talking about precision accuracy of the model outputs when we're looking at the uncertainty analysis.
Q. What about the sections of your report where you discuss your criticisms of the uncertainty analysis, did you cite any literature or textbook there in support of your analysis or your opinions?
A. I'm not sure I had to.
Q. Did you? Yes or no.
A. I don't think I did specific for some --
Q. Let's move on because I don't have much time left.

I want to talk to post-audits. Have you done post-audits yourself before?

A. I'm assuming you mean looking using the existing model to see how it fit data in the future. Is that what you're referring or what is the context?

Q. Just like it was done here by Norm Davis and -- Norm Jones and Jeff Davis. That kind of post audit, have you done those before?

A. I have done these.

Q. Have you done any post-audit for Camp LeJeune?

A. No.

Q. On page 10 of your report, you had a statement about post-audits and you say right at the top of the page there, right above 3.1.7, you say, "Post-audits may lead to updates in model calibration using these new data to improve model performance."

But that's not always the case, is it?

A. I'm sorry. Can you repeat the sentence you're talking about?

Q. You wrote, "Post-audits may lead to updates in model calibration using these new data to improve model performance" on page 10.

A. Yes.

Q. Do post-audits always lead to updates in model calibration?

A. Not necessarily. It depends on data available.

Q. You reviewed the post-audit Davis and Jones; right?

A. Right.

Q. Were they missing pumping data that should have been used in the post-audit? Are you aware of any pumping data they were missing?

A. I'm not aware of any dataset like that. I just saw what they had in their report. I considered --

Q. The DOJ lawyers asked a lot of questions of these experts about data that may have been missing. So I'm asking: Are you aware of any pumping data that was missing?

MR. ANWAR: Object to form.

THE WITNESS: I don't know.

BY MS. BAUGHMAN:

Q. I want to ask you about mean error. In your report at page 60, you talk about mean error. Actually you calculated mean error separately for points where the observed data is higher and

separately for points where the simulated value is higher; right?

A. Yes. That's page 61, yes.

(Spiliotopoulos Exhibit 16 was marked.)

BY MS. BAUGHMAN:

Q. Turn to Konikow's rebuttal report, Exhibit 16. On page 17, he discusses your method of calculating mean error. And right above his opinion -- this is an opinion to it -- right above opinion 13, he said, "This is not a common or standard way to complete mean error. Based on my experience and expertise, the standard methodology is to compute the mean error for all data."

Do you agree with Dr. Konikow?

A. I think there are different ways of looking at the error in terms of how you try to interrogate the model calculations.

Q. You didn't cite any textbook or publication or standard in supportive your methodology of computing mean error in your report; right?

MR. ANWAR: Object to form.

THE WITNESS: My experience and expertise.

BY MS. BAUGHMAN:

Q. Did you cite any literature, any standard, anything in support of your method?

A. No. Neither did Dr. Konikow.

Q. Also on page 60 of your report, in paragraph 2, you stated in paragraph 2 on page 60, "Observed concentrations of zero correspond to nondetections."

Do you see that?

A. Yes.

Q. Wouldn't you agree that nondetect values do not necessarily have a value of zero? Their value can be anywhere below the detection level; right?

A. I have to go back to their report because I believe that they show zeros as nondetections in their expert report. That's my recollection. I'm just using the data in their table to show them in this graph.

Q. Let me ask you this: You agree that assuming that a nondetect can be substituted by a value of .1 micrograms per liter is arbitrary; right?

MR. ANWAR: Object to form.

THE WITNESS: It's a way of putting the

data in the plot instead of completely excluding them because they're nondetects.

BY MS. BAUGHMAN:

Q. You could also put the issue in the plot by using half the value of the detection limit; right?

A. Theoretically, yes. There are different ways of showing them.

Q. Are you aware of any literature indicating that what you did is an acceptable or standard practice of assuming a nondetect is .1 as opposed to half of the detection limit?

MR. ANWAR: Object to form.

THE WITNESS: I'm not sure I can answer your question like that. All I did here was to use the data and put them in the plot because they were not shown before. So whether it's half the detection limit, .1 or something, in the report of Jones and Davis, those data were not plotted anywhere.

BY MS. BAUGHMAN:

Q. If a detection limit is 10 micrograms per liter, you agree with me it's possible the actual value could be five or nine or one micrograms per liter rather than zero; right?

A. I don't know. It depends on the data. You have look at them very carefully. There are ways of evaluating that.

Q. Just to go back an issue we talked about earlier regarding retardation factor and bulk density and distribution co-efficient, that subject, would you agree that only the retardation factor is used in the contaminant fate and transport equation?

A. The way it's formulated in MT3D, that is correct.

MS. BAUGHMAN: I'll pass the witness.

MR. ANWAR: Sure.

EXAMINATION

BY MR. ANWAR:

Q. Good evening, Dr. Spilotopoulos. I know it's been a long day. Thanks for your time. I just had a few questions I wanted to follow up on. Bear with me. I'm going to try to make this as quick as possible.

During the course of Ms. Baughman's examination, you were asked a number of questions about what data ATSDR did and didn't consider.

Do you recall that questioning?

A. Yes.

Q. How much sampling data did ATSDR have to consider in their models?

MS. BAUGHMAN: Objection to the form.

THE WITNESS: The large number of data listed in those tables, essentially only a handful were used because those were groundwater samples to be used for model calibrations.

BY MS. BAUGHMAN:

Q. What was the timeframe for that handful of concentration level sampling data?

A. With respect to water supply wells for Tawara Terrace, I think they were somewhere between end of December '84, beginning of '85, maybe a couple months into '85 after the wells were turned off and a set of measurements in 1991 I believe for Hadnot Point, there were the measurements again around like the end of '84, beginning of '85 at the extraction wells, a few values after that.

And then there was also a dataset from the remediation phase I believe at two wells downgradient of well HB-651 in the landfill, so in an area outside the industrial area, for example, where the focus of the calculations was or even near well 651.

Q. When I say sampling data, I'm referring to contaminant concentration level data.

Do you understand that?

A. Yes. That's what I'm referring to. When I'm answering your question, I'm talking about the sampling data, concentration data that were used in the model calibrations process.

Q. Why is sampling data or concentration level data important for evaluating the accuracy of a groundwater model for a fate and transport model?

A. In the absence of data, there's no way of testing the accuracy of the model. And then depending on the number of datapoints you have and how spread out they are, within period of interest, you can build confidence into the model accuracy because important things like arrival of contaminants or the variability of concentrations in the aquifer over time can be somewhat tested rather than assumed based on general assumptions for parameters or operation of the system.

Q. Throughout your report, you were asked about it today, you referenced the limited data or the lack of data.

Do you recall that?

A. Yes. I mentioned the lack of site-specific data and the lack of sampling data for model calibrations.

Q. You anticipated my question. Much of the discussion was focused on certain site-specific data that was and wasn't considered.

But when you're referring to the lack of data in your report, are you also referring to sampling data?

MS. BAUGHMAN: Objection. Leading. Object to form.

THE WITNESS: I'm considering both, the data that go into constructing the model, site-specific data, operational data, and then I'm also look at the sampling data that were used for model calibrations if we're talking about the fate and transport model.

BY MR. ANWAR:

Q. Now, you were asked a number of questions today about references that you considered. Do you recall that discussion?

A. Yes.

Q. Could you turn to page 94 of your report, Exhibit 4?

A. Yes.

Q. What is starting on page 94 -- strike that.

Is page 94 entitled References?

A. Yes.

Q. Is this the list of references you considered in forming your expert opinions in your report?

A. You mean the list from page 94 onward and through 100?

Q. Yes.

A. Yes.

Q. I wanted to direct your attention to a couple of references. If you go to page 98, at the bottom of page 98, there is a reference by Doherty.

Do you see that there?

A. Yes.

Q. Is this a reference you considered in offering opinions about the uncertainty analysis performed in ATSDR's model?

MS. BAUGHMAN: Objection. Leading. Objection to the form.

THE WITNESS: It is a reference that I used in my report, and I considered many points in that reference.

BY MR. ANWAR:

Q. If you turn to page 100, there's another reference in the middle of the page, Sepúlveda and Doherty. Do you see that?

A. That's another -- yes. That's another reference on the uncertainty analysis, yes.

Q. Did you consider that in forming your expert witness in this case?

MS. BAUGHMAN: Objection. Leading. Objection to the form.

THE WITNESS: It is referenced in my report. I don't know if it was -- probably more than one point, yes.

BY MR. ANWAR:

Q. Could you turn pack to page 98. You were asked some questions earlier in the deposition about the Woburn study. Do you recall that?

A. Yes.

Q. If you turn to or if you look near the bottom of the page with the author -- by the authority starting Costas, do you see that?

A. Yes.

Q. Is that a reference you considered in regard to the Woburn study?

MS. BAUGHMAN: Objection. Leading. Object to the form.

THE WITNESS: Yes, in fact. Yes, yes, yes.

BY MR. ANWAR:

Q. And then if you turn to page 99, near the bottom of the page, there is a reference starting with the author name, last name Lagakos. Do you see that?

A. Yes.

Q. Did you consider that reference as well?

A. I looked at it as well.

MS. BAUGHMAN: Objection. Leading.

BY MR. ANWAR:

Q. Does this reference relate to the Woburn study that you were discussing earlier in your deposition?

A. Yes.

Q. Now, earlier in your deposition, you were asked a number of questions about what organizations you do and you don't belong to. Do you recall that?

A. Yes.

Q. Your professional organizations. Do you recall that?

A. Yes.

Q. Now, looking at your CV, Exhibit 1.

A. Okay.

Q. And you discussed this with Ms. Baughman during her examination. But to the right-hand side, you have Example Areas of Expertise; is that right?

A. Correct.

Q. And the example areas of expertise there are groundwater remedy design and evaluation, water resource evaluation and management, environmental data analysis, and groundwater modeling.

Do you consider yourself an expert in all of these fields or areas?

A. Yes.

Q. What is that expertise based on?

A. My education, training, more than 20 years of professional experience in the field working on a variety of projects with extremely qualified colleagues as part of the firm that I work for, in collaboration with other experts in the field as part of the different project work where collaboration was involved.

Q. Tell me a little bit about your

education. Do you have a Ph.D.?

A. Yes. I have a Ph.D. in the optimization of groundwater management systems. That involves both the evaluation of environmental data and groundwater modeling and numerical method and approaches for designing groundwater remediation systems or other types of groundwater management systems in an optimal way. So that involves advanced mathematics and coding.

Q. Do you know, does Mr. Maslia have a Ph.D.?

A. I don't think so, but I'm not sure. I don't think so.

Q. Now, you mentioned your 20 years of experience working in the field. Can you describe that to me a bit more?

MS. BAUGHMAN: Objection. Form.

THE WITNESS: I have worked in a wide variety of projects involved in groundwater remediation for different contaminants of concern, a wide variety of radio nucleides to volatiles, metals. I have worked in different projects, many of them very high profile. I would consider Hanford one of the most high profile ones. I provided work there for over 15 years.

I was the technical lead for all the system performance evaluations, delineation of contaminant plumes, evaluation of environmental data there, including statistics and other methods to determine or evaluate the progress of remediation or design of monitoring systems, designing of various tests, collaborated with Pacific Northwest National Lab and a lot of that work there.

I have done work in the litigation field with respect to interstate dispute resolution, usually involving groundwater management issues, the use of groundwater for irrigation and other similar topics for generally disputes between states. And I have supported expert work conducted by other experts, well recognized experts in our field working for S.S. Papadopulos & Associates various labels.

I've also been involved in a very high profile yet confidential -- unfortunately for me because it hasn't been published -- on a very challenging work in modeling groundwater flow in fractured rock.

These are the things that come off my head, including other work that was done before I

came back to the United States from Greece.

BY MR. ANWAR:

Q. During the course of your 20 years working -- 20 plus years working in the field, have you built and evaluated groundwater models?

A. Routinely.

Q. Does that include building or evaluating groundwater flow models?

A. Yes. Just to make sure, both building and evaluating because as part of the work that S.S. Papadopulos does is we come in the picture when difficult technical problems come up. And our services are requested to provide expertise and in forming opinions or helping out with a solution.

Q. During the course of your 20 plus years in the field, have you built and/or evaluated fate and transport models?

A. Also routinely, yes.

Q. What about water distribution models?

A. I've worked on water distribution models as part of my work as a civil engineer when I was in Greece for a period of three years. I have formal education on that subject as well. And at the time I worked on updating the water main

distribution network of the City of Athens, so a pretty large one.

Q. Are your opinions in your expert report and that you're offering in this case based on your education and over 20 years of experience working in the field?

MS. BAUGHMAN: Objection. Leading. Object to the form.

THE WITNESS: The opinions that I provided were based on my experience and expertise from over 20 years working on projects or problems like that.

BY MR. ANWAR:

Q. And as part of your education and working in the field over the course of 20 years, have you referred to or reviewed literature sources during the course of your work?

MS. BAUGHMAN: Objection. Form.

THE WITNESS: Can you clarify the question? You mean --

BY MR. ANWAR:

Q. Have you kept abreast of the developments in groundwater modeling during the course of your 20 years working in the field?

MS. BAUGHMAN: Objection. Form. And

object to leading.

THE WITNESS: As part of my work at SSPA, I have participated in conferences to stay abreast with developments in our field. I have collaborated with experts in developing codes and computational tools.

I have participated in the development of these tools in relation to MODFLOW, for example, myself on different occasions. And I've also been lucky to be working with other experts that have -- perform similar work and provided similar contribution. So this is where both mentoring in my early years, but also continuing learning experience at my company has occurred over these years.

BY MR. ANWAR:

Q. Thank you. Those are all the questions I have.

MS. BAUGHMAN: We're finished.

THE VIDEOGRAPHER: Off the record at 1836.

(Whereupon, at 6:36 p.m., the taking of the instant deposition ceased.)

COMMONWEALTH OF PENNSYLVANIA )
COUNTY OF ALLEGHENY ) SS:

C E R T I F I C A T E

I, Ann Medis, RPR, CLR, CSR-WA and Notary Public within and for the Commonwealth of Pennsylvania, do hereby certify:

That ALEXANDROS SPILIOTOPOULOS, PH.D, the witness whose deposition is hereinbefore set forth, was duly sworn by me and that such deposition is a true record of the testimony given by such witness.

I further certify the inspection, reading and signing of said deposition were not waived by counsel for the respective parties and by the witness.

I further certify that I am not related to any of the parties to this action by blood or marriage and that I am in no way interested in the outcome of this matter.

IN WITNESS WHEREOF, I have hereunto set my hand this 19th day of March, 2025.

_____
Notary Public

COMMONWEALTH OF PENNSYLVANIA ) E R R A T A
COUNTY OF ALLEGHENY ) S H E E T

I, ALEXANDROS SPILIOTOPOULOS, PH.D, have read the foregoing pages of my deposition given on March 18, 2025, and wish to make the following, if any, amendments, additions, deletions or corrections:

| Page | Line | Change and reason for change: |
|---|---|---|
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |
| ____ | ____ | _____ |

In all other respects, the transcript is true and correct.

_____
ALEXANDROS SPILIOTOPOULOS, PH.D

_____ day of _____, 2025.

_____
Notary Public

GOLKOW, a Veritext Division
One Liberty Place
1650 Market Street, Suite 5150
Philadelphia, Pennsylvania 19103
877.370.3377

March 19, 2025

Haroon Anwar, Esquire
U.S. Department of Justice
1100 L Street NW
Washington, DC 20005

Re: Deposition of ALEXANDROS SPILIOTOPOULOS, PH.D
Notice of Non-Waiver of Signature

Dear Mr. Anwar:

Please have the deponent read his deposition transcript. All corrections are to be noted on the Errata Sheet.

Upon completion of the above, the Deponent must affix his signature on the Errata Sheet, and it is to then be notarized.

Please forward the signed original of the Errata Sheet to Laura J. Baughman, Esquire for attachment to the original transcript, which is in her possession. Send a copy of same to all counsel.

Please return the completed Errata Sheet within 30 days of receipt hereof.

Sincerely,

Ann Medis, RPR, CLR, CSR-WA

cc:

Laura J. Baughman, Esquire

# EXHIBIT 2

# Expert Report of
# Alexandros Spiliotopoulos, PhD

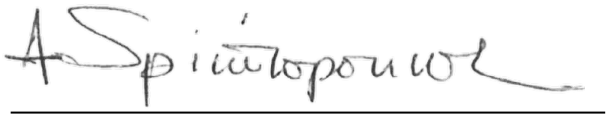
**In the United States District Court for the Eastern District of North Carolina**

**No. 7:23-cv-897**

**In Re: Camp Lejeune Water Litigation**

**This document relates to:**
**ALL PLAINTIFFS**

***Prepared by:***



**Alexandros Spiliotopoulos, PhD**

**S.S. PAPADOPULOS & ASSOCIATES, INC.**
**Environmental & Water-Resource Consultants**

**December 9, 2024**

**1801 Rockville Pike, Suite 220, Rockville, Maryland 20852-1649 • (301) 718-8900**

# Table of Contents

**Page**

## Attachment



## List of Figures

## List of Tables

# List of Acronyms

| | |
|---|---|
| 1,2-tDCE | trans-1,2- Dichloroethylene |
| ATSDR | Agency for Toxic Substances and Disease Registry |
| EPA | U.S. Environmental Protection Agency |
| ft/d | Feet per day |
| HB | Holcomb Boulevard |
| $g/cm^3$ | Grams per cubic centimeter |
| $g/ft^3$ | grams per cubic foot |
| gpm | gallons per minute |
| HP | Hadnot Point |
| HPHB | Hadnot Point and Holcomb Boulevard |
| LHS | Latin Hypercube Sampling |
| mL/g | Milliliters per gram |
| µg/L | micrograms per liter |
| NRC | National Research Council |
| PCE | tetrachloroethylene |
| SSP&A | S.S. Papadopulos & Associates, Inc. |
| TCE | trichloroethylene |
| TOC | total organic carbon data |
| TT | Tarawa Terrace |
| USMCB | United State Marine Corps Base |
| UST | underground storage tank |
| VOC | volatile organic compound |
| WTP | water treatment plant |

# REPORT

# Section 1
# Background and Experience

I, Alexandros Spiliotopoulos of S.S. Papadopulos & Associates, Inc. (SSP&A) was retained by the U.S. Department of Justice to write an expert report and provide my expert opinions in the litigation entitled *In Re: Camp Lejeune Water Litigation*, No. 7:23-CV-897, pending in the Eastern District of North Carolina. I am providing this expert report and my opinions to evaluate the allegations in Plaintiffs' Master Complaint, to respond to the expert reports and opinions of Plaintiffs' experts, Morris Maslia, Mustafa Aral, Norman L. Jones, and R. Jeffery Davis, and to evaluate the Agency for Toxic Substances and Disease Registry's (ATSDR's) water modeling related to Camp Lejeune, which is the subject of Plaintiffs' experts reports and opinions. My opinions are based on my review of the available data and information.

I am a Senior Associate and Senior Hydrogeologist at SSP&A. I hold a Ph.D. degree in civil and environmental engineering from the University of Vermont, and a university degree in civil engineering from the University of Patras, Greece. My expertise includes the application of hydrogeology, modeling, optimization, and parameter estimation to evaluate the origin, distribution, fate, and transport of contaminants in the environment. I have more than 20 years of relevant professional experience evaluating the nature and extent of contamination in aquifers, developing groundwater flow and contaminant transport models, and conducting environmental assessments in the context of regulations and guidance or directives from various government agencies. My Curriculum Vitae is provided as Attachment A. The list of documents that I have considered and/or relied upon will be provided separately.

To conduct my evaluation and render my expert opinions, I relied on my education, research, and professional experience. The documents and information that I considered are of the type that can be reasonably relied upon to support my opinions and are regularly relied upon by practitioners in my field. The materials that were reviewed include, but are not limited to, data, reports, published literature, aerial photographs, correspondence with state agencies, interview summaries, and sworn deposition testimony. I visited the United State Marine Corps Base (USMCB) Camp Lejeune once as part of this evaluation. I was assisted by SSP&A staff.

The hourly rate charged by SSP&A for my services is $268. I have not testified as an expert witness at trial or by deposition in the last 4 years.

# Section 2
# Opinions

The opinions presented in this report were reached by applying accepted methodology in the fields of hydrogeology, groundwater modeling, and civil and environmental engineering. The opinions expressed in this report are my own and are based on the data and facts available to me at the time of writing. I hold these opinions to a reasonable degree of scientific certainty. I reserve the right to supplement the discussion and findings presented in this report.

1. ATSDR implemented complex calculation methodologies for reconstructing past conditions at Camp Lejeune "to provide [an] epidemiological study with quantitative estimates of monthly contaminant concentrations in finished drinking water because contaminant concentration data and exposure information are limited."[1,2] Due to the absence of sufficient historically observed data and site-specific parameters, the results of these calculations are highly uncertain and cannot be used for determining dose reconstructions at the level of detail that ATSDR presented in their analyses.
   See Section 4

2. ATSDR's dose reconstruction groundwater model for drinking water in Tarawa Terrace was constructed and calibrated using parameters and assumptions that are incorrect or not representative of site conditions, resulting in conservative and biased-high estimated monthly contaminant concentrations.
   See Section 4.1.1; Section 4.1.2;

3. ATSDR's dose reconstruction groundwater model for drinking water in Tarawa Terrace was constructed and calibrated using different parameters and assumptions than for the Hadnot Point model, even though both models simulated similar hydrogeologic conditions. This resulted in faster plume migration and higher contaminant concentrations in the Tarawa Terrace model.
   See Section 4.1.2.2; Section 4.1.2.3; Section 4.2.3.2

4. Application of parameter values based on site-specific data to the ATSDR's dose reconstruction groundwater model for drinking water in Tarawa Terrace would result in substantially lower estimated monthly contaminant concentrations. Furthermore, the model uncertainty range would also be lower.
   See Section 4.1.2.5

5. ATSDR admitted that its dose reconstruction groundwater model for drinking water in Tarawa Terrace resulted in biased-high estimates of monthly contaminant concentrations at one of the water-supply wells. ATSDR used these estimates for their dose reconstruction, resulting in more conservative and biased-high dose reconstruction for the period this well was in service.
   See Section 4.1.2.6

[1] ATSDR-TT, Chapter A, p. A2

[2] ATSDR-HP, Chapter A, p. A13

6. ATSDR's dose reconstruction groundwater model for drinking water in Tarawa Terrace estimated monthly contaminant concentrations that were conservative and biased-high, not reflecting observed data that indicated absence of contamination in the aquifer.
   See Section 4.1.2.7

7. The presentation of the results of the uncertainty analysis conducted by ATSDR for the Tarawa Terrace model was visually misleading by showing a narrow uncertainty range around the calibrated model. Alternate visual presentation of the results indicates estimated monthly concentrations are clearly biased high in the early years.
   See Section 4.1.3.1

8. ATSDR's uncertainty analysis was not bound by historical concentration data, and as a result, focused only on model precision and not accuracy in predicting COC concentrations. ATSDR's uncertainty analysis was presented as though it evaluated the model's accuracy. It did not. Rather, the uncertainty analysis evaluated model precision for parameter ranges that ATSDR selected. ATSDR's uncertainty range is reflective of the narrow range of model parameter values considered in their analysis.
   See Section 4.1.3.2

9. The uncertainty analysis conducted by ATSDR to evaluate the potential range of dose reconstruction estimated monthly contaminant concentrations for drinking water in Tarawa Terrace and did not encompass uncertainty bounds representative of site-specific conditions, resulting in biased-high uncertainty range;
   See Section 4.1.3.2

10. ATSDR applied two different numerical codes for dose reconstruction groundwater modeling for drinking water in Tarawa Terrace, of which the results are not in agreement, due to inconsistent application of contaminant source terms in the two codes. Neither ATSDR, nor Mr. Maslia or Dr. Aral, provided sufficient scientific justification for selecting the higher estimated monthly contaminant concentrations for their dose reconstruction.
    See Section 4.1.4

11. ATSDR's dose reconstruction groundwater model for the volatile organic compound (VOC) degradation by-products in Tarawa Terrace used parameters and assumptions that are incorrect or not representative of site conditions, resulting in conservative and biased-high estimated monthly contaminant concentrations.
    See Section 4.1.4

12. The results of the Tarawa Terrace Flow and Transport Model Post-Audit conducted by Dr. Jones and Mr. Davis indicate that ATSDR's dose reconstruction groundwater model for drinking water in Tarawa Terrace used parameters and assumptions that resulted in conservative and biased-high estimated monthly contaminant concentrations.
    See Section 4.1.5

13. Prior to offering opinions as experts in this litigation, Mr. Maslia and Dr. Aral should have used the data that Dr. Jones and Mr. Davis used to conduct the Tarawa Terrace Flow and Transport Model Post-Audit to update the calibration of the dose reconstruction groundwater model.
    See Section 4.1.5

14. ATSDR's dose reconstruction groundwater model for drinking water in Hadnot Point was constructed and calibrated using parameters and assumptions that are uncertain or incorrect, resulting in conservative and biased-high estimated monthly contaminant concentrations.
    See Section 4.2.1; Section 4.2.2; Section 4.2.3; Section 4.2.4

15. ATSDR incorrectly interpreted field sampling data. For one of the water-supply wells in Hadnot Point, ATSDR included an erroneous concentration value in its model calibration, resulting in conservative and biased-high simulated concentrations, not representative of aquifer conditions.
    See Section 4.2.3.3

16. ATSDR's dose reconstruction model for the VOC degradation by-products was constructed based on the same limited set of observed data, available after December 1984. ATSDR's historical reconstruction prior to December 1984 cannot be verified.
    See Section 4.2.4

17. ATSDR's sensitivity analysis for the various contaminant sources in Hadnot Point indicated that the timing of source-release start date is uncertain and, therefore, it is impossible to determine the historical period that contamination was present in groundwater.
    See Section 4.2.5.1.1

18. The sensitivity analysis of the dose reconstruction groundwater model conducted for drinking water in Hadnot Point was based on parameter variability unsupported by data. Particular combinations of extreme parameter values resulted in conservative and biased-high estimated monthly contaminant concentrations. The results of the sensitivity analysis were incorrectly presented as an uncertainty analysis range.
    See Section 4.2.5.1.2

19. The analysis conducted to evaluate the potential range of dose reconstruction estimated monthly contaminant concentrations for drinking water in Hadnot Point only partially addressed model uncertainty, and it indicated that calibrated reconstructed concentrations were conservative and biased high.
    See Section 4.2.5.2

# Section 3
# Introduction

This section provides overviews of: important concepts in groundwater modeling; historical operations and groundwater contamination at Camp Lejeune; and studies conducted in Camp Lejeune and related scientific discourse.

## 3.1 Overview of Groundwater Modeling

Models are "*simplified representation[s] of the complex natural world*."[3] Using mathematics and computer software, modelers can simulate and quantitatively assess environmental processes.[4] However, models can never reflect the complexity and uniqueness of the systems they are intended to replicate and are therefore of limited use.[5] It is important to understand the limitations of models.

### 3.1.1 Model Uses

Water models are used in a number of ways. Models can be used to forecast future impacts of an action, like the change in groundwater levels caused by pumping from a well.[6] Modeling may also be used to replicate past conditions. This is sometimes called hindcasting.[7] Anderson et al. (2015) indicate that "*[h]indcasting applications are 'uniquely challenging' because it is not possible to collect additional observations to augment the existing historical dataset, which is often meager*."[8]

### 3.1.2 Model Development

Model development begins with a "conceptual" model. A conceptual model incorporates our understanding of the field setting to construct a description of the groundwater flow system.[9] This is done using collected field data and related information from previous investigations and studies in the area.[10] The conceptual model is, therefore, a qualitative summary of what is known about the processes occurring in the hydrogeological system, such as the boundaries, aquifer properties, groundwater flow, etc.[11]

As described in the expert report of Dr. Remy Hennet, the hydrogeological system encompasses the composition of the geologic materials (e.g. sand grains, clay particles, rock fragments) in the subsurface with the presence of water. This composition of geologic materials is a porous medium.[12]

An aquifer is a saturated porous medium that can transmit water flowing from points of high pressure to points of low pressure.[12] This flow occurs through the interconnected pores of the porous medium, within hydrostratigraphic zones of different geologic material and properties. Aquifers are

[3] Anderson et al. (2015), p.5; NRC (1990), p. 52

[4] Harter et al. (2018), p. 47

[5] Anderson et al. (2015), p. 12

[6] Anderson et al. (2015), p. 9

[7] Anderson et al. (2015), p. 9

[8] Anderson et al. (2015), p. 11 (citing Clement (2011) p. 620)

[9] Anderson et al. (2015), p. 17

[10] Anderson (2015), p. 17

[11] Anderson et al. (2015), p. 35

[12] Freeze and Cherry (1997), p.17

encountered at different depths in the subsurface. The soils between the ground surface and the aquifer are what is called the "unsaturated" zone.[13]

Once the conceptual model is constructed and the purpose of the model is defined, the mathematical model that describes the processes incorporated in the conceptual model is selected.[14] These processes are complex. A mathematical model is a set of "governing" equations that calculates the progression of these complex processes in space and time. Definitions of "boundary" and "initial" conditions are required for the solution of these mathematical models.

Numerical codes are algorithms that carry out the calculations of the mathematical model. Scientific software codes have been developed to perform such computations. For example, MODFLOW, a code created by the U.S. Geological Survey, is used to quantitatively analyze groundwater flow through the porous medium.[15]

A groundwater model is the "translation" of the conceptual model of the groundwater system to a numerical model. This translation requires "*designing the grid/mesh, setting boundaries, assigning values of aquifer parameters, and hydrologic stresses, and, for transient models, setting initial conditions*."[16]

Construction of the numerical model involves creating the three-dimensional "grid" which serves as the framework of the numerical model.[17] This "grid" (or, sometimes, mesh) consists of cells (most commonly cube-shaped) intended to represent the porous medium in a piece-wise manner.[18] The center-point of the cell is known as the "node." Figure 1 illustrates an example of a MODFLOW grid, showing aquifer hydrostratigraphy (i.e. model layers).

[13] Freeze and Cherry (1979), p.15

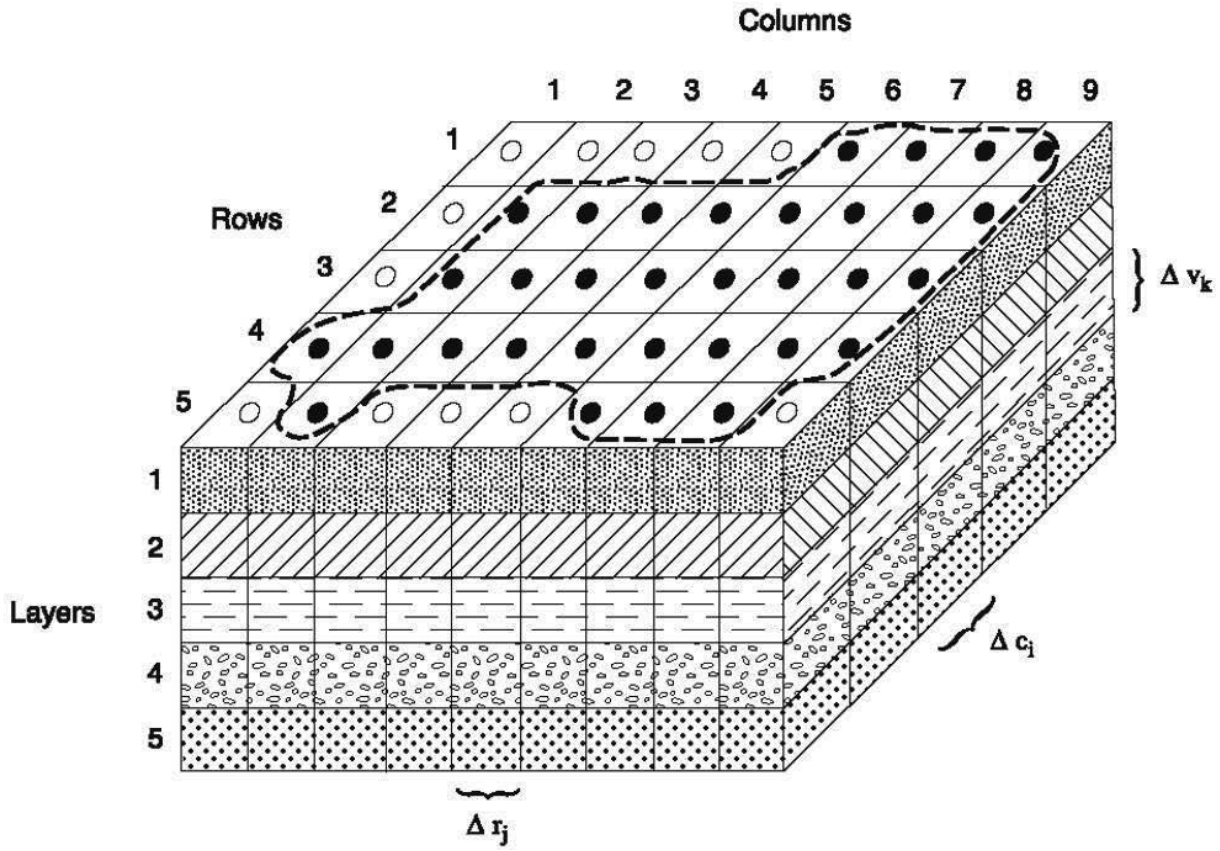
[14] Anderson et al. (2015), p. 17

[15] Anderson et al. (2015), p. 9

[16] Anderson et al. (2015), p. 17

[17] Anderson et al. (2015), p. 17

[18] Anderson et al. (2015), p. 71




*Source: https://perma.cc/Z3FR-XZDA; https://www.usgs.gov/media/images/modflow-2005-hypothetical-aquifer-system*

**Figure 1: Example of a MODFLOW Grid**

Parameters are defined in numerical models with their values assigned in each model cell. Parameters are "*constant term[s] in an equation that reflect[] a relationship*."[19] For example, in the equation $y = 5x$, five is a coefficient which can be divided out to solve for the variable $x$. The coefficient, *5*, has a constant value that reflects the relationship between $x$ and $y$. Parameters are used to reflect relationships and conditions in the natural world, such as the rate at which water can move through certain types of soils. For example, in sands and gravels water movement is much faster than in rocks or clays. In groundwater modeling, the "hydraulic conductivity" is a constant of proportionality, describing the relationship between the rate of groundwater flow and the pressure differential that causes it.[20]

In addition to assigning each cell or node its own parameter values,[21] the modeler also sets boundaries and various other conditions.[22] This allows modelers to re-create features of the natural environment, such as confining layers in the sub-surface, or stresses to the system, such as the operation of pumping wells.

[19] National Judicial Conference (2010), p. 40

[20] Freeze and Cherry (1979), p. 16

[21] Anderson et al. (2015), p. 203

[22] Anderson et al. (2015), p. 17

### 3.1.3 Model Calibration

Following its development, the model is then calibrated. Calibration is a process by which the modeler conducts "history matching," by adjusting model parameters until the model outputs reasonably match measured field observations.[23] Modelers can use a parameter estimation code (such as PEST) to assist in determining calibration targets.[24] The goal of calibration is to adjust the model parameters so that the model results are as close to observed field data as possible.[25] This is important because the calibrated model should be as accurate as possible to be an appropriate tool for estimating the quantities identified by its intended use.[26]

### 3.1.4 Sensitivity Analysis

Sensitivity analysis is the process by which one or more parameters are manipulated, to see how model outputs change in response to parameter changes.[27] If modifying a parameter causes a relatively large change in model results, this indicates to the modeler that he or she needs more data to constrain that parameter.[28]

### 3.1.5 Uncertainty Analysis

Models are inherently uncertain.[29] For a variety of reasons, "*a groundwater model cannot give a single true answer*."[30] One reason for that is non-uniqueness. This means that different variations of parameters can provide results that are close to field observations.[31] Moreover, there are assumptions required in designing models and approximating the environment that cannot be fully understood.[32] Uncertainty analysis may provide a range of possible outcomes and help assess a model's error margins.[33] Uncertainty analysis is a statistical analysis that provides a range of probabilities, which are used to characterize confidence in the model's outputs.[34]

The calibrated model output (prediction) should conform with the following general rule: "*ideally, the value of that prediction should lie somewhere near the centre of the uncertainty band of the prediction. In this way, the potential for predictive error is minimized*."[35]

Confidence in model outputs is essential when important decisions rely on the outputs of these models. Important aspects of a model, with direct implications for the issues discussed in this report, are its precision and accuracy.[36] Hill and Tiedeman use an analog from archery to describe these terms:

---

[23] Anderson et al. (2015), p. 19, 202; Harter et al. (2018), p. 57; ASTM D5981/D5981M-18 (2018); Reilly and Harbaugh (2004), p. 23

[24] Anderson et al. (2015), p. 18.

[25] Anderson et al. (2015), p. 18

[26] Reilly and Harbaugh (2004), p. 4

[27] Reilly and Harbaugh (2004), p. 3; ASTM D5611-94 (2016)

[28] Harter et al. (2018), p. 58; ASTM D5611-94 (2016); Reilly and Harbaugh (2004), p. 2

[29] Anderson et al. (2015), p. 12; National Research Council (1990), p. 216

[30] Anderson et al. (2015), p. 12

[31] Anderson et al. (2015), p. 12

[32] National Research Council (1990), p. 221–30

[33] Anderson et al. (2015), p. 18

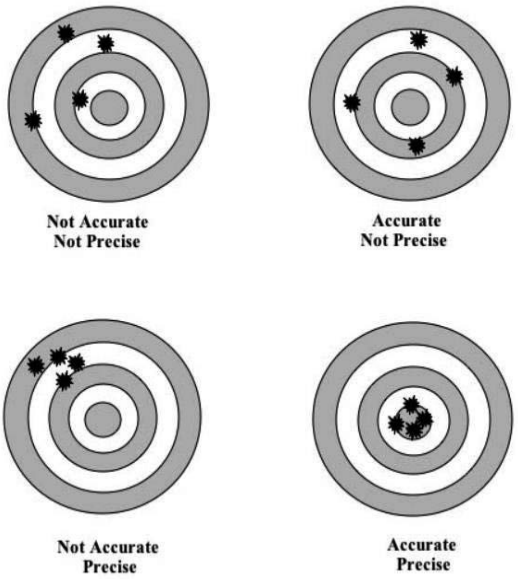
[34] Anderson et al. (2015), p. 457

[35] Doherty (2015), p. 52

[36] Hill and Tiedeman (2007), p.13

- Precision: "*a set of shots is precise if the shots fall within a narrow range, regardless of whether they are near the bull's eye*."[37] The equivalent to this analog, when considering a groundwater model that attempts to reconstruct historical conditions, is its uncertainty analysis. The model can be run many times, and model results fall within a narrow range. However, model results can be far off from the observed data.
- Accuracy: "*a set of shots is accurate if the shots are distributed in a narrow range around the bull's eye*."[38] For the groundwater reconstruction model, this means that its results are close to the observed data.

The National Oceanic and Atmospheric Administration (NOAA) provided a schematic to illustrate the concepts of 'precision' and 'accuracy' as they are understood in natural sciences. This schematic is depicted in Figure 2.




*Source: https://perma.cc/J794-KUYM; https://celebrating200years.noaa.gov/magazine/tct/tct_side1.html*[39]

**Figure 2: Accuracy versus Precision**

Based on the above, a precise model is not necessarily accurate. In order for a model to meet the objectives of its intended use, it must also be accurate. The definition of accuracy refers directly to the "bull's eye," i.e. the real world in the case of a groundwater model. The real world is described by observed data. In the absence of data, the ability to determine whether a model is accurate is diminished. Hence, history matching, i.e. fitting model results to observed data is critical.

### 3.1.6 Model Updates

Developing hydrologic models is an iterative process.[40] Model calibration, sensitivity analysis and uncertainty analysis are related processes that are all necessary for constructing a reliable model. Modelers

[37] Hill and Tiedeman (2007), p.13

[38] Hill and Tiedeman (2007), p.13

[39] On this website, a discussion is provided regarding geological surveying, but the concepts and definitions apply equally to groundwater modeling.

[40] National Research Council (1990), p. 191

should continually make corrections to models and repeat the steps outlined above throughout the development of the model. Moreover, models should be *"routinely updated as new data become available*."[41]

A post-audit is a "*comparison between conditions simulated in a forecast and conditions that actually occurred*."[42] It may occur years after the model was developed, and uses data collected past the original model simulation timeframe.[43] Post-audits may lead to updates in model calibration using these new data, to improve model performance.[44]

### 3.1.7 Simulating Contaminant Transport

Using the process described above, modelers may attempt to forecast or hindcast the movement of contaminants in groundwater. To track the flow of contaminants in an aquifer, modelers may link ("couple") groundwater flow models, such as MODFLOW, with contaminant fate and transport models.[45] MT3DMS is an example of a contaminant fate and transport model that may be coupled with MODFLOW.

Contaminant sources may be included in the model to simulate their historical contribution to contamination in the aquifer. Mass loading is a parameter that describes how much of a contaminant is introduced in the subsurface and enters the aquifer.[46]Mass loading is an important parameter for understanding how much contamination is assumed to be entering the system and migrating in the aquifer.Another important consideration in any groundwater model is the presence of wells. Wells pump water out of the aquifer, decreasing pressure around the well. The decrease in pressure creates a "cone of depression," which forces groundwater towards the well screen. Therefore, contamination reaches the pumping well, transported by groundwater in the aquifer. However, contamination doesn't always move at the same speed as groundwater. It is sometimes "retarded" due to soil and contaminant characteristics.[47]

### 3.1.8 Concluding Remarks

Anderson et. al (2015) emphasized the importance of history matching: "*[h]istory matching is important for evaluating a model's fit for purpose: if a model cannot reproduce the measured heads and fluxes with sufficient accuracy, one can have little confidence that the calibrated model will adequately reproduce unmeasured heads and fluxes.*"[48] Although this discussion referred to the results of a groundwater flow model, it is applicable to any model, including those hindcasting contaminant transport in aquifers. In all cases, a model is required to reasonably fit the measured data to reliably tell us what happens when data are not available. As Doherty (2015) states: "[a] *hypothesis is proposed, and evidence is collected to test it.*"[49] The model is a hypothesis, which is tested against observed data. During calibration, the hypothesis is updated until the model fits the observed data. Model calibration is not possible when there are no historical data to match.

As mentioned earlier, a calibrated model is still uncertain. Furthermore, model calibration is further hindered when there are limited or, worse, no historical data to match. In such cases, the uncertainty of the resulting model is vastly exacerbated. Any uncertainty analysis conducted on such a "calibrated" model

[41] Anderson (2015), p.18

[42] Anderson (2015), p. 481.

[43] Anderson (2015), p.18

[44] Anderson (2015), p. 481–82.

[45] Zheng & Bennet (2002), p. 195

[46] National Research Council (1990), p. 140

[47] Anderson et al. (2015), p. 363

[48] Anderson et al. (2015), p. 376

[49] Doherty (2015), p. 179

can only address its precision, but not its accuracy, as Dr. Dan Waddill, a NAVFAC engineer who reviewed and provided feedback to ATSDR on their modeling, aptly indicated in his deposition.[50]

Doherty and Moore (2021) emphasized the importance of historical data: *"[i]t must not be forgotten, however, that it is information, and information alone, that can reduce predictive uncertainty. It follows that if a complex model structure can express information that emerges from site characterisation studies, then it does indeed have the potential to reduce the uncertainties of at least some decision-critical predictions*."[51] In other words, a complex model that attempts to simulate important processes in the subsurface, will be highly uncertain if it is not tied to measured data, i.e., information about the simulated processes.

## 3.2 Historical Operations and Groundwater Contamination at Camp Lejeune

USMCB Camp Lejeune is a military base located near Jacksonville, in Onslow County, North Carolina. Operations began at USMCB Camp Lejeune during late 1941.[52]

The Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB) water distribution systems are of interest because of historical contamination issues. Two of these three water distribution systems were contaminated with VOCs due to contamination in groundwater. Groundwater extracted from water-supply wells was directed to water treatment plants (WTPs) in these areas. Groundwater within the Tarawa Terrace service area was contaminated mostly with tetrachloroethylene (PCE) and PCE biodegradation by-products.[52] Groundwater within the HP service area was contaminated with trichloroethylene (TCE), and to a lesser degree trans-1,2-DCE (1,-tDCE), PCE, and refined petroleum products, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).[52] The HB WTP service area was intermittently supplied with contaminated water from the HP WTP between 1972 and 1985, during interconnection events between the two systems.

ATSDR constructed numerical models to simulate groundwater flow and contaminant transport in the aquifers under Camp Lejeune, and to reconstruct the historical concentrations of contaminants in finished water produced by the treatment plants and delivered to the water-distribution networks. ATSDR constructed two separate models, one of the Tarawa Terrace (TT) family housing area, and another of the Hadnot Point and Holcomb Boulevard (HPHB) areas. ATSDR did not model groundwater flow and contaminant transport in any other areas on base.

ATSDR constructed a water distribution model for HB, to calculate concentrations in the piping network connecting the WTP with the consumers. This was done to calculate the effects of the intermittent connection of HB with the HP WTP mentioned above. For Tarawa Terrace and Hadnot Point, ATSDR did not simulate transient contaminant transport in their water distribution networks. For those WTPs, ATSDR ran a simple mixing model for calculating the weighted contaminant concentration in the influent to the WTP, considering monthly flow rates for each well and corresponding model-simulated concentrations.[53] For each month, the volume of water pumped in a well and the simulated PCE concentration in that volume

---

[50] Deposition of Dan Waddill, 2024, p. 133:18-134:3 ("*What ATSDR did in this case is uncertainty with respect to model precision. That's how tightly the model runs compared to one another, and they did. They created ranges and all of that. But it's precision, and it has nothing to do with uncertainty with respect to model accuracy, which is how -- how closely does that cluster come to the real world, and that's just unknown because they didn't have data to do that kind of analysis.*").

[51] Doherty and Moore (2021), p. 33

[52] ATSDR-HP, Chapter A, p. A7

[53] ATSDR stated that monthly water-supply well flow rates and corresponding simulated concentrations were provided in Chapter K of the TT Report. A reference to Chapter K was provided in Chapter A, indicated as "In press 2007." However, Chapter K was never published (ATSDR-TT, Chapter A, p. A74 and A80)

of water were calculated, and the weighted PCE concentration reflected the aggregate of these quantities for all wells.

To construct these models, ATSDR had to define contaminant source locations and quantify their contributions of contamination to the aquifers. ABC One-Hour Cleaners, "*an off-base dry-cleaning facility that used PCE in the dry-cleaning process*"[54] was indicated as the source of the contamination found in the Tarawa Terrace water-supply wells. However, the timing and quantification of contaminant releases from that source are uncertain, due to lack of historical data. Figure 3 shows the TT WTP Area, including water-supply well locations and the identified contaminant source.

[54] ATSDR-TT, Chapter A, p. A10

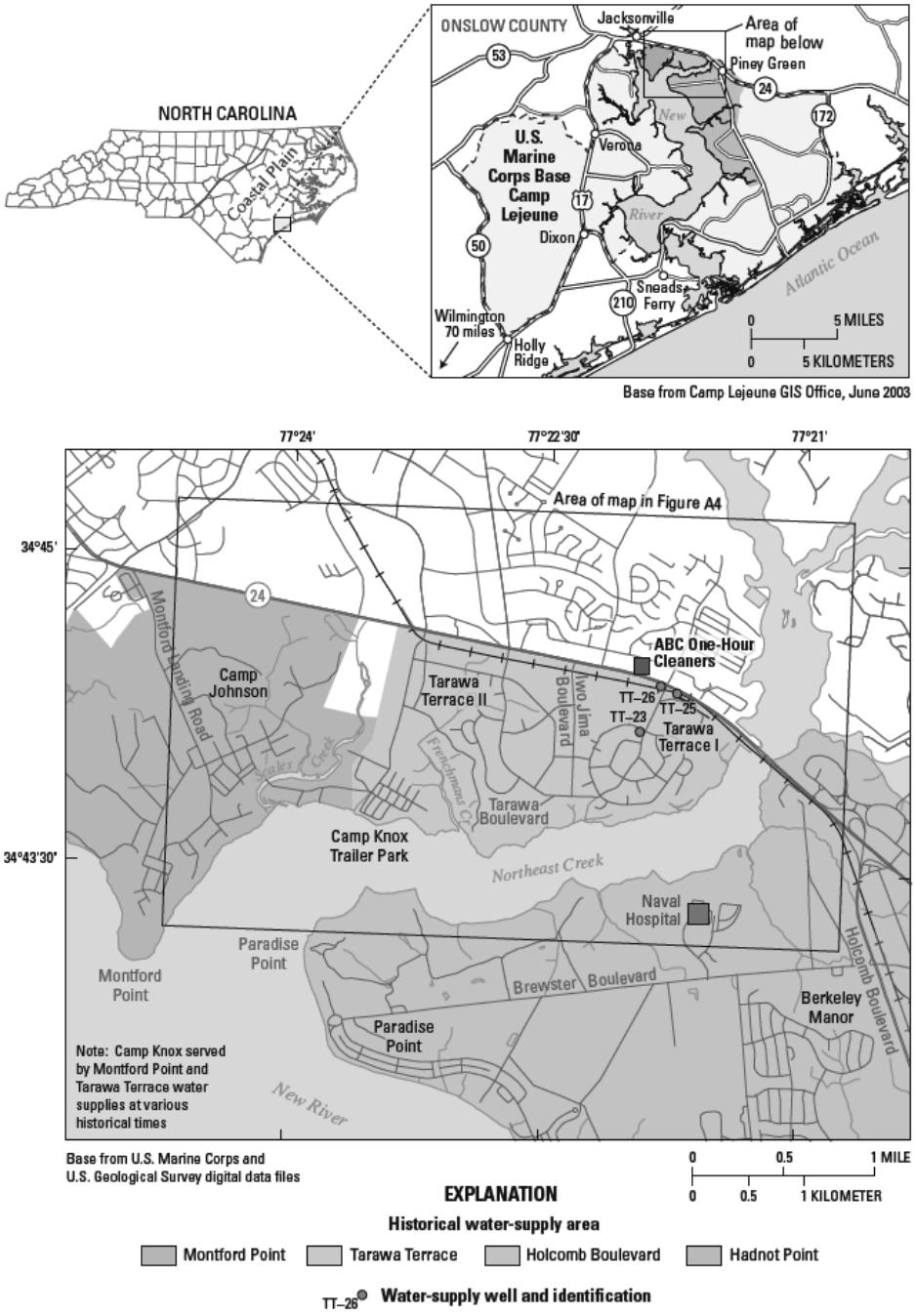



**Figure A1.** Selected base housing and historical water-supply areas, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.



**Figure 3: Map of Tarawa Terrace Area, Camp Lejeune**

Historical base operations and waste-disposal practices have been identified as being responsible for contamination of groundwater and finished-water supplies within the HPHB areas. At Hadnot Point, different sources were defined, based on soil and groundwater sampling data, as well as historical data on infrastructure and operations. Leaking underground storage tanks (USTs), surface spills, and landfill material were some of the contaminant sources identified by ATSDR. Similar to Tarawa Terrace, the timing and quantification of contaminant releases from those sources are uncertain due to a lack of historical data.

Figure 4 shows the HPHB WTP Area, including water-supply well locations and locations of storage tanks. It should be noted that not all of the storage-tank locations were identified as potential sources of contamination.

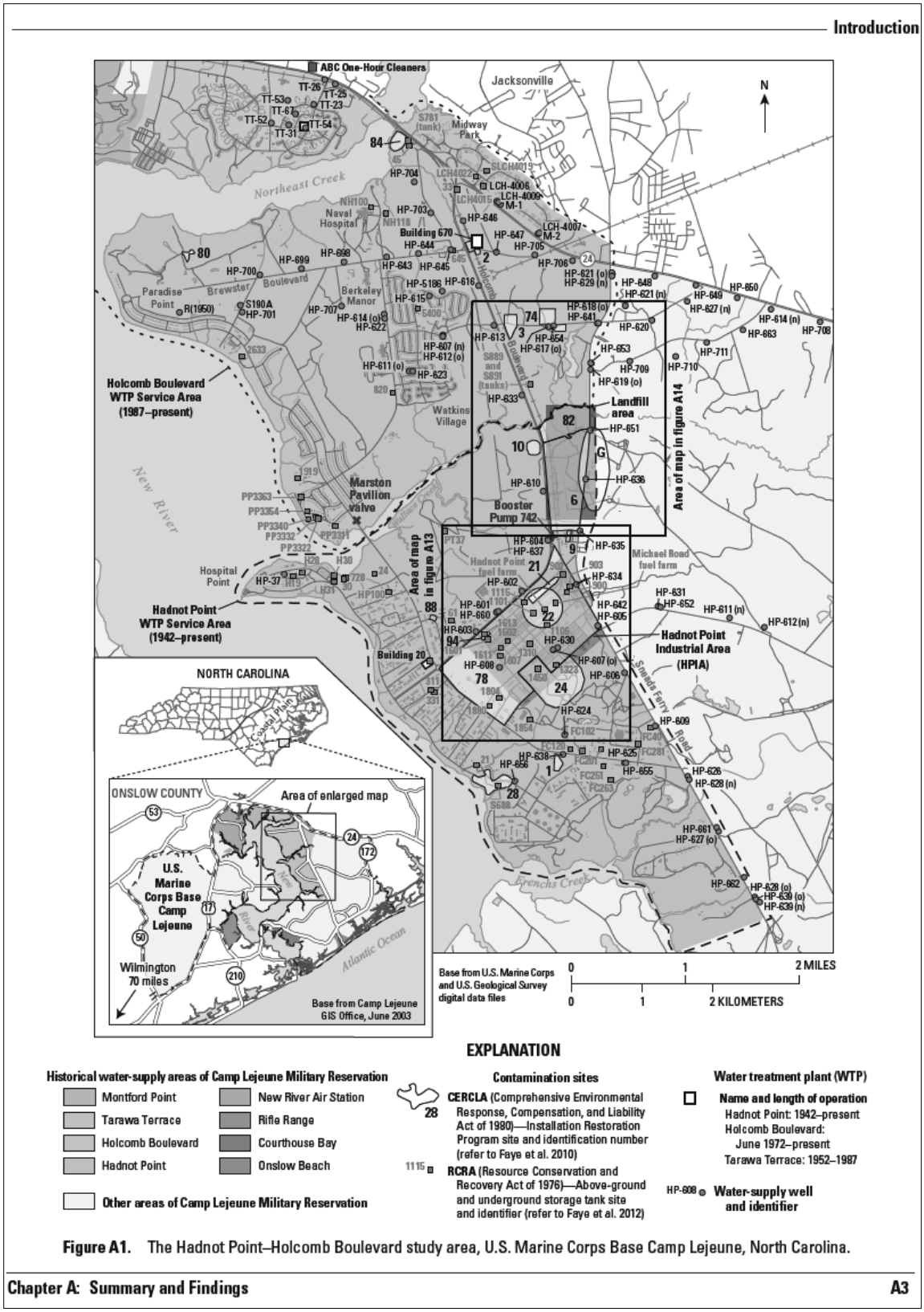



**Figure 4: Map of Hadnot Point-Holcomb Boulevard Area, Camp Lejeune**

ATSDR constructed these groundwater models based on very limited historical data. See the expert report of Dr. Hennet for a detailed discussion of the historical data available to ATSDR. The Tarawa Terrace housing area was constructed in 1951,[55] with pumping of water supply wells beginning in 1952, although more precise dates are not available. Wells were operated in groups at different times, but associated operational data for each well were not available.

At Hadnot Point, operations began in late 1941. Construction of family housing and major infrastructure began in 1942,[56] including the water distribution network. The water treatment plant was constructed during 1941 and 1942.[57] In 1942, 21 water supply wells began operation, with additional wells installed in following years, including replacements of several wells.[58] Similar to Tarawa Terrace, wells operated in groups, but very limited operational data are available.[59]

In order to simulate the operation of water supply wells and their impact on groundwater flow and the migration of contamination in the aquifer, ATSDR developed hypotheses for the historical pumping schedules and corresponding flow rates for the water supply wells. These pumping schedules were developed using complex calculation procedures that were based on limited to no historical data, or other ancillary information.

Limited data were available with respect to the hydrogeologic setting within the local scale of the aquifer. ATSDR constructed groundwater flow models based on this limited dataset, implementing generalized assumptions on the geologic framework, the distribution of the hydraulic properties within the model domain, and boundary conditions.

Finally, limited data were available for constructing the geochemical conceptual model underpinning the contaminant transport model used for simulating contaminant plume migration in the aquifer. Critical parameters impacting the migration of contaminants in groundwater were not based on site-specific data. Rather, they were ultimately defined during model calibration.

ATSDR asserted that their modeling approach provided a high level of detail and accuracy to estimate monthly exposure concentrations in finished water.[60,61] However, assumptions and/or parameter values used by ATSDR in constructing these models were incorrect or inconsistent with site-specific data. As a result, reconstructions of estimated historical monthly contaminant concentrations in finished water produced by the treatment plants and delivered to the water-distribution networks were conservative and biased high, as discussed in detail in Section 4.

## 3.3 Timeline and Scientific Discourse on ATSDR's Camp Lejeune Water Modeling

What follows is a brief timeline summarizing ATSDR's study of water contamination at Camp Lejeune and related events.

- **1989:** The Environmental Protection Agency (EPA) placed USMCB Camp Lejeune and an off-base dry cleaner, ABC One-Hour Cleaners, on its National Priorities List.[62]

[55] ATSDR-TT, Chapter A, p. A10

[56] ATSDR-HP, Chapter A, p. A2

[57] ATSDR-HP, Chapter A, p. A11

[58] ATSDR-HP, Chapter A, p. A11

[59] ATSDR-HP, Chapter A, p. A13

[60] ATSDR-TT, Chapter A, p. A97

[61] ATSDR-HP, Chapter A, p. A181

[62] Maslia Deposition (2024), 86:3-23; ATSDR-TT, Chapter A; ATSDR-HP, Chapter A

- **1997:** ATSDR completed a Public Health Assessment (PHA) for Camp Lejeune.
  - The 1997 PHA noted that ATSDR "was established by Congress in 1980 under [CERCLA]" and that "ATSDR has been required by law to conduct a public health assessment at each of the sites on the EPA National Priorities List."[63]
  - The 1997 PHA recommended conducting an epidemiological study on specific birth defects and cancer in children who were exposed in utero to the COCs at Camp Lejeune.[64]
  - ATSDR made the decision to utilize water modeling to quantify exposure assessments for the epidemiological study based on prior modeling efforts related to Dover Township, New Jersey.[65]

- **2002/2003:** ATSDR started working on water modeling efforts related to Camp Lejeune.[66]
  - Morris Maslia, Project Officer for ATSDR's Exposure-Dose Reconstruction Program, was Project Lead for water modeling on Camp Lejeune.
  - Mustafa Aral, a Georgia Tech Professor, was also on ATSDR's water modeling team for Camp Lejeune.

- **March 28-29, 2005:** ATSDR held an "Expert Peer Review Panel" regarding "ATSDR's Water-Modeling Activities in Support of the Current Study of Childhood Birth Defects and Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina."[67]

- **May 2007:** The United States Government Accountability Office (GAO) issued a "Report to Congressional Committees" entitled "Activities Related to Past Drinking Water Contamination at Marine Corps Base Camp Lejeune."
  - In reference to the 2005 Expert Peer Review Panel, GAO commented: "But all of the panel experts raised concerns about the limited historical record of the amount of PCE or TCE concentration identified at individual Camp Lejeune wells. They said that with limited historical data there would be minimal potential for water modeling to provide accurate information about the level of concentration of the contamination and thus about each individual's total amount of exposure. As an alternative to estimating the extent of each study individual's exposure using the water modeling results, four panel experts suggested ATSDR could use simpler categories of whether and to what extent individuals were exposed to water contamination."[68]

- **June 2007–February 2008:** ATSDR completed and published water modeling reports related to Tarawa Terrace entitled "Analyses of Groundwater Flow, Contaminant Fate and Transport, and

[63] ATSDR PHA (1997); Maslia Deposition (2024), 86:24-87:17

[64] ATSDR PHA (1997); Maslia Deposition (2024), 87:23-88:23

[65] Maslia (2024), Deposition, September 26, 91:2-16

[66] Maslia (2024), Deposition, September 26

[67] ATSDR Expert Review Panel Report and Transcripts (2005)

[68] GAO (2007), p. 55

Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions," Chapters A- F, H.[69]

ATSDR's Tarawa Terrace reports indicated that the water modeling was intended to support an epidemiological study, not for the purpose of making exposure assessments in individuals.

- "The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to drinking water contaminated with volatile organic compounds (VOCs) at U.S. Marine Corps Base Camp Lejeune, North Carolina (Plate 1), were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who resided in family housing at Camp Lejeune."[70]
- "ATSDR is using water-modeling techniques to provide the epidemiological study with quantitative estimates of monthly contaminant concentrations in finished drinking water[] because contaminant concentration data and exposure information are limited. Results obtained by using water-modeling techniques, along with information from the mother on her water use, can be used by the epidemiological study to estimate the level and duration of exposures to the mother during her pregnancy and to the infant (up to 1 year of age). Using water-modeling techniques in such a process is referred to as historical reconstruction (Maslia et al. 2001)."[71]
- "ATSDR's exposure assessment cannot be used to determine whether you, or your family, suffered any health effects as a result of past exposure to PCE-contaminated drinking water at Camp Lejeune."[72]

- **March 26, 2008:** ATSDR held a Technical Meeting with the United States Marine Corps and Navy to present its water modeling efforts related to Tarawa Terrace.[73]

- **June 19, 2008:** The United States Marine Corps and United States Department of the Navy (DON) provided comments, which were drafted by the Navy's water modeling expert Dr. Dan Waddill, to ATSDR about its water modeling efforts related to Tarawa Terrace.

  The Marine Corps' and Navy's comments included the following:

  - "Model simulations provide monthly concentrations from 1952 to 1987, but measured concentrations for model calibration are available only in 1982 and 1985. Thus, the majority of the simulated concentrations cannot be compared to measured data."[74]

[69] Chapters G and I were completed and published in April 2008 and February 2009, respectively.

[70] ATSDR-TT, Chapter A, p. iii

[71] ATSDR-TT, Chapter A, p. A2

[72] ATSDR-TT, Chapter A, p. A98

[73] GAO (2007)

[74] Department of Navy (2008), CLJA_2019ATSDR04-0000002372–2379

- "Simulated concentrations did not fall within calibration targets for a majority of the measured PCE concentrations at the water supply wells, suggesting that the 'accuracy' of the model is less than the chosen calibration standard of ± 1/2-order of magnitude."[75]
- "Due to lack of measured PCE concentrations, the Tarawa Terrace model was not validated. Therefore, the model was not 'put at risk,' and it is difficult to judge the accuracy of the simulated PCE concentrations beyond the limited times when calibration data are available."[76]

The Marine Corps and Navy made the following recommendations:

- "Improve communication with the public and other stakeholders by developing a method for presenting the uncertainty in the model-derived PCE concentrations. The method should be clear and readily understood, perhaps using error bars or presenting a concentration range rather than a single number. The method should be applied consistently whenever concentrations are discussed or presented in model reports, websites, public meetings, etc."[77]
- "Convene an expert panel to examine the model results and determine the best use for the data. Overall, the panel should develop a path forward that is scientifically sound and will best meet the critical concerns of the public."[78]
- "Apply all lessons learned from the Tarawa Terrace modeling efforts to the scoping of the approach for Hadnot Point."[79]

Around this timeframe, ATSDR took down a public webpage that generated estimated monthly contaminant concentrations based on an individual's address. Mr. Maslia testified that "in working with the Department of Navy, they expressed some reservations that there were insufficient qualifiers on the data, not the table itself. But when somebody just put in an address and got a value out, it did not explain to them the limits of the data or the simulated data."[80]

- **March 2009:** ATSDR published its "Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace."[81]

  In responding to the Marine Corps' and Navy's comments, ATSDR reaffirmed that the Tarawa Terrace water modeling was intended to support an epidemiological study and not for the purpose of making exposure assessments in individuals.

  - "ATSDR maintains that the models (flow, transport, and mixing) are sufficiently calibrated, given the quantity and accuracy of data provided and the intended use of the simulated historically reconstructed concentrations. Although the DON is correct in pointing out that some simulated results did not meet the calibration target, ATSDR believes that the DON should assess these results in terms of: (1) similar peer-reviewed reports, (2) currently established model calibration practices, and (3) the intended use of

[75] Department of Navy (2008), CLJA_2019ATSDR04-0000002372–2379

[76] Department of Navy (2008), CLJA_2019ATSDR04-0000002372–2379

[77] Department of Navy (2008), CLJA_2019ATSDR04-0000002372–2379

[78] Department of Navy (2008), CLJA_2019ATSDR04-0000002372–2379

[79] Department of Navy (2008), CLJA_2019ATSDR04-0000002372–2379

[80] Maslia (2010), Deposition, June 30, 79:25-80:5.

[81] ATSDR (2009)

the modeling results by the epidemiological study. That is, are the ATSDR analyses within the accepted norm of current-day modeling practices, are the ATSDR analyses an exception to this norm, and will there be sufficient reliability for an epidemiological study?"[82]

- "To address the issue of the intended use of the water-modeling results by the current ATSDR epidemiological study, the DON should be advised that a successful epidemiological study places little emphasis on the actual (absolute) estimate of concentration and, rather, emphasizes the relative level of exposure. That is, exposed individuals are, in effect, ranked by exposure level and maintain their rank order of exposure level regardless of how far off the estimated concentration is to the "true" (measured) PCE concentration. This rank order of exposure level is preserved regardless of whether the mean or the upper or lower 95% of simulated levels are used to estimate the monthly average contaminant levels. It is **not** the goal of the ATSDR health study to infer which health effects occur at specific PCE concentrations—this is a task for risk assessment utilizing approaches such as meta-analysis to summarize evidence from several epidemiological studies because a single epidemiological study is generally insufficient to make this determination. The goal of the ATSDR epidemiological analysis is to evaluate exposure-response relationships to determine whether the risk for a specific disease increases as the level of the contaminant (either as a categorical variable or continuous variable) increases."[83]

- **April 29-30, 2009:** ATSDR held an "Expert Panel" regarding "ATSDR's Methods and Analyses for Historical Reconstruction of Groundwater Resources and Distribution of Drinking Water at Hadnot Point, Holcomb Boulevard, and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina."

- **2009:** The National Research Council (NRC) published a report entitled *Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects*.[84]

  The 2009 NRC Report reviewed and provided comments on ATSDR's water modeling related to Tarawa Terrace, including the following:

  - "The National Research Council (NRC) conducted this review in response to a request from the U.S. Navy, the department under which the Marine Corps operates. The Navy was mandated by the U.S. Congress (Public Law 109-364, Section 38) to request a review

[82] ATSDR (2009), CLJA_WATERMODELING_01-09_0000033272

[83] ATSDR (2009), CLJA_WATERMODELING_01-09_0000033272

[84] NRC (2009); The 2009 NRC Report described the NRC as "organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities." It described the National Academy of Sciences as "a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters."

by the NRC to address the evidence on whether adverse health outcomes are associated with past contamination of the water supply at Camp Lejeune."[85]

- "Sophisticated computer modeling techniques were used by ATSDR to make predictions about the monthly concentrations of PCE to which residents of Tarawa Terrace were exposed. To provide perspective on its estimates, ATSDR compared its monthly estimates with the U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) for PCE in drinking water of 5 ug/L, which was established in 1985. The model estimated that starting in November 1957, the concentration of PCE delivered to residents exceeded that MCL and remained well above it until the wells were closed in 1985."[86]
- "Some of the modeling approaches used by ATSDR were 'cutting-edge,' meaning that they used computer codes and modeling techniques that are still in the research stage and have yet to be validated. Furthermore, the absence of measurement data for the first 30 years of the contamination period means the predictions, even if based on validated codes and models, cannot be evaluated for accuracy. The actual concentrations may have been higher or lower than the predictions, but that cannot be assessed. Other uncertainties were introduced into the models because assumptions had to be made about how the water system was operating. For example, little information was available on which wells were supplying water at specific time periods, so assumptions had to be made about when the contaminated wells were operating. Another uncertainty is that the models did not take into account the DNAPL form of pollutants. Given the multiple uncertainties and likely variation in contaminant concentrations, the committee concluded that the Tarawa Terrace modeling predictions should only be used to provide a general estimate of the timeframe and magnitude of exposure."[87]

The NRC recommended:

- "Because any groundwater modeling of the Hadnot Point system will be fraught with considerable difficulties and uncertainties, simpler modeling approaches should be used to assess exposures from the Hadnot Point water system. Simpler modeling will not reduce the uncertainty associated with the estimates, but they have the advantage of providing a broad picture of the timeframe and magnitude of exposure encountered by people who used water from that system more quickly and with less resources than complex modeling exercises."[88]

- **September 2011:** Dr. T. Prabhakar Clement, an NRC Committee Member and Auburn University Professor, published an article in *Groundwater* entitled "Complexities in Hindcasting Models–When Should We Say Enough is Enough?"[89]

  Dr. Clement's article echoed the NRC's concerns about the uncertainty in ATSDR's water model related to Tarawa Terrace and recommended a simpler approach for the water model related to Hadnot Point and Holcomb Boulevard to meet policy-oriented goals.

[85] NRC (2009), p. 1
[86] NRC (2009), p. 4
[87] NRC (2009), p. 4
[88] NRC (2009), p. 5
[89] Clement (2011)

- "[E]ven if one had a 'perfect' groundwater model, the final outcomes of the study would have considerable uncertainties due to lack of knowledge about actual exposures… ."[90]
- "For the CLJ project, the judgment call was made by the NRC panel, which consisted of a diverse group of 14 experts who volunteered their time to study various aspects of the problem for 2 years and prepared a report, which was reviewed by 10 external reviewers… As voluntary expert committees, such as the NRC panel, do not have any direct self-interest, their collective wisdom is likely to recommend a reasonable practical solution, although by no means it would be the perfect solution." [91]
- "The overall response to the NRC Study was mixed. Various groups of health scientists, environmental activists, one of the modeling teams, and the former CLJ residents were disappointed and severely criticized the study's conclusion that additional scientific studies cannot provide more definitive answers. In 2009, two senators from North Carolina introduced a bill to furnish hospital care, medical services, and nursing home care to veterans who were stationed at the base while the water was contaminated. In February 2010, a North Carolina congressmen introduced the *The Janey Ensminger Act* in the House of Representatives to require the Department of Veterans Affairs to provide healthcare benefits. These new policy developments directly address the healthcare needs of the community."[92]

- **January/February 2012:** ATSDR's water modeling team, led by Morris Maslia, published comments in response to Dr. Prabhakar Clement's article.

  While they disagreed with Dr. Clement's uncertainty concerns over the use of complex hindcasting models or reconstruction, ATSDR's water modeling team acknowledged the purpose of the Camp Lejeune water modeling relating to policy-oriented goals.

  - "The calibration of a model must either stand or fall on its own merits, without the benefit of future data collection that may be accomplished later in time or the lost opportunity for data collection previously foregone. At the time of calibration, when model results are provided to policy makers, a "hindcasting" model is *not* uniquely disadvantaged compared with a forecasting model just because model predictions are historical rather than latter in time. Few, if any, policy makers or the public would accept the premise that policy decisions must be delayed for several years or several decades to further validate an existing model when a decision must be forthcoming."[93]

- **August 6, 2012:** The President signs the Honoring America's Veterans and Caring for Camp Lejeune Families Act of 2012 (the Janey Ensminger Act), "*to furnish hospital care and medical services to veterans who were stationed at Camp Lejeune, North Carolina, while the water was contaminated at Camp Lejeune, to improve the provision of housing assistance to veterans and their families, and for other purposes*."[94]

---

[90] Clement (2011), p. 4

[91] Clement (2011), p. 7

[92] Clement (2011), p. 8

[93] Maslia et al. (2012), p. 11

[94] 38 U.S.C. § 301 (note).

- **October 2010–March 2013:** ATSDR completed and published water modeling reports related to Hadnot Point and Holcomb Boulevard Report entitled "*Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina*," Chapters A-D.

  ATSDR's reports on Hadnot Point and Holcomb Boulevard indicated that the water modeling was intended to support an epidemiological study and not for the purpose of making exposure assessments in individuals.

  - "*The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting epidemiological studies to evaluate the potential for health effects from exposures to finished water contaminated with volatile organic compounds (VOCs) at U.S. Marine Corps Base Camp Lejeune (USMCB Camp Lejeune), North Carolina*."[95]
  - "*The epidemiological studies require estimates or direct knowledge of contaminant concentrations in finished water at monthly intervals. When direct, past knowledge of contaminant concentrations in finished water is limited or unavailable, historical reconstruction is used to provide estimates of contaminant concentrations. At USMCB Camp Lejeune, historical reconstruction methods include linking materials mass balance (mixing) and water- distribution system models to groundwater-flow and contaminant fate and transport models (Maslia et al. 2007, 2009a). Results obtained from the historical reconstruction process, along with household information regarding water use and consumption, can be used in the epidemiological studies to estimate the level and duration of contaminant exposures*."[96]
  - "*ATSDR's exposure estimates cannot be used alone to determine whether you, or your family, suffered any health effects as a result of past exposure to TCE-contaminated drinking water at USMCB Camp Lejeune*."[97]

- **January 16, 2013:** ATSDR Director, Christopher Portier, sends letter to the Department of Veterans Affairs (VA) Under Secretary for Benefits, General Allison Hickey.
  - "*The Agency for Toxic Substances and Disease Registry (ATSDR) has conducted a series of environmental and epidemiologic assessments of contaminated drinking water at USMC Base Camp Lejeune. The foundation of our effort is based on modeling of the contamination of the drinking water supply before 1987. The modeling was necessary because there were relatively few drinking water samples tested for VOCs during the period of contamination; none prior to 1982, when VOC contamination was first detected*."[98]

[95] ATSDR-HP, Chapter A, p. A2

[96] ATSDR-HP, Chapter A, p. A2

[97] ATSDR-HP, Chapter A, p. A182

[98] ATSDR (2013), CLJA_WATERMODELING_01-0000076158–76159

- "*I hope this information is useful as the Department of Veterans Affairs evaluates claims from veterans who served at USMC Camp Lejeune prior to the release of our full water modeling report in the spring. ATSDR is also on schedule to release its mortality study and birth defects and childhood cancers study in spring 2013. When we finalize our water modeling and these epidemiologic studies, I will make certain that we brief the Department of Veterans Affairs staff on our findings. I would also like to recognize the efforts of your Department in supporting ATSDR's work and serving Camp Lejeune veterans and their families who were exposed to contaminated drinking water*."[99]

- **December 4, 2013:** ATSDR study entitled "Evaluation of exposure to contaminated drinking water and specific birth defects and childhood cancers at Marine Corps Base Camp Lejeune, North Carolina: a case–control study" is published in *Environmental Health*.
  - "Limited historical, contaminant-specific data were available, therefore ATSDR conducted a historical reconstruction of contaminant levels in the drinking water using groundwater fate and transport and water-distribution system models. Modeling provided monthly average estimates of the concentrations of the contaminants in drinking water delivered to residences." [100]

- **2017**: The VA "amends its adjudication regulations regarding presumptive service connection, adding certain diseases associated with contaminants present in the base water supply at U.S. Marine Corps Base Camp Lejeune (Camp Lejeune), North Carolina, from August 1, 1953, to December 31, 1987."[101]

- **2014-2024:** ATSDR conducted other epidemiological studies related to Camp Lejeune relying on the Camp Lejeune water modeling to conduct relative exposure assessments.

- **October 24, 2024:** ATSDR published a study entitled "Cancer Incidence among Marines and Navy Personnel and Civilian Workers Exposed to Industrial Solvents in Drinking Water at US Marine Corps Base Camp Lejeune: A Cohort Study" in *Environmental Health Perspectives*. Unlike past ATSDR epidemiolocal studies, this study did not rely on an exposure assessment based on ATSDR's water models related to Camp Lejeune.[102]

- **October 26, 2024:** Mr. Maslia and Dr. Aral are identified as experts for Plaintiffs in the *Camp Lejeune Justice Act* litigation.

[99] ATSDR (2013), CLJA_WATERMODELING_01-0000076158–76159

[100] ATSDR Env Health (2013), CLJA_HEAL THEFFECTS-0000165861–165879

[101] 82 FR 4173

[102] Bove (2024). Deposition, October 18, p. 20:3–11.

# Section 4
# Bases for Opinions

ATSDR conducted water modeling for Tarawa Terrace and subsequent water modeling for Hadnot Point and Holcomb Boulevard. For Tarawa Terrace, ATSDR stated "*ATSDR is using water-modeling techniques to provide [an] epidemiological study with quantitative estimates of monthly contaminant concentrations in finished drinking water because contaminant concentration data and exposure information are limited*."[103] For Hadnot Point and Holcomb Boulevard, ATSDR stated "*[t]he epidemiological studies require estimates or direct knowledge of contaminant concentrations in finished water at monthly intervals. When direct, past knowledge of contaminant concentrations in finished water is limited or unavailable, historical reconstruction is used to provide estimates of contaminant concentrations*."[104] Regarding uncertainty, ATSDR noted that "*[h]istorical data on the levels of contaminants in the drinking water is very limited*"[105] and "*[t]hat is why there is uncertainty and variability*."[106] ATSDR further acknowledged this uncertainty by stating that "*ATSDR's exposure assessment cannot be used to determine whether you, or your family suffered any health effects as a result of past exposure to [] contaminated drinking water at Camp Lejeune*."[107]

Mr. Maslia's report offers several opinions on the acceptability of "historical reconstruction" methods, as well as examples of past projects that utilized historical reconstruction for similar purposes to ATSDR's work at Camp Lejeune. Mr. Maslia admitted that many of the modeling projects he has worked on through his career did not use historical reconstruction. He did, however, emphasize two historical reconstruction projects in his report: Dover Township, New Jersey; and Woburn, Massachusetts.[108] However, these projects were very different in both scope and purpose from ATSDR's Camp Lejeune projects.

- Mr. Maslia testified that he was asked to apply the techniques used in the Dover Township study to Camp Lejeune.[109] In the Historical Reconstruction of the Water-Distribution System Serving the Dover Township Area, New Jersey, ATSDR's Exposure Dose Reconstruction Program modeled "*the percentage of water derived from different sources that historically supplied the water-distribution system*."[110] In other words, ATSDR estimated "*the percentage of water that a study subject might have received from each well and well field that supplied the water-distribution system*."[111] Unlike ATSDR's work at Camp Lejeune, the Dover Township study did not involve groundwater models, but rather focused on contaminant transport within the water distribution systems. Moreover, the study did not estimate

[103] ATSDR-TT, Chapter A, p. A2

[104] ATSDR-HP, Chapter A, p. A2

[105] ATSDR-TT, Chapter A, p. A99

[106] ATSDR-HP, Chapter A, p. A182

[107] ATSDR-TT, Chapter A, p. A98; ATSDR-HP, Chapter A, p. A182

[108] Maslia expert report (2024), p. 97

[109] Maslia (2024), Deposition, September 26, 91:2–16

[110] Maslia et al. (2001), p. 1

[111] Grayman et al. (2004)

concentrations of contaminants in water, but rather the "proportionate contribution" of a given well to an individual's drinking water.[112]

- In the Woburn, Massachusetts exposure study, a water distribution system model was used to simulate the percentage of a household's water that came from supply wells G and H.[113] A groundwater model was used to "*demonstrate the plausibility that contaminated water reached*" those wells, then a water distribution system model was used to assess "*the potential for a residence to receive water from wells G and H and not on actual contaminant concentration in the wells*."[114]

ATSDR's work at Camp Lejeune, therefore, is both significantly more complex and uncertain than the projects Mr. Maslia cited. Moreover, these studies were being used for a less precise purpose; here, Mr. Maslia states that ATSDR's Camp Lejeune studies may be used to show, definitively, the concentration of contaminants to which a given individual was exposed.[115] This is not what the ATSDR reports themselves say the purpose of the study was, and it is not what was done at Dover Township or Woburn.

For example, to calculate the estimated monthly contaminant concentrations, ATSDR implemented complex calculation methodologies. As Mr. Maslia indicated in his 2010 deposition, "*we used, I believe, more sophisticated methods*."[116] When asked whether these methods were so sophisticated as to be novel and unreliable, Mr. Maslia indicated that these methods were "*[n]ot unreliable. Novel application, yes*."[117] Mr. Maslia provided a more detailed description of the application of these methods: "*[w]e were predicting -- or reconstructing backwards in time for 30, 35 years at a monthly interval, which is a -- from a groundwater modeling standpoint, a fairly fine timeline, typically. And in terms of, say, remediation practices where they use these similar models, you may look at years – or five – of years trying to clean up.*"[118] He also highlighted that "*you do not necessarily see published results in terms of monthly values. So that was a very refined time step in terms of a groundwork model.*"[119] Mr. Maslia characterized this by saying "*[s]o from that standpoint, that's probably, you know, edge of the envelope of what's been done*."[120]

Mr. Maslia was deposed again in 2024 and commented on his 2010 statements, saying that these methods allowed ATSDR "*to go backwards in time, reconstruct based on either available data in the 1980s or current day information*."[121] Mr. Maslia continued his description of the calculation approach by indicating that *"[m]any modeling remediation-type studies collect field data present day and then, of course, project forward in time, but this was a unique application of -- of going backwards in time.*"[122]

In his expert report, Mr. Maslia provided examples of studies that ATSDR conducted as part of its Exposure-Dose Reconstruction Program.[123] Mr. Maslia indicated that *"[t]he overall goal of the Exposure-Dose Reconstruction Program (EDRP) was to enhance the agency's capacity to characterize exposure and*

[112] Maslia et al., 2001, p. 2—4.

[113] Lagakos et al. (1986), p. 585.

[114] Costas et al. (2002), p. 2–4.

[115] Maslia (2024), Expert Report, p. 97

[116] Maslia (2010), Deposition, June 30, p. 45

[117] Maslia (2010), Deposition, June 30, p. 45

[118] Maslia (2010), Deposition, June 30, p. 45

[119] Maslia (2010), Deposition, June 30, p. 45-46

[120] Maslia (2010), Deposition, June 30, p. 46

[121] Maslia (2024), Deposition, September 26, p. 216

[122] Maslia (2024), Deposition, September 26, p. 216

[123] Maslia (2024), Expert Report, p. 12

*dose to better support health assessments and consultations, health studies, and exposure registries*."[124] It is important to view such studies from the standpoint of (a) whether calculations are performed for hindcasting past conditions or predicting future conditions; and (b) how the results of these studies are used, e.g. remedial design versus, for example, health effects. The uncertainty of the model results can be significant and its impact on decision making can be substantial.

When predictive calculations are performed, the associated uncertainty of these calculations may be high or very high, depending on assumptions regarding the parameters used in the corresponding models. These uncertainties can be reduced as more data become available and the model can be further constrained. However, this is not possible when calculations are used for hindcasting. In that instance, the historical data available cannot be further augmented. Things become more complicated when available data are limited or non-existent. Under these circumstances, developing calculation tools requires relying heavily on professional judgment. As will be shown below, professional judgment and expert knowledge cannot replace site-specific data that should inform parameter values in the models, or lack of observed data that should constrain the model calibration. Without these two pieces of information, "novel" or "edge of envelope" approaches can be very complex, incorporating professional judgment for interpreting aquifer and chemical characteristics, but they cannot overcome the inherent limitations associated with the lack of data. In that sense, they can even be considered speculative and unfounded.

Parameter estimation methods and programs have been developed over the last three decades to assist the complex process of calibrating models to observed data.[125] Numerous studies have been published and conferences held on this subject.[126] However, over the last two decades, the focus of scientific research has shifted from calibration to uncertainty analyses, recognizing the fact that "*environmental models are built to make predictions that support the making of important management decisions. These predictions are often accompanied by a large amount of uncertainty – uncertainty that must be accommodated in any sensible decision-making strategy. Quantification of uncertainty allows evaluation of the risks associated with different management strategies*."[127] In this context, "predictions" refer to the model output, regardless of whether its results are used for hindcasting or forecasting, as the uncertainty analysis investigates the non-uniqueness of the model solution.[128]

In recent years, advanced uncertainty analysis methods have been developed to take advantage of computational capabilities provided by model computers.[129] Advanced uncertainty methods recognize the need for "*the development of means to explore calibration-constrained predictive uncertainty*."[130] For the uncertainty of a model prediction, critical to the variability of model parameters is "*the extent to which this variability is constrained by the necessity for model outputs to respect historical measurements of system state.*"[131] In other words, the entire discussion about model calibration and uncertainty is founded on the concept of *respecting historical measurements*. When historical measurements are not available, uncertainty bounds rely solely on professional judgment. As will be shown in the discussion below, historical and site-specific data can disprove assumptions based on professional judgment and expert knowledge. As a result, actual conditions can vary significantly from conditions assumed based on

[124] Maslia (2024), Expert Report, p. 12

[125] Doherty (2015), p.1

[126] 2023 PEST Conference – The Path from Data to Decisions, March 5-10, 2023, La Jolla, CA

[127] Doherty (2015), p.1

[128] Anderson et al. (2015), p. 378

[129] Anderson et al. (2015), p. 469

[130] Doherty (2015), p.2

[131] Doherty (2015), p.2

professional judgment. Advanced uncertainty methods that specifically consider calibration datasets have become the prevailing standard in recent years due to their holistic approach to uncertainty.[132,133]

The Pacific Northwest National Laboratory (PNNL) conducted an analysis to address issues related to hydrologic uncertainty and its impacts on dose from contaminated sites and waste disposal facilities. The impact of ignoring site-specific data was highlighted: *"[t]he complex model assumed the availability of an extensive dataset on which to base the random field characterization of the subsurface. Uncertainty in predicted dose was correspondingly small, with the peak dose coefficient of variation being 30%. When the variances of parameters in the simplified model were based on a generic dataset, the uncertainty in predicted peak dose was much larger; the coefficient of variation was 52% in this case. When the variances of parameters in the simplified model were based on the available site-specific data, the coefficient of variation for the peak dose was reduced to 22%*."[134] In other words, generic datasets for model parameters, even when selected based on professional judgment and expert knowledge, can fail to properly quantify uncertainty, compared to considering site-specific data. The resulting uncertainty can be much higher when generic data are used for constructing the model.

Examples of use of models include the evaluation of the nature and extent of contamination and/or design of a system for containing a contaminant plume, aquifer restoration to certain cleanup standards, or evaluation of ultimate fate and transport of a contaminant plume.[135] Model uncertainty may have significant impacts on the design of plume containment or aquifer restoration systems, as simulation results may substantially under- or over-estimate plume migration patterns and aquifer response to pumping. This type of model failure can be mitigated by updating model calibration via collection of more data during the remediation phase and revising model predictions. It can also be mitigated by expanding the remedial design.

However, when models are used for hindcasting or forecasting conditions that are directly translated to substantially more important decisions, such as health impacts, the implications of model uncertainty have to be viewed more critically. Camp Lejeune is a suitable case in point. ATSDR reconstructed historical conditions at Camp Lejeune to calculate how much contamination (i.e., dose)[136] people at Camp Lejeune were exposed to, by implementing "*a unique application of -- of going backwards in time,"*[137] and "*reconstructing backwards in time for 30, 35 years at a monthly interval*,"[138] using "*[n]ovel application*"[139] of significant complexity.

In his expert report, Dr. Aral concurred with the following statement by Dr. Robert Clark, Chair of the Expert Review Panel for the ATSDR Camp Lejeune studies: "*[f]rom a scientific viewpoint it would be ideal to have independent datasets. One set could be used to calibrate the models, and the second data set used for validation. If one is developing a model based on experimental data this approach can be built into the combined experimental and modeling effort. However, it has been my experience that such an ideal situation rarely exists in "real world" situations. Therefore, in my opinion, the best approach is to use the available datasets in conjunction with sound engineering principles and the investigator's best judgment to establish the validity of the exposure models.*"[140] Dr. Aral then stated that "*I concur with Dr. Clark's*

[132] Tonkin and Doherty (2009)

[133] Fienen et al. (2006)

[134] Meyer and Orr (2002), p. 43

[135] Ahlfeld et al. (1988); Wagner (1995)

[136] ATSDR-TT, Chapter A, p. A98

[137] Maslia (2024), Deposition, September 26, p. 216

[138] Maslia (2010), Deposition, June 30, p. 46

[139] Maslia (2010), Deposition, June 30, p. 45

[140] Aral (2024), Expert Report, p. 48

*assessment given above. It is my opinion that ATSDR used the best available datasets, sound science and engineering principles, and professional judgment to establish the best possible reconstructed values of historical contaminant concentrations, and that, within a reasonable degree of scientific and engineering certainty, these were the contaminant levels delivered to Tarawa Terrace, Hadnot Point, and Holcomb Boulevard*."[141] Dr. Clark indicated that ideal conditions rarely exist in the "real world" and that "available datasets" should be used. In Camp Lejeune, "available datasets" are practically non-existent. In fact, there are little to no site-specific data for key modeling parameters, historical operational data for water-supply wells, or, more importantly, observed data to use for constructing and calibrating the model. It is not obvious what Dr. Aral referred to when he stated that "*ATSDR used the best available datasets."* The reality is that ATSDR constructed a model based almost exclusively on professional judgment and assumptions that cannot be tested.

Dr. Clement, a professor in the Department of Civil Engineering at Auburn University, published an issue paper in the journal *Groundwater* in 2011, expressing his opinions regarding ATSDR's modeling approaches and methods in Tarawa Terrace.[142] He commented on ATSDR's uncertainty analysis, indicating that "*the results appear to be reasonable because the Monte Carlo simulations indicated a narrow band within which 95% of the model-simulation results resided. The figure shows that 95% confidence band becomes narrower as we move back from the 1980's (where there is no data); this implies that the groundwater model was able to make confident hindcasts for the 1950s and 1960s even if there are no past data to calibrate the model. The figure also shows that closer to the initial starting point the confidence band is almost 100%, implying that our knowledge of initial conditions, initial source loadings, and initial stresses is almost exact."* In his comments, Dr. Clement highlighted the shortcomings of the uncertainty analysis conducted by ATSDR. He indicated that ATSDR's analysis implied almost exact knowledge of past conditions. But that would be impossible, given that there were no past data to calibrate the model, and there was no confidence in the assumptions about the history (i.e., variability in timing and magnitude) of the contaminant contributions from the identified source, or generally in the aquifer conditions.

The NRC, in its review of the scientific evidence on water contamination at Camp Lejeune,noted that "*the absence of measurement data for the first 30 years of the contamination period means the predictions, even if based on validated codes and models, cannot be evaluated for accuracy*."[143] The NRC further stated, regarding the model challenges and limitations for Tarawa Terrace, that "*[a]lthough ATSDR recognized and tried to account for the limitations and uncertainties associated with its models, the committee judges that—because of the sparse set of water-quality measurements, the need to make unverifiable assumptions, and the complex nature of the PCE source—it is virtually impossible to estimate exposure to historical levels of PCE and its degradation products accurately. Reporting precise values based on model predictions gives the misleading impression that the exposure of the former residents and workers at Tarawa Terrace during specific periods can be accurately defined.*"[144] For Hadnot Point, the NRC indicated that "*any groundwater modeling of the Hadnot Point system will be fraught with considerable difficulties and uncertainties.*"[145]

The NRC also opined on ATSDR's use of complex calculation approaches in the absence of historical observed data: "*Even with the use of reasonable and, in some cases, advanced approaches, limitations in data availability and quality cannot be overcome*."[146]

---

[141] Aral (2024), Expert Report, p. 48

[142] Clement (2011)

[143] NRC (2009), p. 4

[144] NRC (2009), p. 16

[145] NRC (2009), p. 5

[146] NRC (2009), p. 22

Dr. Aral also states in his expert report: "*[t]he NRC committee should accept the fact that answers to uncertainty questions cannot be answered "accurately.*"[147] Dr. Aral continued, saying that: "*Our uncertainty analyses are not provided to give "accurate" answers to the problem studied. Instead, our uncertainty analyses are used as estimates that would indicate the variability range of deterministic results provided earlier."*[148] In response to the NRC's comment about "*some important limitations in ATSDR's modeling efforts because of the sparse set of water quality measurements, the need to make unverifiable assumptions, and the complex nature of the PCE source contamination,*"[149] Dr. Aral admitted that there are limitations to the modeling analyses conducted by ATSDR.[150] He also suggested that the level of detail of the uncertainty analyses conducted by ATSDR enveloped the effect of those uncertainties.[151] And he concluded by saying that "*an uncertainty that can be verified would no longer be uncertain*."[152]

However, as discussed above, model accuracy is key to a model that is used as an important decision-making tool. When no site-specific data or historical observed data are available, the model cannot be assessed for its accuracy, and the same is true about its uncertainty. As will be shown below, the ATSDR model outputs can vary significantly when simple corrections to key model parameters are made, or the uncertainty of important factors (such as the source release history) are considered. However, these outputs are outside the realm of uncertainty determined by ATSDR in their analyses. This is evidence of the fact that a process can be complex, and expert knowledge and professional judgment can be imparted in the analysis, but neither can substitute for observed data.

**In Summary (Opinion 1): ATSDR constructed models for historical reconstruction. To construct these models, they combined complex processes and methods. However, these models were largely not constructed using site-specific data or calibrated to observed data for the first 30 years of simulation. ATSDR relied extensively on professional judgment for constructing these models. Despite the extensive assumptions and substantial uncertainties underpinning these models, ATSDR used the models to calculate monthly estimates of concentrations in the water-supply wells and the water treatment plant. ATSDR's uncertainty analyses did not assess model accuracy, as there were no observed data to support such assessment. Thus, model accuracy was replaced by process complexity and professional judgment.**

Below are detailed discussions of the bases for my remaining opinions, provided separately for the Tarawa Terrace and Hadnot Point-Holcomb Boulevard areas.

In what follows, an important clarification is necessary regarding the historical reconstruction of contaminant concentrations at the WTPs. ATSDR stated that "*for this study, finished water is defined as groundwater that has undergone treatment at a water treatment plant and was subsequently delivered to a family housing unit or other facility. Throughout this report and the Hadnot Point–Holcomb Boulevard report series, the term finished water is used in place of terms such as finished drinking water, drinking water, treated water, or tap water*."[153] However, ATSDR used simulated contaminant concentrations in the influent to the WTP to estimate concentrations in the water delivered to a family housing or other facility. In this process, ATSDR ignored any contaminant losses that would occur during treatment. This was an important assumption of significant impacts, as discussed in the expert report of Dr. Hennet (2024). Therefore, references to historical reconstruction of VOC concentrations hereafter are associated with

[147] Aral (2024), Expert Report, p. 56

[148] Aral (2024), Expert Report, p. 56

[149] Aral (2024), Expert Report, p. 56

[150] Aral (2024), Expert Report, p. 56

[151] Aral (2024), Expert Report, p. 56

[152] Aral (2024), Expert Report, p. 56

[153] ATSDR, Chapter A, Supplement 6, p. S6.21

concentrations in the influent to the treatment plant, and not after-treatment "finished" water that entered the water distribution network.

## 4.1 Tarawa Terrace

Water quality samples taken at Camp Lejeune in the 1980s revealed contamination of VOCs. Because there were no water quality samples analyzed for the VOCs addressed in Mr. Maslia's and Dr. Aral's reports prior to the 1980s, ATSDR attempted to use mathematical modeling to reconstruct historical concentrations of these contaminants in water supply wells and at the WTPs in the absence of measured data.

ATSDR used a model to reconstruct groundwater flow and contaminant transport at Tarawa Terrace family housing. In creating their conceptual model, ATSDR relied on past investigations of hydrogeologic conditions in the aquifer below Camp Lejeune. Using the conceptual model, ATSDR created a groundwater flow model, using MODFLOW. The groundwater flow model was created with limited available data. The groundwater flow model was then used to create a contaminant fate and transport model, using MT3DMS, which also relied on limited data. Next, ATSDR performed model calibration, sensitivity analysis, and uncertainty analysis.

Based on my professional judgment, there were insufficient data to conduct reliable model calibration and uncertainty analysis. Given the fact that prior to 1982, no water quality data were available, ATSDR's model was highly uncertain. ATSDR's uncertainty analysis evaluated a range of parameter values, some of which, when compared to site specific data, did not reflect the site conditions. An uncertainty analysis should provide a range of potential model outcomes that envelops the calibrated model. The calibrated model should generally sit in the middle of the uncertainty range. However, ATSDR's calibrated model sits at the top of the uncertainty range, especially for approximately the first ten years of the simulation timeframe. This demonstrates that the calibrated model was biased high.

Moreover, as discussed below, ATSDR improperly characterized the PCE source release date and overestimated the gradual mass loading into the aquifer from that source.

ATSDR developed a second model, TechFlowMP, to simulate (a) the presence of PCE in both gas and water, for considering volatilization of PCE in the unsaturated zone, and (b) the migration of PCE degradation by-products in groundwater. Unlike TechFlowMP, MT3DMS could only simulate PCE concentrations in groundwater. TechFlowMP calculated PCE concentrations in groundwater that were lower than those calculated using MT3DMS, because of inconsistent implementation of the contaminant source term.

The NRC highlighted the model challenges and limitations: "*Although ATSDR recognized and tried to account for the limitations and uncertainties associated with its models, the committee judges that—because of the sparse set of water-quality measurements, the need to make unverifiable assumptions, and the complex nature of the PCE source—it is virtually impossible to estimate exposure to historical levels of PCE and its degradation products accurately. Reporting precise values based on model predictions gives the misleading impression that the exposure of the former residents and workers at Tarawa Terrace during specific periods can be accurately defined.*"[154]

The NRC also opined on ATSDR's use of complex calculation approaches in the absence of historical observed data: "*Even with the use of reasonable and, in some cases, advanced approaches,*

[154] NRC (2009), p. 16

*limitations in data availability and quality cannot be overcome*."[155] Dr. Waddill indicated his agreement with this conclusion in his deposition.[156] I concur with this conclusion.

As part of this litigation, Dr. Jones and Mr. Davis conducted a post-audit, which considered data from the site remediation and extended the model to 2008. This extended model consistently overestimated concentrations of contaminants in groundwater compared to observed values. This demonstrates that ATSDR's Tarawa Terrace's calibrated model resulted in concentrations higher than those observed in the aquifer.

### 4.1.1 Available Data are Limited or Non-Existent

To create the groundwater flow model, ATSDR used available data, which included:

- Horizontal hydraulic conductivities from 36 aquifer test analyses at Tarawa Terrace and adjacent areas;[157]
- Aquifer-specific yield and storativity values, computed from four aquifer tests in the vicinity of Tarawa Terrace;[158] and
- Precipitation data from the Maysville-Hoffman Forest station with records from 1951-1994.[159]

Pumpage information at individual supply wells were not available for the study period. ATSDR developed assumed well pumping schedules and flow rates through a complex process. To do that, they relied on ancillary data, including well-capacity data and average water supply demand for the TT WTP for different periods (i.e., sparse data).[160]

All other model parameters were based on a literature review and the professional judgment of the modelers.

Limited data were available on the actual operation of water supply wells. In the absence of documentation of historical water supply well operations, ATSDR modeled a hypothetical well pumping schedule, which was used in the groundwater flow model.

To construct the contaminant transport model, ATSDR used model parameters that were based on a literature review and the professional judgment of the modelers.

Model calibration was based on:

- Contaminant concentration data at water supply wells from 1984-1985 and 1991;[161] and
- Contaminant concentration data at monitoring wells from previous remediation investigations.[162]

Although operations at ABC One-Hour Cleaners started sometime in 1954,[163] sampling data from water supply wells were not available before January 1985. This means there was a thirty-year period for which there is no historical water quality data that could be used to inform the model calibration. Appendix D lists all the sampling data from the water supply wells and WTP available to ATSDR.

---

[155] NRC (2009), p. 22

[156] Waddill (2024), Deposition, August 6, p. 124:5

[157] ATSDR-TT, Chapter C, p. C14

[158] ATSDR-TT, Chapter C, p. C40

[159] ATSDR-TT, Chapter C, p. C21

[160] ATSDR-TT, Chapter C, p. C22

[161] ATSDR-TT, Chapter E, p. E4

[162] ATSDR-TT, Chapter E, pp. E5-E23

[163] Brigham (2024), Expert Report

No measured data or information was available on the mass loading from the contaminant source. ATSDR relied on information on solvents used by ABC One-Hour Cleaners and site investigations of the Superfund site in the 1990s. ATSDR relied on this information to estimate contaminant mass loading into the aquifer, which was assumed to be constant from 1953 to 1984. ATSDR increased its initial estimate of mass loading to a much higher value during model calibration.

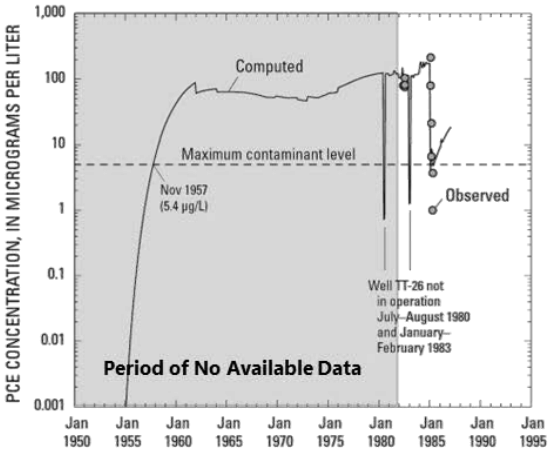



**Figure F27.** Computed and observed concentrations of tetrachloroethylene (PCE) in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951–December 1984. [µg/L, microgram per liter]

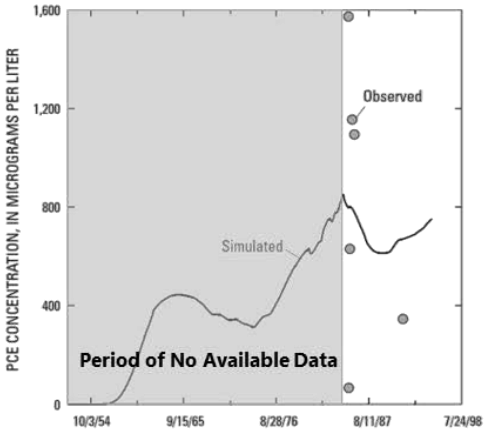



**Figure F16.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1952–December 1994 (see Figure F6 for location).

**Figure 5: Period of No Available Data for ATSDR's Model Reconstruction in Tarawa Terrace**

**In Summary (Opinion 2): All of this is to say that the data ATSDR had to inform its modeling for reconstructing thirty years of historical aquifer conditions were extremely limited. Data that were available only existed for short time periods mainly between 1982 and 1985. As illustrated by the yellow highlighted area in Figure 5,[164] ATSDR calibrated a model with limited to no data to constrain that calibration. In some sense, this is like fitting a line to a point. Even after expert knowledge is applied, there are multiple configurations of model outputs that could fit the observed data, just as there are multiple ways to fit a line to a point. Although ATSDR attempted to quantify that uncertainty, certain parameter ranges they used in their uncertainty analysis did not encompass the full range of values known from site specific data, resulting in biased high estimates.**

### 4.1.2 ATSDR's Model Calibration was Based on Limited Data and was Biased High

ATSDR conducted its calibration of the TT groundwater flow model relying on a limited dataset. According to ATSDR, *"[h]istorical water level data were mainly unavailable prior to 1978, with the exception of one or two measurements at the time of construction of several wells*."[165] Furthermore, "*[w]ell construction data also were somewhat limited and possibly affected the assignment of pumpage to model layers*."[166] Hence, monthly pumping rates of all wells in the model were developed using a complex reconstruction process based on assumptions. These rates were fixed but uncertain, and underpinned model performance.

[164] ATSDR-TT, Chapter F, pp. F34 and F43

[165] ATSDR-TT, Chapter C, p. C38

[166] ATSDR-TT, Chapter C, p. C39

As ATSDR admitted, "*for the most part, simulation results are unqualified for the years 1951-1977, based on comparisons of observed and simulated water levels.*"[167]

The contaminant transport model was constructed based on numerous assumptions on parameter values as site specific data were limited or nonexistent. Also, the timing of releases from the source at ABC One-Hour Cleaners and the magnitude of its contributions to contamination were uncertain. This means that there are legitimate questions about whether ATSDR's model reconstruction of historical concentrations is accurate. This is especially true considering that ATSDR admitted that "*simulated PCE concentrations moderately to substantially overpredicted observed concentrations at water-supply wells*."[168] Mr. Maslia acknowledged "it overpredicts" in his 2024 deposition.[169]

For its model calibration, ATSDR considered 36 observed PCE concentrations at water-supply wells from samples collected at different times in 1985 (29 samples) and July 1991 (7 samples). ATSDR considered a calibration target range of "+/- one-half order of magnitude range" of the observed concentration.[170] Figure 6 shows ATSDR's Table F13, with its model calibration results, including simulated and observed PCE concentrations at the water supply wells, and the corresponding calibrated target range for each well.

[167] ATSDR-TT, Chapter C, p. C38

[168] ATSDR-TT, Chapter F, p. F33

[169] Maslia (2024), Deposition, September 26, p. 228.

[170] ATSDR-TT, Chapter F, p. F32

**Table F13.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply wells and calibration target range, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; J, estimated]

| Site name | Date | PCE concentration, in µg/L | | Calibrated target range, in µg/L |
|---|---|---|---|---|
| | | Observed | Simulated | |
| [1]RW1 | 7/12/1991 | ND | 0.0 | 0.0–2.0 |
| [1]RW2 | 7/12/1991 | 760 | 1,804 | 240–2,403 |
| [1]RW3 | 7/12/1991 | ND | 0.0 | 0.0–2.0 |
| [2]TT-23 | 1/16/1985 | 132 | 254 | 41.7–417 |
| | 2/12/1985 | 37.0 | 254 | 11.7–117 |
| | 2/19/1985 | 26.2 | 253 | 8.3–82.8 |
| | 2/19/1985 | ND | 253 | 0.0–10.0 |
| | 3/11/1985 | 14.9 | 253 | 4.7–47.1 |
| | 3/11/1985 | 16.0 | 253 | 5.2–52.5 |
| | 3/12/1985 | 40.6 | 253 | 12.8–128 |
| | 3/12/1985 | 48.0 | 253 | 15.4–154 |
| | 4/9/1985 | ND | 265 | 0.0–2.0 |
| | 9/25/1985 | 4.0 | 279 | 0.3–12.6 |
| | 7/11/1991 | ND | 193 | 0.0–5.0 |
| [2]TT-25 | 2/5/1985 | ND | 6.2 | 0.0–10.0 |
| | 4/9/1985 | ND | 8.6 | 0.0–2.0 |
| | 9/25/1985 | 0.43J | 18.1 | 0.14–1.4 |
| | 10/29/1985 | ND | 20.4 | 0.0–10.0 |
| | 11/4/1985 | ND | 20.4 | 0.0–10.0 |
| | 11/13/1985 | ND | 20.4 | 0.0–10.0 |
| | 12/3/1985 | ND | 22.8 | 0.0–10.0 |
| | 7/11/1991 | 23.0 | 72.6 | 7.3–72.7 |
| [2]TT-26 | 1/16/1985 | 1,580 | 804 | 500–5,000 |
| | 2/12/1985 | 3.8 | 804 | 1.2–12 |
| | 2/19/1985 | 55.2 | 798 | 17.5–175 |
| | 2/19/1985 | 64.0 | 798 | 20.2–202 |
| | 4/9/1985 | 630 | 801 | 199–1,999 |
| | 6/24/1985 | 1,160 | 732 | 367–3,668 |
| | 9/25/1985 | 1,100 | 788 | 348–3,478 |
| | 7/11/1991 | 340 | 670 | 111–1,107 |
| [2]TT-30 | 2/6/1985 | ND | 0.0 | 0.0–10.0 |
| [2]TT-31 | 2/6/1985 | ND | 0.15 | 0.0–10.0 |
| [2]TT-52 | 2/6/1985 | ND | 0.0 | 0.0–10.0 |
| [2]TT-54 | 2/6/1985 | ND | 5.8 | 0.0–10.0 |
| | 7/11/1991 | ND | 30.4 | 0.0–5.0 |
| [2]TT-67 | 2/6/1985 | ND | 3.9 | 0.0–10.0 |

[1]See Figure F6 for location

[2]See Figure F1 for location

Note: Calibration target ranges for analyses listed as not detected are detection limits noted in Table F2

**Figure 6: Simulated and Observed PCE Concentrations at Water Supply Wells in Tarawa Terrace (ATSDR, Table F13, Chapter F)**

According to ATSDR "*[o]f the total of 36 comparisons of simulated to observed PCE concentrations in all water-supply wells used to calibrate the Tarawa Terrace fate and transport model (Table F13), including 'non-detected' results, 17 comparisons or 47 percent conformed to the calibration standard, and 19 comparisons or 53 percent violated the standard*."[171] ATSDR also calculated the geometric bias of the calibrated model, which is another type of metric for comparing simulated and observed values.[172] A geometric bias of 1.0 indicates perfect agreement between the two sets of values. ATSDR calculated the geometric bias of its calibrated model for the 19 pairs of values corresponding to detection (i.e., excluding non-detections).[173] The calculated geometric bias was 5.9, much higher than 1.0, indicating a biased-high calibrated model.

A statistical evaluation of the contaminant transport model calibration for the entire historical period could not be performed as observed data were not available prior to 1985. Hence, the resulting model, which describes thirty years of aquifer conditions beginning in 1951 and attempts to reconstruct potential contamination in the aquifer during those years, was calibrated to limited water-quality data available only after 1985. The calibrated model was biased high.

In his 2011 paper in *Groundwater*, [174] Dr. Clement expressed concerns about the fact that the ATSDR "*model was calibrated to limited number of datapoints*." Maslia et al., in their editorial response to Dr. Clement's paper in the same journal in 2012,[175] indicated that ATSDR completed a four-stage calibration process. However, they never addressed the main point of Dr. Clement's opinion regarding the lack of historical water-quality data for model calibration.

**In Summary (Opinion 2): ATSDR's model calibration did not rely on observed data prior to 1984. In fact, the model was calibrated to a very limited dataset even after 1984. Calibration statistics indicate that estimated monthly contaminant concentrations were conservative and biased-high.**

In this section, I focus on certain assumptions and parameters due to their significant impact on the model results. It should be noted that this discussion is not intended to be inclusive of all assumptions or parameters I believe were inappropriately selected.

#### 4.1.2.1 The PCE Source Release Start Date at ABC One-Hour Cleaners Was Incorrect.

In its contaminant transport model, ATSDR represented the PCE contamination source at Tarawa Terrace as ABC One-Hour Cleaners. ATSDR used a constant mass loading term, which means that the same amount of contaminant mass was modeled to enter the groundwater every day, for the entire period this source was in place. ATSDR assumed the source was active from January 1, 1953, to December 31, 1984. However, as discussed extensively in the expert report of Dr. Brigham, this start date is likely incorrect. According to Dr. Brigham, ABC One-Hour Cleaners opened in June 1954. Based on my review of Dr. Brigham's expert report, July 1, 1954, is a more appropriate start date for the release of PCE into the soil at ABC One-Hour Cleaners. The impact of this discrepancy in release start dates is that the PCE plume reached the water supply wells sooner in ATSDR's model.

**In Summary (Opinion 2): ATSDR's model was constructed based on incorrect information regarding the start date of contaminant releases from ABC One-Hour Cleaners. This incorrect assumption resulted in estimated monthly contaminant concentrations that were conservative and biased-high in the early 1950s.**

---

[171] ATSDR-TT, Chapter F, p. F33

[172] Geometric bias is the mean value of the logarithmic ratios of simulated to observed values

[173] ATSDR-TT, Chapter F, p. F33

[174] Clement (2011)

[175] Maslia et al. (2012)

#### 4.1.2.2 Selected Geochemical Parameters Were Incorrect

As discussed in the expert report of Dr. Hennet (2024), one of the most important parameters in characterizing the rate of migration of a contaminant plume is its retardation. If a contaminant plume's migration is not retarded relative to groundwater flow, the retardation factor is equal to 1, and the contaminant moves at the same velocity as the groundwater. When a contaminant's velocity is slower than groundwater , the retardation factor is greater than 1. The retardation factor is calculated using the distribution coefficient of the contaminant ($K_d$), the dry bulk density of the aquifer ($\rho_b$), and the total porosity of the aquifer (n). Wiedemeier et al. (1999) provide a more extensive discussion on the calculation of the retardation factor.[176]

ATSDR miscalculated one of the parameters in the retardation factor, the bulk density. Below is a discussion on how the components of the retardation factor were defined by ATSDR and where the error was made.

##### 4.1.2.2.1 Bulk Density Value was Incorrect

Data for the dry bulk density of the aquifer were not available. To estimate the dry bulk density, the specific gravity ($G_s$) of the soil, the density of water ($\rho_w$), and the aquifer total porosity (n) are required. ATSDR referred to literature sources for ranges of these properties that are appropriate for soils encountered at Camp Lejeune. Morris and Johnson (1967) analyzed hundreds of sand, clay, and silt samples, and reported associated ranges of specific gravity for each group. Based on these ranges, ATSDR assigned a specific gravity of 2.7 to all sediments represented by the seven layers of the MT3DMS model. The density of water is equal to 1,000 g/cm$^3$. Total porosity estimated from two samples collected in the vicinity of ABC One-Hour Cleaners was 32.9% for the clayey sand, and 36.5% for the silty sand.

To calculate the bulk density, the following formula is used:[177]

$$\rho_b = \frac{Gs \times \rho_w}{1 + \frac{n}{1-n}}$$

ATSDR calculated the bulk density of the aquifer to be 170 pounds per cubic foot (lbs/ft$^3$) or 77,100 grams per cubic foot (g/ft$^3$). When this value is converted to g/cm$^3$, it is equal to 2.7 g/cm$^3$. This number is not characteristic of soils at Camp Lejeune, as ATSDR later indicated in their analysis for Hadnot Point.[178] Closer inspection of the calculated value indicates that ATSDR did not apply this formula in its entirety; the denominator in this fraction was never included in the calculation. As a result, the calculated bulk density was much higher than it should have been. This has a significant impact on the calculation of the retardation factor, resulting in faster (sooner) arrival of PCE at the water-supply wells, as will be described in Section 4.1.3.2. In the Hadnot Point model, this error was not repeated. ATSDR used a value of 1.65 g/cm$^3$, or 46,700 g/ft$^3$, as was found in the literature for soils in Camp Lejeune.[179]

##### 4.1.2.2.2 Distribution Coefficient ($K_d$) Value was Out of Range and Biased Low

ATSDR indicated that no site-specific data were available for estimating the $K_d$. For that reason, they referred to literature sources for $K_d$ values, for soils similar to those encountered at Camp Lejeune.[180] According to this literature source, the range of $K_d$ values was:

---

[176] Wiedemeier et al. (1999), p. 142-43

[177] Wiedemeier et al. (1999), p. 142-43

[178] ATSDR-TT, Chapter A, Supplement 6, p. S6.14

[179] ATSDR-HP, Chapter A, Supplement 6, p. S6.14

[180] ATSDR-TT, Chapter F, p. F28

- 0.25-0.76 mL/g, averaging 0.39 mL/g, for sands;
- 0.21-0.71 mL/g, averaging 0.40 mL/g, for silts; and

ATSDR used a mean value of 0.40 mL/g as the starting value in the model calibration process. However, the final $K_d$ value, determined by ATSDR through model calibration, was 0.14 mL/g. This value is out of range for the soils in the aquifer at Camp Lejeune. In addition, this value was more than two times lower than the value used by ATSDR for PCE in the Hadnot Point model, despite ATSDR's statement that the same aquifers are encountered in both models.[181] ATSDR ultimately selected a $K_d$ value of 0.30 mL/g for PCE, through "*refinement during the model calibration process*."[182]

The reason for this significant drop in the $K_d$ value estimated by ATSDR during model calibration is the erroneous value for the bulk density that ATSDR calculated, as discussed above.

#### 4.1.2.3 ATSDR's $K_d$ Adjustments During Model Calibration were Biased Low

To compensate for the erroneously calculated bulk density, ATSDR's calibrated $K_d$ value was below the range that ATSDR considered reasonable for the soil types at Camp Lejeune. Note that ATSDR did not make the same mistake with the bulk density in the Hadnot Point model, meaning they corrected the bulk density and $K_d$ values later. However, they did not return to the Tarawa Terrace model to make adjustments based on this knowledge.

ATSDR started the calibration process using parameter values that were based on assumptions considering limited data and, mainly, literature sources. As mentioned above, one of the parameters that was adjusted during model calibration was the distribution coefficient ($K_d$). The starting value of 0.40 mL/g corresponded to a retardation factor of 6.44.[183] This starting $K_d$ value was reduced by a factor of 3, to 0.14 mL/g, for a retardation factor of 2.93.

If ATSDR had used a retardation factor of 6.44, corresponding to the initial $K_d$ value of 0.40 mL/g, this would have resulted in slower migration of the PCE plume that originated from ABC One-Hour Cleaners and reached well TT-26 first. It would also have resulted in lower concentrations at well TT-26 as more mass would have been sorbed by the soils. However, ATSDR selected the much lower $K_d$ value and, therefore, retardation rate, resulting in a PCE plume that arrived sooner at well TT-26 than it would have if a higher retardation rate were selected. As a result, ATSDR estimated that there were higher PCE concentrations in the influent to the WTP at earlier times than there would have been if the higher retardation factor were selected.

**In Summary (Opinions 2 and 3): ATSDR's model was constructed based on parameter values that were either incorrect (bulk density) or out of range ($K_d$). Parameter values were not based on site-specific data but obtained from literature sources. In addition, parameter values in the Tarawa**

---

[181] "Because field data describing contaminant fate and transport parameters is lacking for the HPHB study area and the TT study area is adjacent to the HPHB study area, the probability density functions described by Maslia et al. (2009) were used to generate a range of transport parameters values for the analyses reported herein." ATSDR-TT, Chapter A, Supplement 6, p. S6.34

[182] ATSDR assumed an $f_{oc}$ value of 0.002, and a range of $K_{oc}$ values from the literature (ATSDR-TT, Chapter A, Supplement 6, Table S6.4, p. S6.14). In that same table, ATSDR provided the corresponding calculated range of $K_d$ values for PCE, varying between 0.03 and 21.43 mL/g (the $K_d$ numerical value is the same when units of L/kg are used).

[183] ATSDR considered values of effective porosity from literature sources for soils similar to those in Camp Lejeune. The analysis of soil samples from the literature source cited by ATSDR provided the basis for the estimates ATSDR considered. According to this analysis, and for the fine silty and clayey sands in the aquifer system in Camp Lejeune, the effective porosity is about 20%, which is the value used by ATSDR in the model (ATSDR-TT, Chapter F, p. F28)

**Terrace model were different than those used in the Hadnot Point model, even though both models simulated similar hydrogeologic conditions. These incorrect assumptions resulted in faster plume migration in the aquifer and estimated monthly contaminant concentrations that were conservative and biased-high.**

#### 4.1.2.4 Site-Specific Data for Calculating $K_d$ Resulted in Higher $K_d$ Value

As mentioned earlier, ATSDR considered reported values from literature sources for estimating a $K_d$ value for PCE, for soils such as those at Camp Lejeune. However, site-specific data were available for the calculation of $K_d$. Site-specific total organic carbon data (TOC) were available from samples collected between 1997 and 2007. These data can be used to calculate the soil-specific parameter, $f_{oc}$, representing the fraction of organic carbon in the soil or sediment. To calculate the $K_d$, $f_{oc}$ is multiplied by the compound-specific parameter, $K_{oc}$.[184] $K_{oc}$ is a constant representing the organic carbon partition coefficient, (i.e., the partitioning of a contaminant between organic carbon in the solid phase and the aqueous phase) and can be found in the literature. In fact, ATSDR listed compound-specific values for the contaminants considered in Camp Lejeune in their Table D12.[185] A tabulated list of the available data is provided in Appendix A.

The available data included some very low and very high values. To remove the potential effect of such very high or very low values on the calculation of the mean $K_d$, I calculated the geometric mean of the range instead. The geometric mean is less sensitive to extreme values, providing a measure that reflects the central tendency without being heavily influenced by very high or very low values. The geometric mean value for samples from all depths was 0.40 mL/g. When considering only samples collected near and below the water table (i.e., depths equal to or greater than 10 feet), the corresponding geometric mean was 0.42 mL/g. Both these values are greater than the value of 0.14 mL/g that ATSDR determined through model calibration.

Very high or very low $K_d$ values can skew the calculated mean $K_d$ value.[186] To further remove the impacts of very high or very low values in the dataset, I calculated the median value of the available data for samples from all depths, and from samples collected near and below the water table. The corresponding median values were 0.40 and 0.30 mL/g, respectively. These values are within the range that ATSDR considered from the literature for soils similar to those encountered in Camp Lejeune.

I calculated retardation factors corresponding to $K_d$ values of 0.30 and 0.40 mL/g. For this calculation I used a bulk density of 1.65 g/cm$^3$ (which is appropriate for soils of the type found at Camp Lejeune and used by ATSDR later in their Hadnot Point model), and not the erroneous 2.7 g/cm$^3$ in ATSDR's calibrated model for Tarawa Terrace. I also used a porosity value of 20%, which is consistent with the value in the ATSDR model. The corresponding retardation factors for $K_d$ values of 0.30 and 0.40 mL/g were 3.48 and 4.30, respectively, which are both greater than ATSDR's calibrated value of 2.93.

#### 4.1.2.5 Model Estimated Monthly Contaminant Concentrations in the Influent to the WTP Would be Lower if the Source Starting Date and $K_d$ Value Were Adjusted to Site-Specific Data

The resulting historical reconstruction of PCE concentrations at well TT-26 and the influent to the water treatment plant would be different if the following adjustments to the ATSDR model were made:

- Correct starting date for the ABC One-Hour Cleaners source (July 1, 1954); and

[184] Wiedemeier et al. (1999), p. 145

[185] ATSDR-TT, Chapter D, p. D15

[186] Helsel et al. (2020), p. 2

- $K_d$ value equal to 0.3. This value corresponds to the median value of the site-specific data and is equal to the value ATSDR used in Hadnot Point. The corresponding retardation factor is 3.48.

The resulting historical reconstruction of PCE concentrations at well TT-26 and the influent to the WTP are depicted in Figure 7 and Figure 8, respectively. These graphical representations serve only to demonstrate how variable the model outputs are to changes in parameters. They should not be interpreted as definitive, mean monthly concentrations of contaminants in the influent to the WTP.

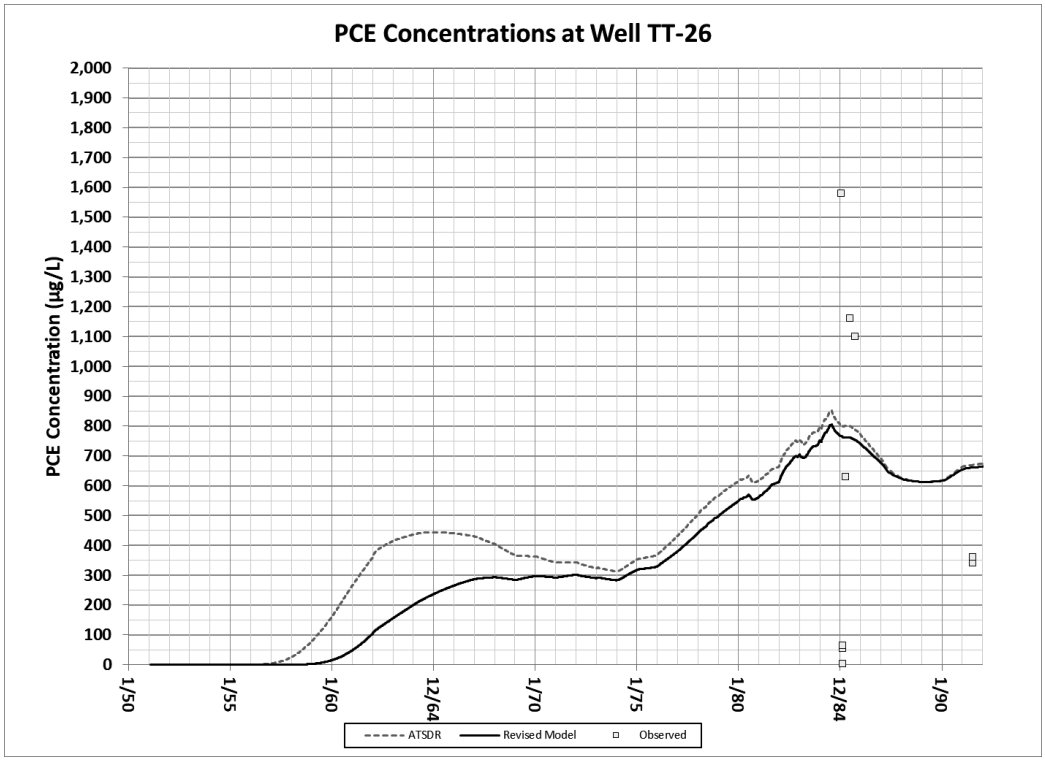



**Figure 7: Model Simulated PCE Concentrations at Well TT-26 for Corrected Source Date and Retardation Factor 3.48**

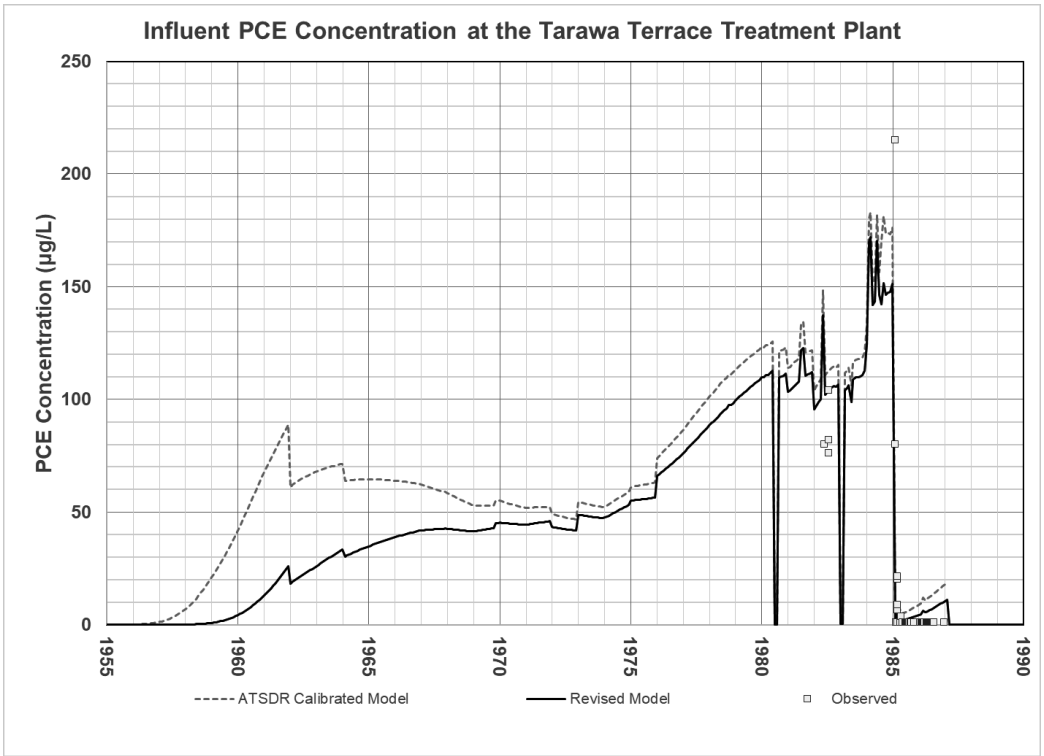



**Figure 8: Model Simulated PCE Concentrations in the Influent to the TT WTP for Corrected Source Date and Retardation Factor 3.48**

**In Summary (Opinion 4): These model results illustrate how the ATSDR calibrated model, adjusted only to account for site-specific data for $K_d$, and correct implementation of the continuing source at ABC One-Hour Cleaners, estimates a historical reconstruction that fits the data equally well. It also indicates (a) a slower arrival of contamination to well TT-26 and, therefore, the influent to the WTP, and (b) much lower concentrations than those calculated by ATSDR over a period of about 15 years from the initial PCE releases. The uncertainty range for such historical reconstruction would also be lower, as it would be based on slower plume migration and lower concentrations for many years after the start of contaminant releases from the source.**

**This also demonstrates that using a groundwater model for hindcasting is highly uncertain in the absence of site-specific data for assigning parameter values and a lack of observed data to constrain the model calibration. While professional judgment is essential in model construction, it cannot guarantee model accuracy absent these data.**

#### 4.1.2.6 Elevated Concentrations at Pumping Well TT-23 Are Biased High and Inflate WTP Concentrations

The ATSDR model calculated monthly concentrations at each well. ATSDR argued that those concentrations were within the calibration standards. However, concentrations at TT-23 were much higher, almost two times as high as the measured concentrations. In addition, following the well being shut down, measured concentrations dropped precipitously to non-detections, but ATSDR model's simulated concentrations remained elevated.

ATSDR explained this discrepancy by suggesting different factors for the elevated model-simulated concentrations.[187] It is not possible to test ASTDR's hypotheses for explaining these enormous differences. ATSDR contended that such factors are not built into the model, and therefore, the simulated concentrations would inevitably be higher than the measured ones.

Nonetheless, ATSDR did not apply any adjustment to the simulated concentrations to reflect the admittedly lower concentrations at TT-23. Instead, ATSDR used those high model-simulated concentrations in their mixing model, thereby inflating the calculated PCE concentrations in the influent to the WTP.

**In Summary (Opinion 5): ATSDR's model simulated substantially higher concentrations at supply well TT-23 than indicated by observed data. Although ATSDR admitted the discrepancy, they did not correct these elevated concentrations before using them for calculating the mixed concentration in the influent to the WTP. As a result, they inflated the estimated monthly contaminant concentrations at the WTP for several months during which well TT-23 was in service.**

#### 4.1.2.7 ATSDR's Model Calibration Did Not Fully Consider Non-Detections and Overestimated Plume Migration

Comparing the observed versus simulated concentrations highlights additional issues regarding model performance. ATSDR included non-detections in its model calibration, but the calibrated model did not reflect those observed non-detections.

ATSDR constructed a scatterplot of simulated and observed PCE concentrations.[188] Non-detections were not shown in that figure, as non-detections listed as zeros are not visible in a logarithmic-scale scatterplot. This is because a logarithmic scale can only show numbers greater than zero. I replaced the observed non-detections with a value of 0.1 and I reconstructed the scatterplot so that observed non-detections are not hidden from the plot. Figure 9 shows both scatterplots for comparison.

In the plot on the right in Figure 9, the points along the vertical axis indicate non-detections in field samples corresponding to higher concentrations calculated by the model, encompassing a range that extends to hundreds of micrograms per liter (μg/L). Most of these calculated concentrations are within ATSDR's arbitrary range of acceptable calibration results. But, this reveals some important issues with the calculated concentration trends.

[187] ATSDR-TT, Chapter A, p. A25; ATSDR-TT, Chapter F, p. F32

[188] ATSDR-TT, Chapter F, Figure F12, p. F33

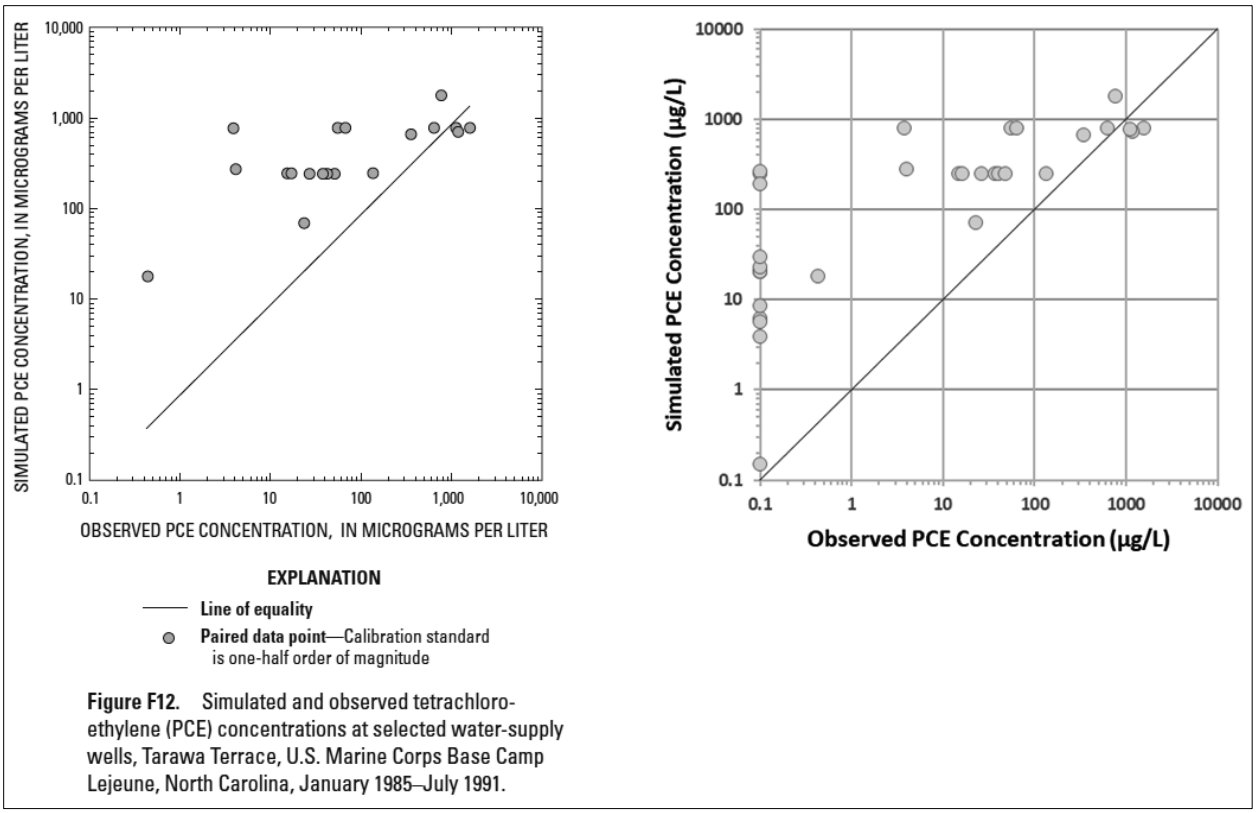



**Figure F12.** Simulated and observed tetrachloroethylene (PCE) concentrations at selected water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1985–July 1991.

**Figure 9: Comparison of Calibration Scatterplots With and Without Non-Detections**

Figure 10 shows the plots produced by ATSDR, illustrating the historical reconstruction of concentrations at the pumping wells based on the calibrated model results, against the available observed concentrations.[189] Brown arrows have been added to those plots to indicate periods when simulated concentrations trend upward, contrary to what the observed data indicate. Also, red arrows have been added to indicate the significant discrepancies between simulated and observed data.

According to plot F15 for well TT-25, model results indicate that PCE arrived at that well around 1983 and concentrations continued increasing. It should be noted that this plot only shows the reported J-value[190] of 0.48 µg/L in September 1985, and not the additional observed data listed in ATSDR's Table F13, which indicate non-detections from February to December 1985. It should also be noted that the horizontal axis in this plot is not at a scale appropriate for clearly identifying the dates of the individual samples.[191]

[189] Plots of simulated and observed PCE concentrations in wells (ATSDR-TT, Chapter F, pp. F34 and F35); PCE plume map in model Layer 3 in December 1984 (ATSDR-TT, Chapter F, p. F40).

[190] J values represent a reported concentration below the detection limit of the instrument for the implemented method of analysis in the laboratory, but with sufficient "noise" to be estimated at a very low level.

[191] It appears that the single observed data point is not plotted at the correct date, as the model-simulated concentration at that date is much higher than the value of 0.48J of September 25, 1985, reported in ATSDR's Table F13 (ATSDR-TT, Chapter F, p. F33).

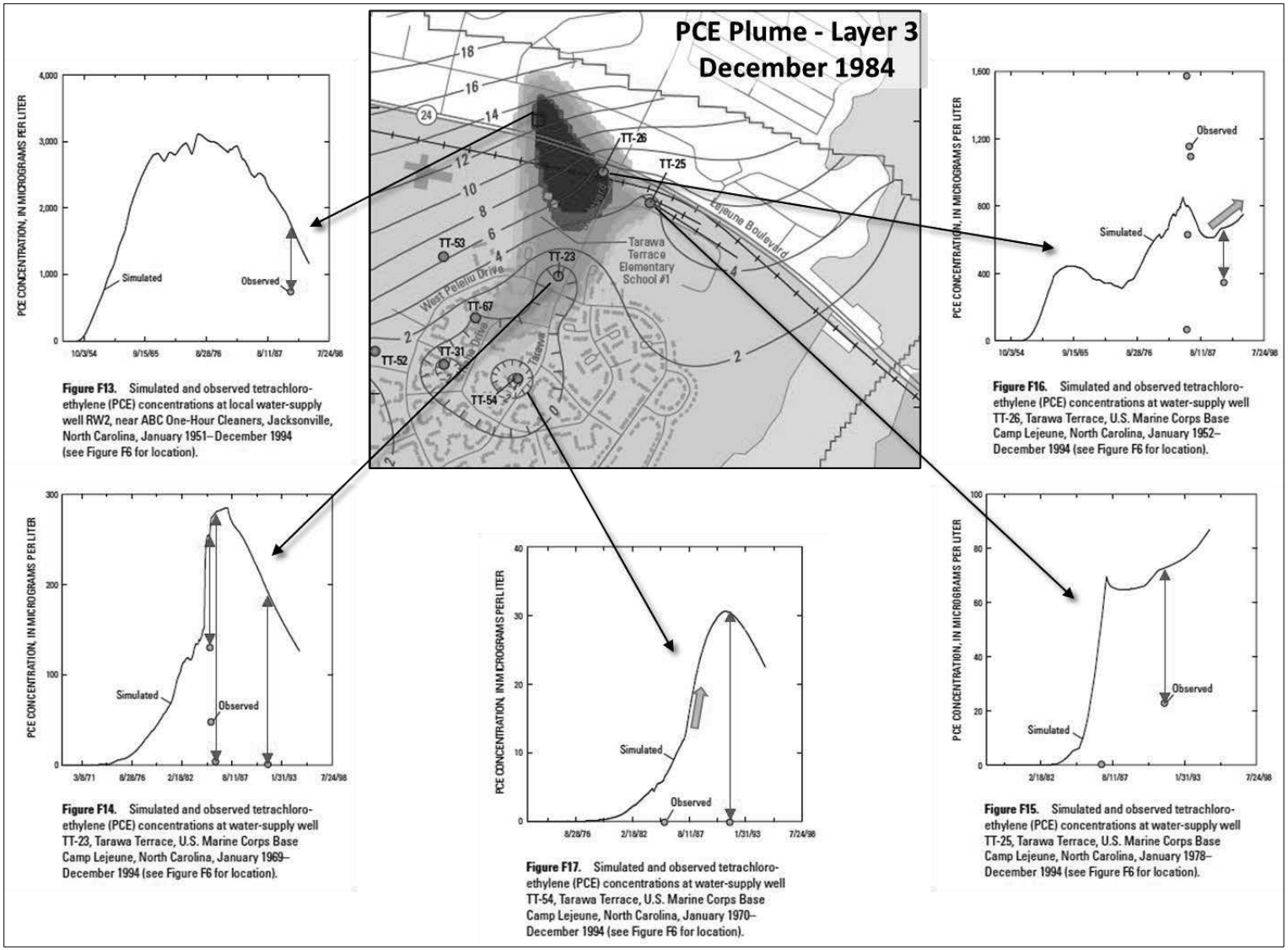



**Figure F13.** Simulated and observed tetrachloroethylene (PCE) concentrations at local water-supply well RW2, near ABC One-Hour Cleaners, Jacksonville, North Carolina, January 1951–December 1994 (see Figure F6 for location).

**Figure F16.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1952–December 1994 (see Figure F6 for location).

**Figure F14.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-23, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1969–December 1994 (see Figure F6 for location).

**Figure F17.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-54, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1970–December 1994 (see Figure F6 for location).

**Figure F15.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-25, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1978–December 1994 (see Figure F6 for location).

**Figure 10: Comparison of Observed and ATSDR Model-Calculated Concentrations at Pumping Wells**

The model results also indicate a low value of 5.8 µg/L at the distant pumping well TT-54, south of well TT-23 in February 1985, when the observed value is non-detection. In fact, plot F17 indicates that the calibrated model estimated the first arrival of the PCE plume at that well around 1978, with concentrations increasing after that time. This is not supported by the non-detection in the sample collected in February 1985.

After 1985, when the wells were shut down, concentrations simulated by the ATSDR model continued to rise. However, reported concentrations from groundwater samples taken at wells TT-26, TT-25 and TT-23 indicated decreasing concentrations, compared to the period when the wells were operating (plots F15 and F16 in Figure 10).

The discrepancies between observed and simulated concentrations at well TT-23 (Section 4.1.2.6) are illustrated in plot F14 in Figure 10.

Well TT-54 had a reported non-detection in July 1991. However, the ATSDR model indicated an increasing concentration trend at well TT-54, suggesting that the PCE plume continued arriving at that well until that time.

This is unlikely to be accurate. ATSDR's Tarawa Terrace model results overestimated observed concentrations, the extent of the contaminant plume, and simulated concentrations after the pumping wells were turned off.

**In Summary (Opinion 6): The model was not reliably calibrated. Model results indicate biased-high estimates of contaminant mass in the aquifer, where observed data indicate the absence of contamination. Simulated concentrations at well TT-26 andwell TT-54, located thousands of feet south of well TT-26, trended upward when observed data indicated a downward trend or no contamination, respectively. ATSDR's model overestimated the plume migration extent and rate of migration, which were both conservative and biased-high.**

### 4.1.3 ATSDR's Uncertainty Analysis was Limited and Biased-High

ATSDR states that the Tarawa Terrace groundwater model is "*subject to varying degrees of uncertainty which are associated with: (1) limited or lack of data, (2) erroneous data due to precision and accuracy limitations, and (3) simplifications of mathematical equations represented by the model*."[192] However, according to ATSDR, "*[t]hese probabilistic results provide additional confidence that the deterministically derived results (for example, the historically reconstructed PCE concentrations in Tarawa Terrace finished water) are reasonable and conform well to field observations and data."*[193]

Regarding model calibration and uncertainty analysis, "*realizations are all constrained by the necessity to respect expert knowledge and the need to allow the model to replicate observed system behavior*."[194] It is therefore important for the model to "replicate observed system behavior." Here, observed system behavior refers to the measured or observed data taken from Tarawa Terrace water supply wells and the WTP. Recall the discussion on model precision and accuracy.

The uncertainty analysis of ATSDR's Tarawa Terrace model did not consider the "observed system behavior," as historical data were not available to guide this analysis. Recall (Section 4.1.2) that Dr. Clement expressed concerns about the fact that the ATSDR "*model was calibrated to limited number of*

[192] ATSDR-TT, Chapter I, p. I3

[193] ATSDR-TT, Chapter I, p. I54

[194] Sepulveda and Doherty (2015)

*datapoints*,"[195] which Maslia et al. (2012) did not address in their response. As a result, the calibrated model and uncertainty analysis focused on model precision and not accuracy. Recall Figure 2 in Section 3.1.5: ATSDR's calibration and uncertainty analyses results are precise but not accurate, as described by the bottom-left bullseye in the graphic.

As will be discussed in the following sections, ATSDR's uncertainty analysis relied solely on the parameters and results of the calibrated model for estimating its uncertainty range, on the premise that the calibrated model successfully reconstructed the history of contamination at the site. The significant implications of the lack of historical data and assumptions made by ATSDR and implemented in the model are discussed below.

#### 4.1.3.1 ATSDR's Presentation of Uncertainty Analysis Results is Visually Misleading

ATSDR stated that the uncertainty analysis they conducted provides confidence that model results are reasonable and conform to observed data. However, ATSDR's presentation of its uncertainty analysis results is visually misleading because they used a logarithmic scale, which visually compresses the uncertainty range around their calibrated model. In Figure 11, the uncertainty range appears to be a narrow band enveloping the calibrated model. However, the logarithmic scale for PCE concentrations on the vertical axis of Figure 11 spans over six orders of magnitude.[196]

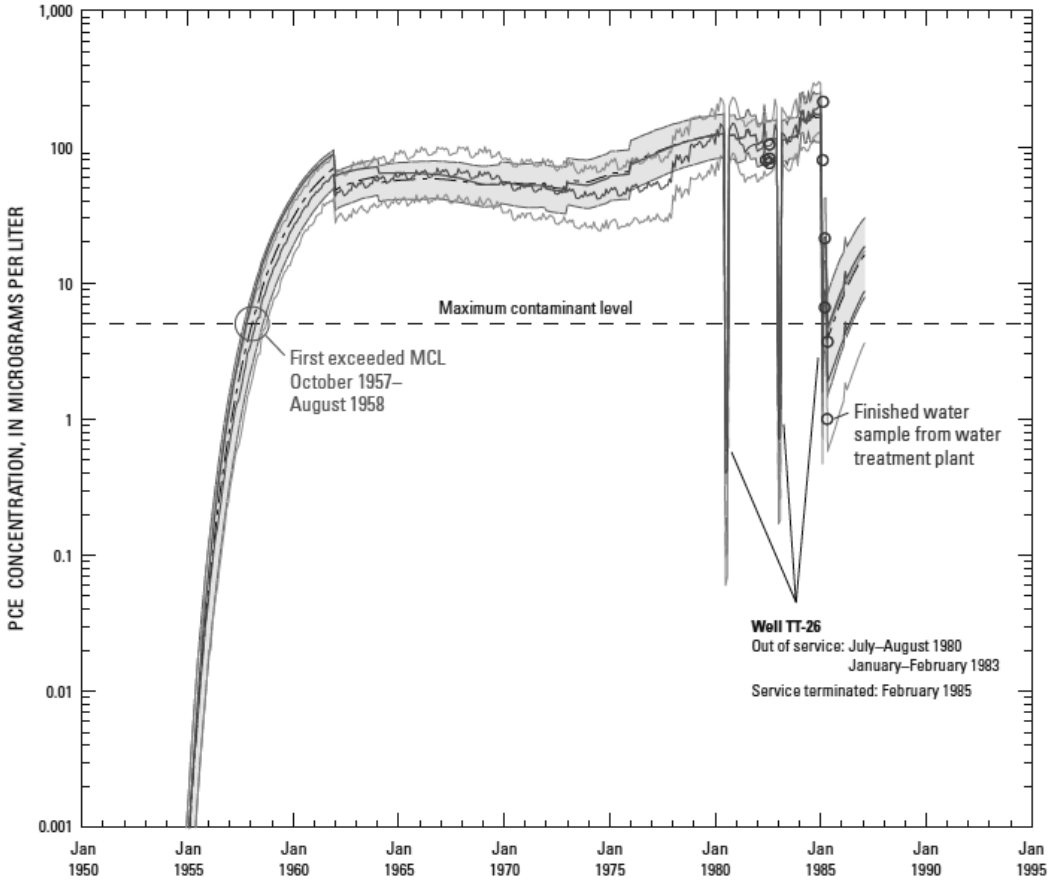
Logarithmic scales are appropriately used to visualize a wide range of values, where data span many orders of magnitude. This makes it easier to visualize and compare results. However, the difference between the high and low values in Figure 11 is not significant enough to justify the use of a logarithmic scale. The reconstructed historical concentrations only vary between non-detections and about 200 µg/L, i.e., a range of approximately two orders of magnitude, and not the six orders of magnitude displayed on Figure 11. By displaying a wide range of simulated PCE concentrations increasing exponentially, Figure 11 visually condenses the range of uncertainty around the calibrated model. This is not appropriate for the data presented in the figure, because the extent of the uncertainty range and the performance of the calibrated model within that range are not easily visible.

For these data, an arithmetic scale would be more appropriate to illustrate the extent of uncertainty range in a visually-accurate manner. A modified version of Figure 11 using an arithmetic scale for PCE concentrations on the Y-axis is provided in Figure 12.

Figure 12 depicts the uncertainty range calculated by ATSDR for two scenarios: (a) without considering pumping uncertainty (yellow shaded area), and (b) including pumping uncertainty (red lines). Also shown in this figure is the historical reconstruction of PCE concentrations in the influent to the WTP, simulated by ATSDR's calibrated model (black line).

[195] Clement (2011)

[196] An order of magnitude is a range of magnitude extending from some value to ten times that value (Merriam-Webster Dictionary). For example, the values 12 and 120 are separated by an order of magnitude. More generally, the values 12 and 253 can be said that they are separated by about an order of magnitude.



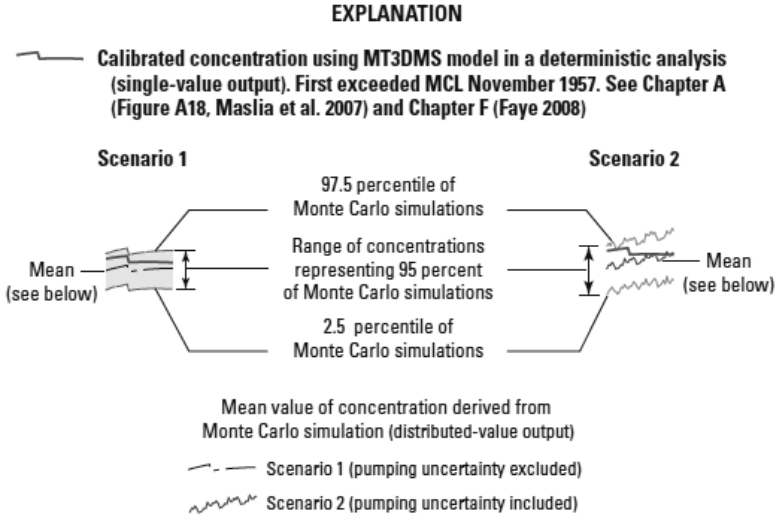




**Figure I29.** Concentrations of tetrachloroethylene in finished water at the water treatment plant derived from scenario 1 (pumping uncertainty excluded) and scenario 2 (pumping uncertainty included) probabilistic analyses using Monte Carlo simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.
[See Appendix I5 for tabular listing; PCE, tetrachloroethylene; MCL, maximum contaminant level]

**Figure 11: Copy of Figure I29 from ATSDR's Probabilistic Analysis**

As shown in Figure 12, concentrations calculated by the calibrated model are at the upper bound of the uncertainty range in the early years. In a rigorously conducted uncertainty analysis, the concentrations calculated by the calibrated model should be generally in the middle of the uncertainty range (Section 3.1.5). However, the calibrated model-simulated concentrations are almost identical to the upper bound of the uncertainty range in the early years of operation (1957-1963). This demonstrates that the simulated arrival times of PCE at well TT-26 and, as a result, at the WTP, are biased early. Plume migration in the calibrated model is biased high due to the retardation factor selected by ATSDR.

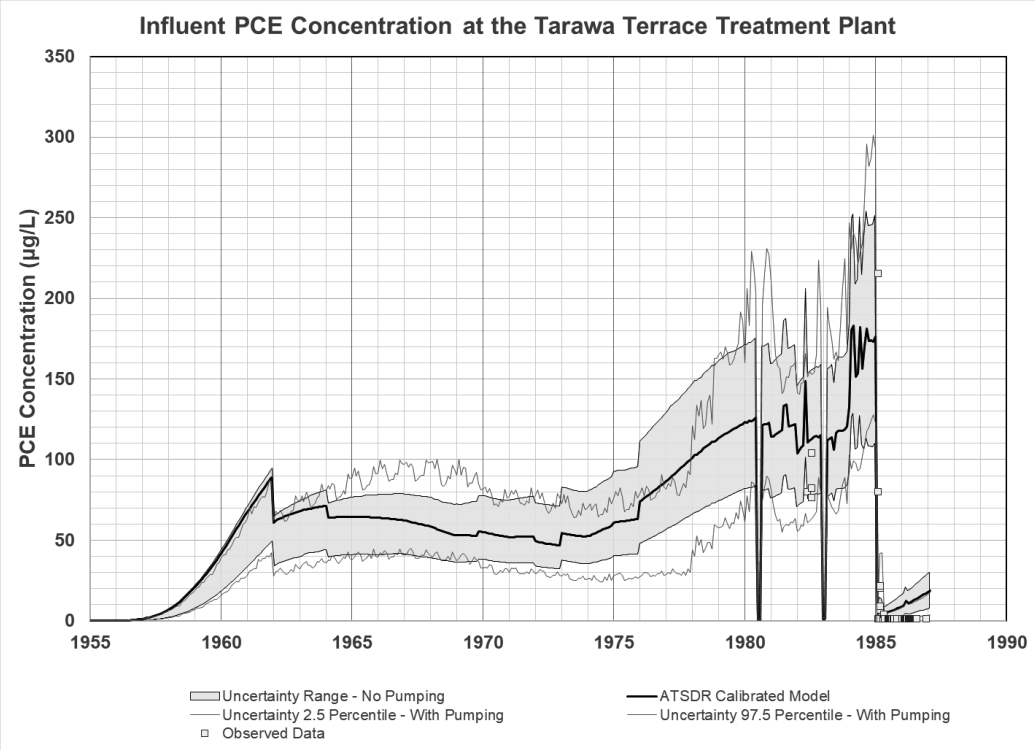



**Figure 12: Reconstruction of ATSDR's Figure I29 - Probabilistic Analysis in Linear Scale**

**In Summary (Opinion 7): ATSDR presented the results of the uncertainty analysis using a format that was visually misleading. The choice of a logarithmic scale ranging over six orders of magnitude depicted a narrow uncertainty range around the calibrated model. However, using a linear scale for the same graph, the results indicate that the uncertainty range is broad and the estimated monthly concentrations are conservative and biased-high in the early years.**

#### 4.1.3.2 ATSDR's Parameter Ranges in the Uncertainty Analysis are Narrow and Biased

As discussed above in Section 3.1.5, an uncertainty analysis is designed to provide a range of possible model outcomes. A Monte Carlo uncertainty analysis, such as the analysis implemented by ATSDR, is a probabilistic uncertainty analysis. Its goal is to quantify the range and likelihood of model outputs.[197] This is accomplished by running the model many times. Each run is referred to as a realization. Each time the model is run, different permutations of parameter values are selected from the range of

[197] ATSDR-TT, Chapter I, p. I30

possible values for each parameter. The modeler selects these parameter value ranges based on the modeler's professional judgment and consideration of field conditions or a literature review.

ATSDR conducted the uncertainty analysis considering a total of 840 realizations.[198] Parameter values varied within a defined range, and values from each range were selected for each realization. The uncertainty analysis was conducted in stages. First, the groundwater flow model was run for each realization, and "*physically implausible realizations*" were discarded using criteria for model fit to data.[199] By doing so, ATSDR acknowledged the importance of generating realizations that would "calibrate" the model and replicate observed conditions.

Then, the contaminant fate and transport model was run for the remaining, physically plausible realizations.[200] ATSDR could not identify and discard similarly "implausible realizations" for the fate and transport model, because there were no concentration data available during the historical period prior to 1982. This means that the complex process implemented for the uncertainty analysis would result in precise but not necessarily accurate solutions, as the latter could not be validated based on observed data.

ATSDR's uncertainty analysis considered multiple permutations of model parameters. I will focus on one, the retardation factor. The variability in retardation factors was limited, impacting the range of uncertainty estimates.

Before discussing the specifics of the implementation of ATSDR's uncertainty analysis, an example is provided to illustrate conceptually how this analysis was conducted and why it was not expansive enough to account for retardation factor variability at Tarawa Terrace.

Assume that 100 cars travel from Point A to Point B, all departing at the same time with little to no traffic. Given the posted speed limits, average speeds will not vary much. Hence, all cars will cover the distance, 200 miles, at the same or about the same travel time, 4 hours, and, travel at the same or about the same average speed, say 50 miles per hour. Does that mean we can conclude, with a high degree of certainty, it always takes 4 hours to go from Point A to Point B?

The answer is no. For example, what if the cars departed during rush hour, rather than when there was no traffic? Then, travel times would be longer.

In order to be sure that the range of travel times is reasonably estimated, additional factors like traffic must be considered. By doing so, the range of calculated travel times would certainly be wider, including much longer travel times.

The importance of this concept is illustrated when examining how ATSDR performed an uncertainty analysis to evaluate how fast PCE would arrive at well TT-26 and at what concentrations. In this analogy, the cars are PCE, the highway between Points A and B is the groundwater in the aquifer, and traffic is the retardation factor.

One of the most critical parameters for determining how fast contaminants will migrate in the aquifer is the retardation factor, which is calculated using $K_d$, bulk density, and porosity. ATSDR evaluated the effects of retardation in their uncertainty analysis by doing something similar to the 100-car example.

---

[198] Two Monte Carlo uncertainty scenarios were considered: Scenario 1, excluding pumping uncertainty, and Scenario 2, including pumping uncertainty. Stopping criteria were applied to determine whether a realization was successfully completed, or it should he halted. Of the 840 realizations, 510 realizations were successfully completed for Scenario 1, and 684 realizations were successfully completed for Scenario 2. See ATSDR-TT, Chapter I, p. I48.

[199] ATSDR-TT, Chapter I, p. I31

[200] ATSDR-TT, Chapter I, p. I31

ATSDR developed hundreds of scenarios (realizations) where, theoretically, retardation factors would vary within some range, in order to assess the impact on travel time of contamination.

To achieve that, ATSDR first defined ranges of values for $K_d$, bulk density, and porosity. Every cell in the model was assigned a random value from the range of each parameter. Therefore, every cell had a different retardation factor. ATSDR repeated this process to develop model inputs for 840 realizations. When inspecting the inputs of these realizations, I observed the following:

The model calibrated $K_d$ was 0.14 mL/g, and the assigned uncertainty range, as implemented in the Monte Carlo realizations, was between 0.11 and 0.31 mL/g. Although this range suggests that the higher $K_d$ values from the site-specific data are within this range and, therefore, they were considered by ATSDR in their uncertainty analysis, this was not the case. This is because ATSDR implemented a "probability distribution function," which is a term to describe how values closer to the mean value of the range are more probable than those away from the mean. In ATSDR's uncertainty analysis, the defined "probability distribution function" resulted in selecting almost 85% of the values from a fraction of the range, between 0.11 and 0.20 mL/g.

Recall that a lower $K_d$ value is associated with lower retardation factors, and therefore faster movement of contaminants through the subsurface. By using mostly smaller values, ATSDR's selection process tended towards the equivalent of a light to no traffic scenario in the 100-car example, and ignored the possibility of rush-hour traffic. Hence, ATSDR leaned toward faster plume migration, resulting in earlier arrival of contamination at well TT-26.

ATSDR followed a similar process to define ranges and select values for the bulk density and porosity.

I further deconstructed the calculation of the uncertainty range and focused on the variability of retardation rates. I simulated influent concentrations to the WTP by running the model 840 times, using ATSDR's retardation inputs developed for their uncertainty analysis as described above, and keeping all other inputs in the model unchanged. The results of these calculations are depicted in Figure 13.

In Figure 13, ATSDR's calibrated reconstruction of historical concentrations is shown by the black line. The range of historical concentrations due to the variability of the retardation range is shown by the blue shaded area, calculated from my 840 realizations. The uncertainty range for the non-pumping scenario is shown by the yellow shaded area. This figure illustrates that the uncertainty due to the variability in retardation factors is very small relative to the overall uncertainty range calculated by ATSDR. This is because ATSDR's range of retardation factors was very narrow.

Figure 13 also illustrates that the calibrated model sits at the upper bound of the retardation-factor uncertainty range (black line at the top of the blue shaded area). This is also an indication of bias, as the calibrated model should be generally in the middle of the uncertainty range (Section 3.1.5). ATSDR's selection of the retardation-factor parameters forced the calibrated model to simulate the fastest arrival of PCE at well TT-26 and, from there, the treatment plant. ATSDR's uncertainty analysis indicated that plume migration could only be slower and at lower concentrations in the early years, when retardation factors are considered.

To further investigate why this happened, I calculated average retardation factors from layers 1 and 3 of the model for each realization and the range of those averages over the 840 realizations. Layer 1 of the model represents the unconfined layer directly beneath the earth's surface, where the contaminant mass was introduced to the aquifer from the contaminant source. Layer 3 of the model represents the aquifer below the confining unit, where water supply well TT-26 was screened. For this investigation, I evaluated how retardation factors varied on average between the contaminant source and the supply well. My evaluation concluded that average retardation factors only varied over a very narrow range in ATSDR's uncertainty analysis. To understand the importance of this, recall the 100-car example.

In that example, each car may travel at different speeds over different sections of the highway. Assuming these sections are of equal length, such as the cells of the model, the total travel time for each car is determined by its average speed over all the sections of the highway. If cars traveled at variable speeds over different sections, but their corresponding average speed over the entire distance was about the same, the total travel time would be about the same for all cars. Each car could drive faster or slower over different portions of the highway, but if their speeds averaged out to the same value, the travel times also average out to the same value. Hence, in the case of retardation factors and travel times, the small variability of the retardation factors means the overall variability of contaminant travel times is also small.

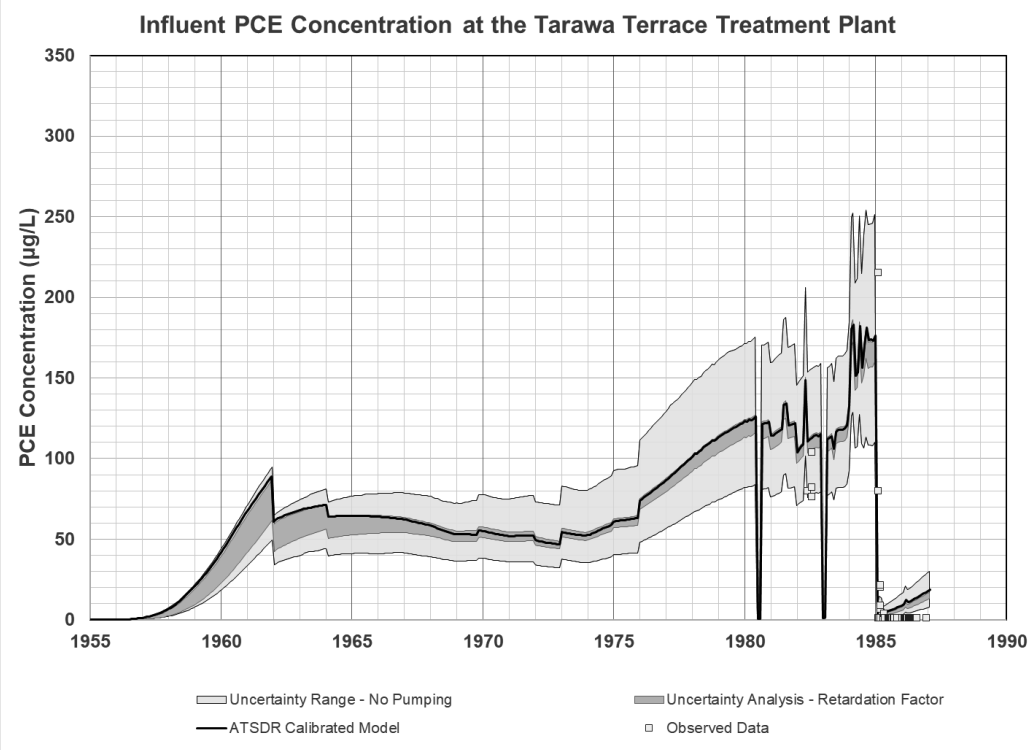



**Figure 13: PCE Concentrations from Calibrated Model and Retardation-Factor Uncertainty Bounds**

This means that the uncertainty analysis did not evaluate a larger portion of the range of possible retardation factors based on the parameter ranges ATSDR defined as reasonable for the site. By doing so, ATSDR ignored the possibility of slower plume migration in the aquifer and later arrival times of contamination at the water supply well. This is not consistent with a rigorous and appropriate uncertainty analysis.

My evaluation concluded that, in Layer 1, the average retardation factor over the 840 realizations ranged from 3.275 to 3.296. In Layer 3, the average retardation factor over the 840 realizations ranged from 3.276 to 3.297. Repeating the same steps above to calculate the median values over the 840 realizations in Layers 1 and 3, I determined that the median values in Layer 1 ranged from 3.122 to 3.146. I also determined that the median values in Layer 3 ranged from 3.123 to 3.148.[201]

This means that, despite the range of parameter values assigned to model cells, mean and median parameter values varied very little. This is not entirely surprising, as the probability distribution functions are constructed to assign parameter variability around the calibrated value of the parameters. But it also

[201] See Appendix C for details

illustrates the inherent limitation of the ATSDR's uncertainty analysis, which is not based on site-specific data for the parameter values and is not informed by historical observed data. Instead, reconstructed historical concentrations vary over a very narrow range selected by ATSDR, as illustrated in Figure 13.

If a wider range of retardation factors were considered, simulated concentrations at the pumping wells would have been different. As an example, Figure 14 illustrates the historical reconstruction of PCE concentrations at pumping well TT-26, comparing the ATSDR calibrated model to an alternative version that uses a retardation factor of 4.3.[202] In this alternative version, the retardation factor of 4.3 is higher than ATSDR's calibrated value of 2.93 and outside the range of average and median retardation factors considered in their uncertainty analysis (3.122 to 3.297, see above). The comparison between the two versions indicates that it is possible to have a different reconstruction than ATSDR's, but that would still have fit within ATSDR's definition of a calibrated model. This is based on ATSDR's calibration criteria of ± one-half order of magnitude and target-range violations that ATSDR considered acceptable for their calibrated model. This alternative reconstruction also lies within ATSDR's calculated uncertainty range during the period when data are available. ATSDR did not consider a wider range of retardation values because they constrained the ranges of key parameter values, such as $K_d$, to low levels.

Figure 15 depicts a comparison of influent concentrations at the TT WTP, calculated by the ATSDR calibrated model, and my alternative version using the higher retardation factor. This figure illustrates that the historical reconstruction calculated using a higher retardation factor is comparable to ATSDR's but outside the uncertainty range calculated for retardation factors based on the 840 realizations for retardation factors that ATSDR developed.

Figure 16 presents a similar comparison, where the results of the ATSDR model and those of its alternative version with the higher retardation factor are shown. In this figure, additional lines are included, showing the total uncertainty bounds that ATSDR calculated, which included the collective uncertainty of all parameters, including pumping uncertainty (i.e., uncertainty evaluation with and without varying the historical pumping configuration). This figure shows that:

- Timeframes of PCE arrival at the WTP could be longer than those estimated by ATSDR, both in its calibrated model and its uncertainty analysis; and
- PCE concentrations at the WTP would be lower than those calculated by ATSDR for at least 10 years, when considering either its calibrated model or even its complete uncertainty analysis considering all parameter uncertainties.

If ATSDR considered higher retardation rates, it could have developed a different calibrated model that would be equally plausible and consistent with site-specific data. This alternative model would then provide a new basis for evaluating uncertainty, as its calibrated parameters would be used for determining corresponding parameter ranges – which, in the case of the retardation factor, the parameter range would have been shifted to higher values than those considered by ATSDR. As a result, the uncertainty range would have been possibly wider, and its bounds would be lower than those calculated by ATSDR.

The impact of using a more appropriate parameter range would be further exacerbated if the correct starting date for mass loading at the ABC One-Hour Cleaners source was used. With those corrections, PCE arrival times at well TT-26 and, therefore, in the influent to the WTP would be longer than those estimated by ATSDR.

ATSDR selected a range of acceptable values for key parameters, such as $K_d$, for their uncertainty analysis based solely on professional judgment and literature sources. However, in their analysis, they considered a smaller subset of that range. In addition, the average values of those parameters in their

[202] This retardation factor is based on a $K_d$ value of 0.40 mL/g from site-specific data (see Section 4.1.2.4) and a bulk density of 1.65 g/cm$^3$.

realizations varied only slightly. As a result, the uncertainty range of the simulated reconstructions for those parameters was narrow and biased high.

When I modified the parameter values in the model to be within the range of site-specific data, the simulated reconstruction was outside ATSDR's uncertainty range. This means that ATSDR's model calibration did not consider appropriate parameter values based on site-specific data. Also, ATSDR's uncertainty analysis was not inclusive of the entire range of parameter values. This demonstrates that the results of model calibration and uncertainty analysis are unreliable in the absence of site-specific data for parameter assignment and a lack of observed data to constrain the model calibration.

ATSDR's upper and lower bounds of uncertainty, shown in Figure 13, that represent 95% of Monte Carlo simulations[203] are therefore unreliable, conservative, and biased-high based on the discussion above.

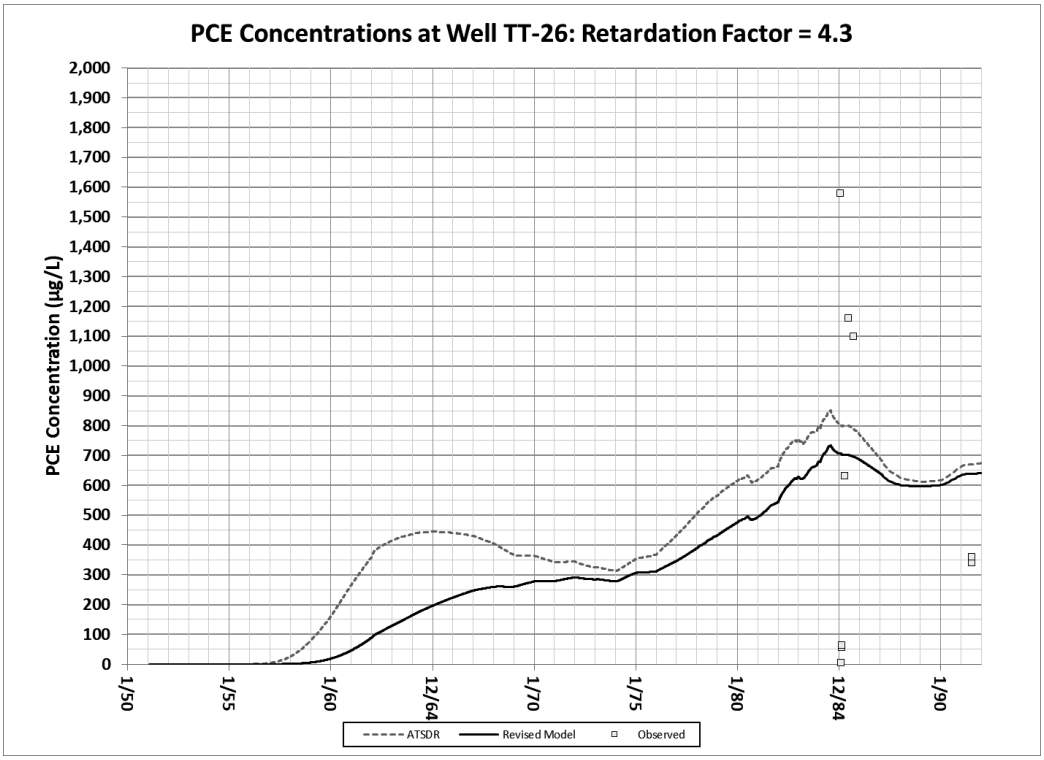



**Figure 14: PCE Concentrations at Well TT-26 for Retardation Factor 4.3**

[203] 2.5 and 97.5 percentile.

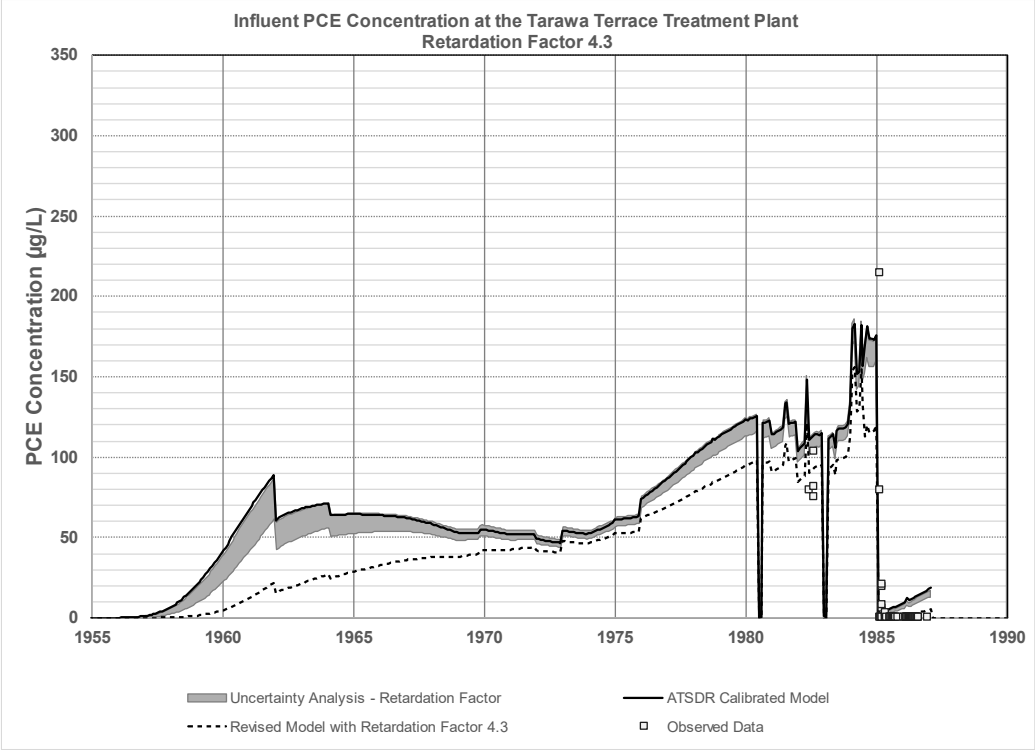



**Figure 15: Influent PCE Concentrations at the Tarawa Terrace Water Treatment Plant for Retardation Factor 4.3**

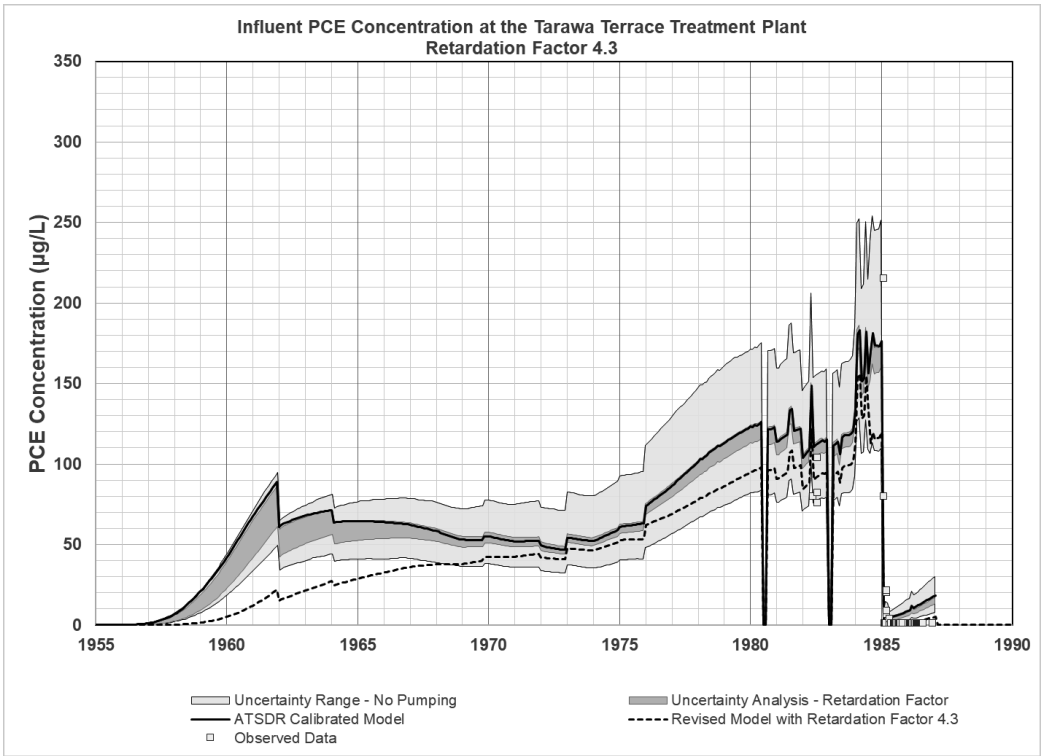



**Figure 16: Influent PCE Concentrations at the Tarawa Terrace Water Treatment Plant for Retardation Factor 4.3: ATSDR vs. Higher Retardation Model**

**In Summary (Opinions 8 and 9): The results of ATSDR's model calibration and uncertainty analysis are unreliable in the absence of site-specific data for parameter assignment and a lack of observed data for constraining the model calibration. The uncertainty analysis was not bound by historical concentration data, and as a result, focused only on model precision and not accuracy in predicting COC concentrations.**

**ATSDR's uncertainty analysis did not evaluate a wider range of possible retardation factors, even based on the parameter ranges ATSDR considered reasonable for the site. Hence, ATSDR ignored the possibility of slower plume migration in the aquifer and later arrival times of contamination at the water supply well. This is not consistent with a rigorous and appropriate uncertainty analysis.**

**ATSDR's selection of the retardation factor parameters forced the calibrated model to simulate the fastest arrival of PCE at well TT-26 and, from there, the treatment plant. ATSDR's calibrated model was biased-high, and the uncertainty analysis indicated that plume migration could only be slower and at lower concentrations in the early years, when retardation factors are considered. If ATSDR considered higher retardation rates, within the range of site-specific data, simulated plume migration would be slower, and reconstruction estimates of monthly contaminant concentrations would be outside ATSDR's uncertainty range.**

### 4.1.4 VOC Degradation By-Products: MT3DMS vs. TechFlowMP Model Results for PCE are Inconsistent and Biased High, and Should be Corrected for Site-Specific $K_d$ Values

ATSDR developed and calibrated groundwater flow and contaminant transport models, using MODFLOW and MT3DMS, to reconstruct historical concentrations of PCE in groundwater extracted by the pumping wells, and the mixed water from the pumping wells entering the WTP. However, ATSDR expanded its analysis to investigate the VOC degradation by-products, including TCE, 1,2-tDCE, and vinyl chloride.

Mr. Maslia stated the following in his expert report: "*To build further confidence in the four-level calibration for TT and to assess model uncertainty, a multiphase, multispecies finite-element model, TechFlowMP (Jang and Aral 2005, 2008), developed by ATSDR's University Partner, MESL, was run using the calibrated parameter values from MODFLOW-96 and MT3DMS (Table 7.8)*."[204] Dr. Aral provided a similar statement in his expert report: *"It also served the purpose of independent reconfirmation of the predictions of the calibrated multiphase subsurface models used by ATSDR at the Camp Lejeune site*."[205]

However, no such purpose was stated in ATSDR's reports. Instead, the multiphase-multispecies model was built to simulate the degradation of VOCs and not build confidence in the results.[206] In fact, Mr. Maslia states the following in his expert report: "*Unlike MT3DMS that simulated contaminant fate and transport in the saturated zone for a single contaminant that does not undergo degradation, TechFlowMP can simulate flow in the unsaturated zone (above the water table), in the saturated zone (below the water table), the degradation of PCE (into TCE, 1,2-tDCE, and VC), and the loss of PCE by accounting for volatilization.*"[207]

[204] Maslia (2024), Expert Report, p. 60

[205] Aral (2024), Expert Report, p.16

[206] ATSDR-TT, Ch. A, p. A41

[207] Maslia (2024), Expert Report, p. 60

The purpose of this multiphase-multispecies modeling effort, undertaken by ATSDR, is clearly stated in Chapter G of ATSDR's report on the analyses for Tarawa Terrace[208]: "*The purpose of this study is to investigate the fate, degradation, and transport of PCE and associated VOC degradation by-products - TCE, 1,2-tDCE, and VC - within the Tarawa Terrace aquifer and Castle Hayne aquifer system at and in the vicinity of Tarawa Terrace.*"

In Chapter G of ATSDR's report about the use of TechFlowMP they further explained: "*The study applies the numerical model TechFlowMP (Jang and Aral 2005b) to the Tarawa Terrace area. Calibration of the fate and transport model is based on the spatial and temporal distributions of contaminants PCE, TCE, and 1,2-tDCE at selected water supply well locations within the Castle Hayne aquifer system. Thus, the application of the TechFlowMP model was used to account for and to simulate (1) parent-daughter chain reactions, (2) multiphase environments (water and vapor), and (3) fate and transport in the unsaturated and saturated zones.*"[209]

The statements above paint a very clear picture of the intended purpose of this modeling effort. TechFlowMP was required for simulating concentrations of PCE's degradation by-products (TCE, 1,2-tDCE, and VC) and not for confirming the MT3DMS results.

Although TechFlowMP and MT3DMS simulated PCE concentrations in groundwater using the same parameters and source mass loading, there is a discrepancy in simulated PCE concentrations between TechFlowMP and MT3DMS. ATSDR indicated that "*PCE concentrations at well TT-26 using TechFlowMP are less than those using MT3DMS (Figure G6a). This is partially due to TechFlowMP simulating (1) the release of PCE from the subsurface (groundwater) to atmosphere, (2) PCE partitioning from the water phase to soil vapor phase, and (3) the placement of the contaminant source at the ABC One-Hour Cleaners site in the unsaturated and saturated zones.*"[210]

However, Robert Faye, a consultant subcontracted to ATSDR to work on the water modeling efforts, commented on this discrepancy, as well as other issues with the TechFlowMP model, in a personal communication with Mr. Maslia.[211] Regarding the PCE concentration discrepancy, Mr. Faye stated that "*[f]rom a technical point of view, I believe most or all of this unfortunate 'mess' has evolved from flawed concepts and applications on the part of GA Tech. Specifically, they applied the calibrated mass loading rate from the MT3DMS model to the unsaturated and saturated zones represented in the model.*"[212] He further indicated that "*applying the calibrated mass loading rate from the MT3DMS model to the unsaturated zone directly equates the actual ('real world') PCE loss rate at ABC One-Hour Cleaners to the MT3DMs mass loading rate. Such an equation is absurd as it does not account for retention and degradation within the unsaturated zone.*"[213] In other words, using the same mass loading rate in TechFlowMP as in MT3DMS, in both the saturated and unsaturated zones (instead of only the saturated zone as in MT3DMS), would inevitably result in lower PCE concentrations in the saturated zone.

In his personal communication with Mr. Maslia, Mr. Faye also commented on the choice of biodegradation rate. He indicated that he had "*rerun the fate & transport model with a biodegradation rate*

[208] ATSDR-TT, Chapter G, p. G4

[209] ATSDR-TT, Chapter G, p. G4

[210] ATSDR-TT, Chapter G, p. G14

[211] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM.

[212] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM. Numbered item 4.

[213] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM. Numbered item 4.

*of 0.0005 as you required*,"[214] referring to Mr. Maslia. He continued saying that "*the results are only marginally acceptable and certainly do not represent our 'best' calibration*."[215] He further stated that he "*will find it very difficult to defend these results to [his] technical peers or in a court of law*."[216]

Mr. Faye proceeded with this comment on the modeling procedure: "*I believe we have violated a fundamental rule of good modeling procedure. We let the 'tail wag the dog' and assigned extraordinary credibility to simulated numbers rather than to well established concepts. When a choice must be made between accepting less than desirable model results or violating or compromising valid conceptual models, I believe we should accept the undesirable results and explain the limitations in that context*."[217] It is not clear what Mr. Faye meant by "*desirable results*" or his admission that the modeling team assigned "*extraordinary credibility to simulated numbers than to well established concepts*."

ATSDR's report on the calculation of the biodegradation rate indicated that the value of 0.0005 was calculated based on only two concentration values at well TT-26, from samples collected on September 25, 1985, and July 11, 1991.[218] However, additional discussion was provided in the ATSDR report: *"[h]alf-lives of PCE reported in the literature range from about 360 to 720 days (Lucius and others 1990). Applying these half-lives to Equation 3 yields first-order degradation rates ranging between 0.001 and 0.002 per day, about twice to four times the rate computed using concentrations at water-supply well TT-26*."[219] Hence, Mr. Faye, the author of the report, indicated that the selected biodegradation rate in the calibrated model was low, and information in the literature would support values two to four times higher. Such a choice would result in lower PCE concentrations in the aquifer.

The above statements from Mr. Faye to Mr. Maslia indicate that the members of the ATSDR modeling team were not in agreement on important modeling aspects, resulting in discrepancies in the results between the two models (MT3DMs and TechFlowMP), and estimated concentrations that could (or should) have been lower than those calculated by ATSDR.

Regardless of the disagreement between the ATSDR modeling teams, TechFlowMP calculated PCE concentrations in groundwater that were lower than those calculated using MT3DMS. However, ATSDR chose to report the concentrations calculated by MT3DMS rather than those generated by TechFlowMP, i.e., the model they acknowledged was inclusive of all processes in the subsurface.[220] Neither ATSDR, Mr. Maslia, nor Dr. Aral, provided sufficient scientific justification for selecting the higher (MT3DMS) estimated monthly contaminant concentrations for their dose reconstruction.

Finally, similar to the selection of the $K_d$ values for PCE (Section 4.1.2.2.2), ATSDR did not utilize site-specific data for assigning $K_d$ values for PCE's degradation by-products. Therefore, the values used by ATSDR in TechFlowMP were lower than those estimated from site-specific data. Specifically, Table 1 provides a comparison of the $K_d$ values used by ATSDR versus those calculated using site-specific data. Calculations were based on the discussion provided in Section 4.1.2.4.

---

[214] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM.

[215] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM.

[216] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM.

[217] CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM.

[218] ATSDR-TT, Chapter F, p. F28

[219] ATSDR-TT, Chapter F, p. F29

[220] ATSDR-TT, Chapter G, p. G14

**Table 1. ATSDR versus Site-Specific $K_d$ Values for Other Contaminants**

| Contaminant | ATSDR Value[a] | Median Value Calculated from Site-Specific Data[b] | |
|---|---|---|---|
| | | All Data | Data Below 10 ft |
| TCE | 0.1 | 0.17 | 0.13 |
| 1,2-tDCE | 0.04 | 0.07 – 0.09 | 0.05 – 0.07 |
| VC | 0.003 | 0.1 | 0.08 |

[a] Values from Table G2, ATSDR-TT, Chapter G, p. G11

[b] Values calculated using the same assumptions as PCE. Values for log $K_{oc}$ from ATSDR's Table D12:[221]

- TCE: 2.00
- 1,2-tDCE: 1.56 – 1.69
- VC: 1.75

Had site-specific data been used, $K_d$ values would have been higher, as shown in Table 1. In that case, arrival times of contaminants at the supply wells would be later, and corresponding concentrations of contaminants at the wells in earlier times would be lower.

**In Summary (Opinions 10 and 11): ATSDR applied two different numerical codes for modeling dose reconstruction. The results of the two codes are not in agreement. This is due, in part, to inconsistent application of contaminant source terms in the two models. Neither ATSDR, Mr. Maslia, nor Dr. Aral, provided sufficient scientific justification for selecting the higher estimated monthly contaminant concentrations for their dose reconstruction. In addition, ATSDR did not use site-specific parameter values for estimating monthly concentrations for the VOC degradation by-products. Had they used site-specific parameter values, the contaminant plumes would migrate slower to the water-supply wells, and the resulting estimated concentrations would be lower.**

### 4.1.5 The Post-Audit Analysis Shows Consistent Bias in Model Results

A post-audit of the ATSDR model was conducted by Mr. Norm Jones of Norm Jones Consulting LLC and Dr. Jeffrey Davis of Integral Consulting Inc. (henceforth referred to as "Jones & Davis"). The post-audit included (a) extending the ATSDR model to simulate conditions through December 2008, and (b) considering pumping and monitoring data to evaluate the ATSDR's model performance "*as an interpretive and predictive tool.*"[222]

The ATSDR model simulated groundwater flow and contaminant transport during the period 1951-1994. In the post-audit, the model was extended to encompass the period 1995-2008. Selection of this timeframe was based on available pumping and monitoring data for this period. Although the post-audit report does not provide a reference for the source of these data, from my review of available documents it appears that a source was the 2018 Focused Remedial Investigation Report[223] (RI) for ABC One-Hour Cleaners.

Execution of the extended groundwater flow and contaminant transport model generated results that were post-processed by Jones & Davis to construct maps and plots for basing their opinions regarding

[221] ATSDR-TT, Chapter D, p. D15

[222] Jones & Davis, (2024), Expert Report, p. 1-2

[223] Black & Veatch (2018)

model performance. Contrary to their opinion, the extended ATSDR model does not reasonably forecast future conditions (1995 to 2008). Model simulation results were consistently biased high, overestimating observed concentrations by 2 to 3 orders of magnitude.

#### 4.1.5.1 Post-Audit Model Results are Biased High

The Post-Audit report presents the results of the extended model and provides a discussion on model performance that is summarized in the following statements: "*In summary, the extended model demonstrates that the original model was developed using sound methods, and the model remains a reliable tool for understanding the general trends of contaminant migration in the Tarawa Terrace region. Based on this post-audit, we can find no significant evidence that would invalidate the analyses performed by ATSDR with the original model*." This statement is not supported by the data as discussed below.

Figure 17 shows Figure 6 of the Post-Audit report, illustrating comparisons between observed and simulated concentrations from the original and extended model. In the Post-Audit report it is stated that "*The points on the plot are mostly centered on the line, but as was the case with the original model, the simulated values appear to be biased on the high side, with the simulated values greater than the observed values. However, when the sites with zero observed or simulated concentrations (not shown on Figure 6) are factored in, the errors are balanced, as indicated by the low ME [Mean Error][224] (21 µg/L) reported above*."[225]

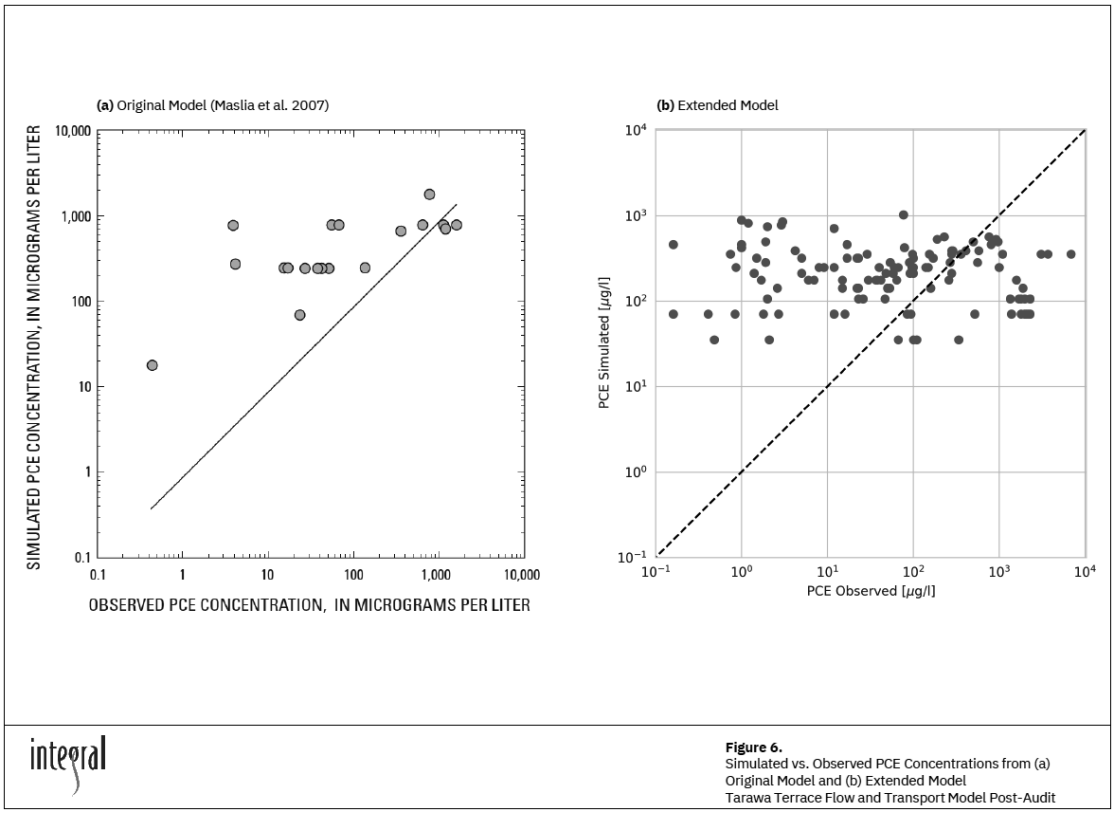



**Figure 17: Observed versus Simulated PCE Concentrations from the Original and Extended Model (Integral, 2024)**

[224] Note: Mean Error is the average of the differences between the simulated and observed values

[225] Jones & Davis, (2024), Expert Report, p. 5-2

Jones & Davis' statement that simulated values were higher than the observed values confirms that the model was biased high. This is consistent with ATSDR's statement about the calibrated model that "*simulated PCE concentrations moderately to substantially overpredicted observed concentrations at water-supply wells*."[226] However, their statement about the mean error is not valid, as will be illustrated below.

Observed concentrations of zero correspond to non-detections. Mean error is the difference between simulated and observed values. It can be negative or positive. A negative mean error indicates that the simulated values are lower than the observed values. A positive mean error indicates that the simulated values are higher than the observed values.

A reconstructed version of Jones & Davis' Figure 6 is shown in Figure 18, to include all zero observed and simulated concentrations. Because a value of 0.0 does not appear on a logarithmic scale, I plotted those concentrations with a surrogate value of 0.1 micrograms/L, so that all values are visible. In Figure 18, I have also included two dashed lines to indicate the bounds of the "+/- one-half order of magnitude range" that ATSDR used for evaluating its model calibration.

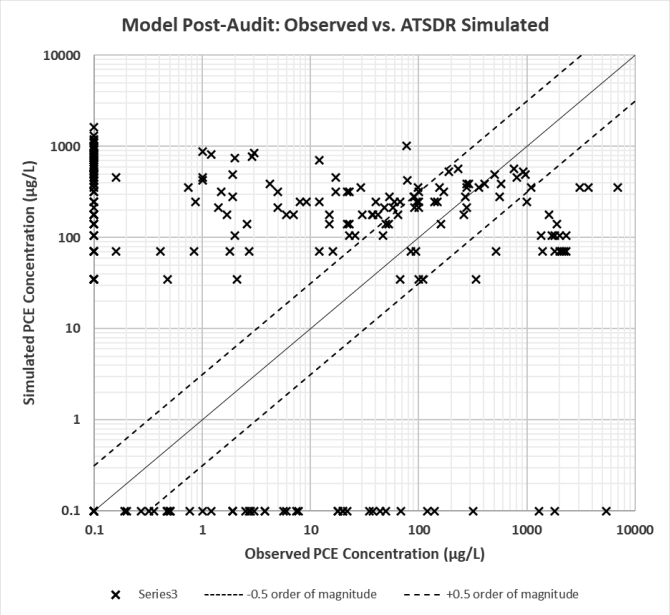



**Figure 18: Scatterplot of Observed versus Simulated PCE Concentrations from the Extended Model**

The following conclusions can be drawn from reviewing the results depicted in Figure 18:

- As stated in Jones & Davis' report, the simulated values are biased on the high side, being consistently greater than the observed values.
- Only a small fraction of the simulated values is within the calibration range.
- While observed concentrations vary by about 3 orders of magnitude, simulated concentrations vary by about one.

[226] ATSDR-TT, Chapter F, p. F33

- For observed non-detections (indicated by the point on the axes origin), the corresponding model simulated values (lined up along the vertical axis) vary between 106 and 1,624 µg/L. Only two simulated concentrations are lower than one hundred (35 and 71 µg/L), or two to three orders of magnitude greater than observed values.
- For all observed concentrations along the horizontal axis, spanning 4 orders of magnitude, the corresponding simulated value is zero.

The first three items above illustrate how the extended model is biased high, consistently overestimating observed data. The last two items illustrate that non-detections and simulated concentrations of zero are largely not correlated, and simulated values are biased high. For this portion of the dataset, when observed values are zero, the simulated values are greater than zero; and when simulated values are zero, observed concentrations are greater than zero. Below is a more detailed discussion on the impact of this discrepancy.

Calculation of the mean error for this portion of the dataset results in large positive errors (when the simulated value is high and the observed value is zero) and large negative errors (when the simulated value is zero and the observed value is high), balancing the total mean error. There are 125 data points for which either the observed or the simulated value are zero. The high observed values include one measurement of 5,400 µg/L, and all other values are less than 2,000 µg/L. If this extreme value is excluded from the comparison, it turns out that:

- There are 40 data points for which the observed value is greater than zero when the simulated value is zero. The mean error for this portion of the dataset is -102 µg/L. If the extreme value of 5,400 µg/L is included in the calculation, the mean error becomes -231 µg/L.
- There are 84 data points for which the simulated value is greater than zero when the observed value is zero. The mean error for this portion of the dataset is 441 µg/L.

This means that the mean error is four times higher when simulated values are greater than zero and observed values are non-detections than the reverse (i.e., when observed values are greater than zero and simulated values are zero). This further illustrates how the model overestimates the observed data and is biased high, especially when observed data indicate no presence of contamination.

To further illustrate these issues, a different plot was constructed to compare the observed and simulated concentrations from the extended model. Figure 19 shows the observed versus simulated concentrations, as well as the calibration range. In this plot, the observed data are ranked in descending order from 1998-2000 (i.e., from the highest observed value to the lowest; not listed chronologically) with their corresponding simulated values. Observed or simulated concentrations of zero are shown in this plot with a value of 0.1, so they are visible in the logarithmic scale. The first (highest) 158 ranked observed concentrations are greater than zero and the remaining 160 are non-detections. The highest observed concentration is 6,900 µg/L. Key observations from this plot are the following:

- Only a small portion of ATSDR model-calculated concentrations lie within the calibration range. All other calculated values are more than one order of magnitude greater than the observed values.
- For observed concentrations below 10 µg/L, corresponding simulated concentrations are consistently about 2 to 3 orders of magnitude greater.
- For observed non-detections, corresponding simulated concentrations are consistently 3 to 4 orders of magnitude greater.
- Only a small fraction of the simulated concentrations is lower than the corresponding observed concentrations.

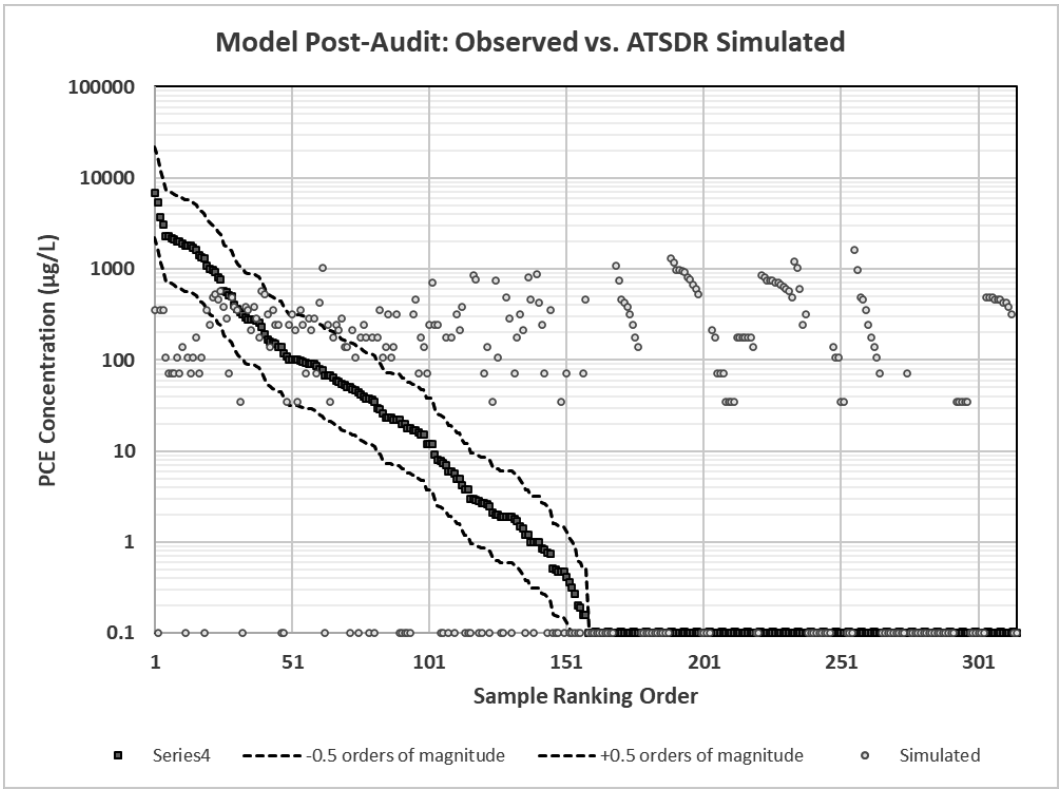



**Figure 19: Observed versus Simulated PCE Concentrations from the Extended Model**

Jones & Davis' report attempts to attribute these discrepancies to complex surface conditions, temporal variability, limitations in model resolution, and measurement variability.[227] While these factors are generally important, these figures clearly illustrate that the discrepancies between observed and simulated concentrations consistently and extensively exceed the generous calibration range that ATSDR defined as appropriate for evaluating the performance of the original model. If ATSDR concluded that this "+/- one-half order of magnitude range" were appropriate for the calibration of the original model, it should also be applicable to this validation dataset; and this assumption is clearly violated in the extended model.

Jones & Davis' report proceeds with a qualitative evaluation of the model results, where plume maps are constructed for different times, also showing monitoring well locations and associated discrepancies between observed and simulated concentrations at those locations. These maps are intended to illustrate that "*the spatial distribution of the errors indicates that there is a good overall agreement between the shape of the plume and the observed PCE concentrations at the monitoring wells.*"[228] However, this conclusion comes after a lengthy discussion that attempts to explain extreme discrepancies at various locations by attributing them to the factors indicated above. In this discussion, Jones & Davis state that "*the 7 wells identified as having anomalies in the observed data have high errors while the remaining 30 wells exhibit low or moderate errors, indicating good overall agreement between the simulated PCE plume and the observed concentrations over the range of the extended simulation*"[229]. The seven wells identified by Jones & Davis as having anomalous observed data are FWS-13, RWS-4A, FWC-11, C5, C13, C14, and RWC-2. Figure 20 depicts a scatterplot of observed and simulated concentrations for the other 30 wells.

[227] Jones & Davis, (2024), Expert Report, p. 5-1

[228] Jones & Davis, (2024), Expert Report, p. 5-3

[229] Jones & Davis, (2024), Expert Report, p. 5-4

The discrepancies between observed and simulated concentrations at these wells follow the same pattern as the entire set of wells. Only a small fraction of the simulated concentrations is within the calibration range, and simulated concentrations are consistently greater than corresponding observed concentrations by 2 to 3 orders of magnitude.

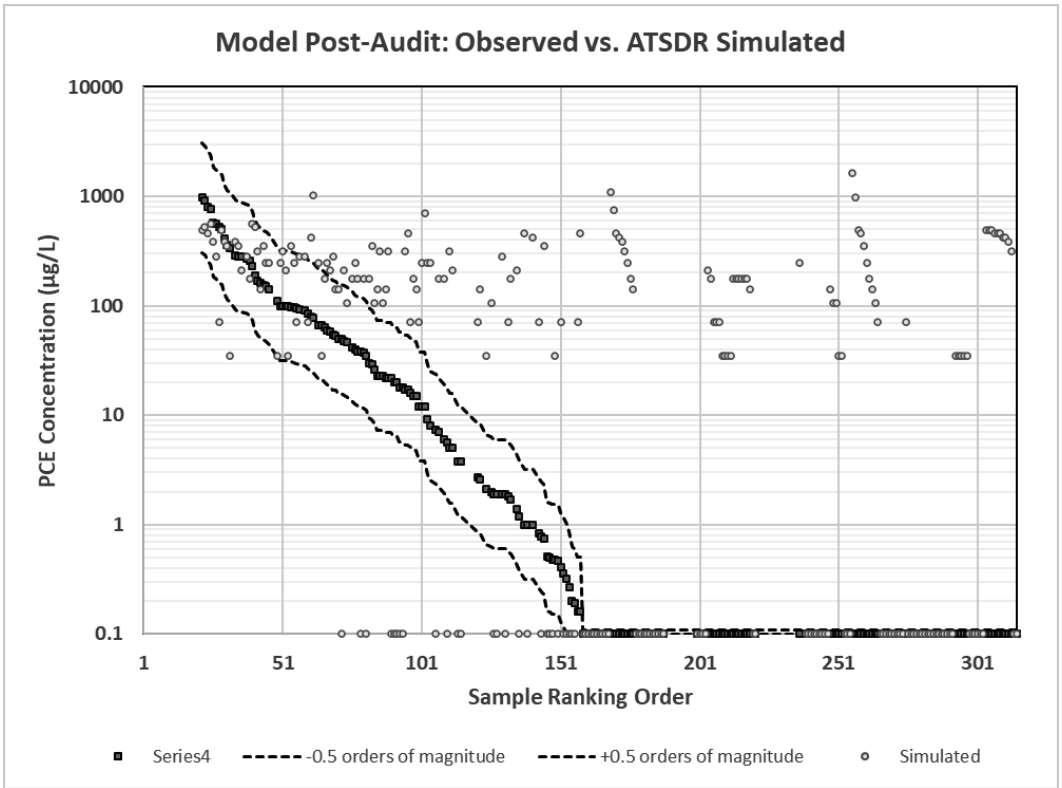



**Figure 20: Observed versus Simulated PCE Concentrations from the Extended Model Excluding Wells with Alleged Anomalies in Observed Concentrations**

For the reasons discussed above, the extension of the original ATSDR model does not reasonably forecast future conditions. Using data from the period 1995-2008 as a validation dataset, model simulation results were consistently biased high, overestimating observed concentrations by 2 to 3 orders of magnitude.

Jones & Davis also stated that "*it is important to qualitatively assess the overall behavior of the simulated plume in addition to quantitatively analyzing the differences in simulated and observed concentrations at specific times and locations.*"[230] However, qualitative assessment of the PCE concentrations simulated by their extended model is generally unhelpful because:

- discrepancies between observed and simulated concentrations are significant and biased;
- comparisons are drawn within a very small area, compared to the overall plume extents; and
- no data are available to evaluate whether the overall extents of the simulated plume are real.

The lack of data available to evaluate the overall extent of the simulated plume is particularly important. Plume extents and concentrations at other locations would provide supporting information for assessing model parameter values and assumptions built into the calibrated model. This directly addresses

[230] Jones & Davis, (2024), Expert Report, p. 5-1

the selection of the calibrated model parameters, and the resulting migration patterns of contamination at the site.

**In Summary (Opinions 12 and 13): The extended ATSDR model (Post-Audit) shows that the model does not reasonably forecast future actual measured conditions (1995 to 2008). Model simulation results were consistently biased high, overestimating observed concentrations by 2 to 3 orders of magnitude. ATSDR's calibrated model used parameters and assumptions that results in biased-high estimate of contaminant concentrations for both the historical reconstruction and the "predictive" period of the post-audit. Therefore, the model should be recalibrated using all available data from the historical and extended period.**

#### 4.1.5.2 There are Issues with Extended Model Inputs and Post-Processed Results

Review of the Post-Audit model files also led to the discovery of certain issues related to the construction of model inputs and the presentation of model results. First, the Post-Audit report states that mass loading at the ABC One-Hour Cleaners source was set up from January 1953 through December 1983.[231] I inspected the model files and confirm that this is the timeframe implemented in the mass-loading input file constructed by Jones & Davis for the extended model. However, this timeframe is incorrect as the source in the ATSDR model was active through December 1984.[232]

In addition, Table 2 of the Post-Audit report lists the pumping wells and their operation (dates and flow rates) for the period 1995-2008. According to this table, well RWC-2 had a pumping rate of 40 gallons per minute (gpm) from 3/7/2004 to 12/16/2004. However, the input file for the well operation in the extended model shows this well with a pumping rate of 20 gpm. This is a discrepancy between Jones & Davis' modeling documentation and actual model files.

Post-processing of the model results presented in Jones & Davis' report requires clarification. In some cases, simulated concentrations corresponding to consecutive sampling events, spanning months or even years, are identical. For example, well RWC-2 is listed as having the same concentration of 106 µg/L 5 separate times between 2/1/2000 and 11/1/2002; and 6 separate times with the same concentration of 71 µg/L between 3/1/2003 and 3/1/2008. This is highly unlikely, if not impossible, in a transient model simulation.

I post-processed the model output to extract the monthly simulated concentrations at the model cell where well RWC-2 is located (confirmed by reviewing Jones & Davis' tables and the model input files). The post-processed results indicated that the simulated concentrations varied in a manner that should be expected due to the transient conditions in the aquifer and the resulting plume migration (shown by the black line in Figure 21). However, the reported concentrations by Jones & Davis (shown by the blue line in Figure 21) do not reflect that variability but, instead, appear to be constant between 2000-2002 and 2003-2008, as indicated above.

---

[231] "The PCE source, which originated from ABC Cleaners and was terminated in the original model at the end of 1983, was left unchanged." Jones & Davis, 2024, p. vi; "For the transport model, PCE was introduced through a single cell corresponding to the ABC Cleaners spill location at a mass loading rate of 1,200 g/day for a period from January 1953 to December 1983" Jones & Davis (2024), p. 1-1

[232] "Mass loading occurred continuously from stress period 26 (January 1953) to stress period 408 (December 1984). Prior to stress period 25 and after stress period 408, the assigned mass loading rate was 0.0 g/d." ATSDR-TT, Chapter F, p. F25

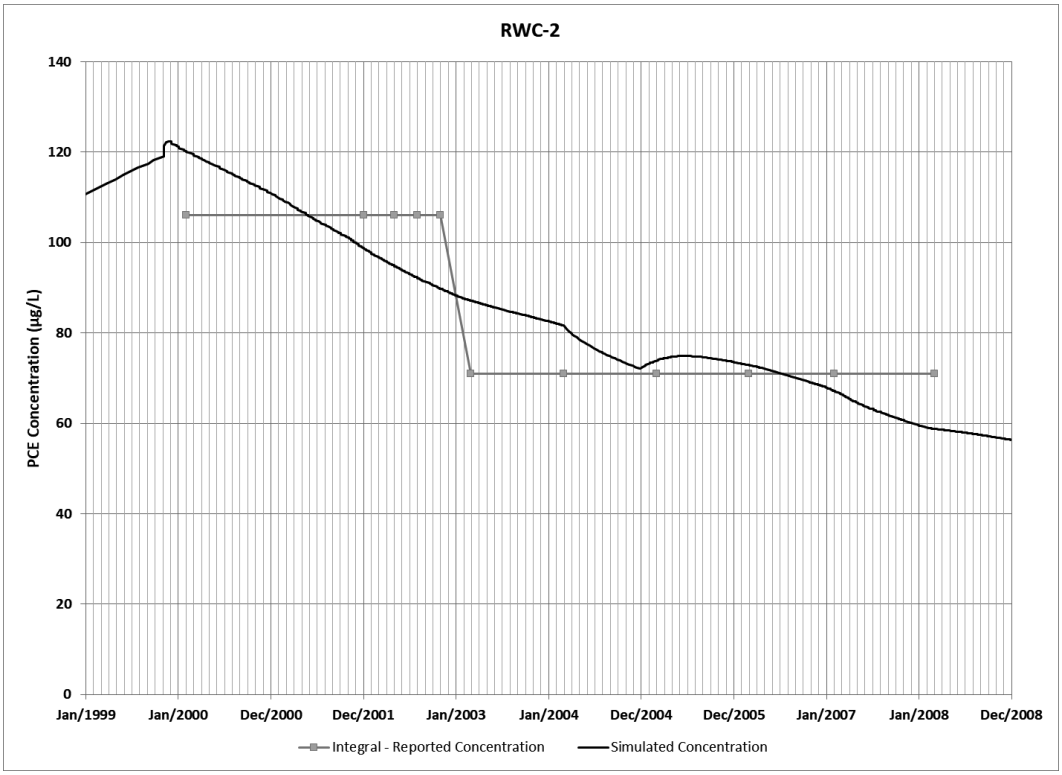



**Figure 21: Observed versus Simulated PCE Concentrations from the Extended Model for Well RWC-2**

In addition, tabulated and mapped reported results in the Post-Audit analysis are inconsistent in some cases. For example, in Table 5, the simulated concentration at well S8 is "<DL" on March 1, 2003. The corresponding observed value on that date is also "<DL."[233] In fact, Table 5 of the Jones & Davis report indicates that both observed and simulated concentrations at that location are always "<DL." However, Figure 9 of Jone & Davis' report shows this well in the plume interval of "greater than 5 to 50" µg/L for June 1997 (indicated by the blue arrow in Figure 22).

Similarly, Jones & Davis reported the simulated concentration at well S9 on 3/1/2003 to be "<DL." The corresponding observed value on that date is also "<DL." However, Figure 11 of Jone & Davis' report shows this well in the plume interval of "greater than 5 to 50" µg/L for March 2003 (indicated by the blue arrow in Figure 23).

[233] Note: although "<DL" means "*below detection limit*" for observed values, it is not clear what "<DL" means for simulated concentrations. See Jones & Davis, (2024), Expert Report, p. 8

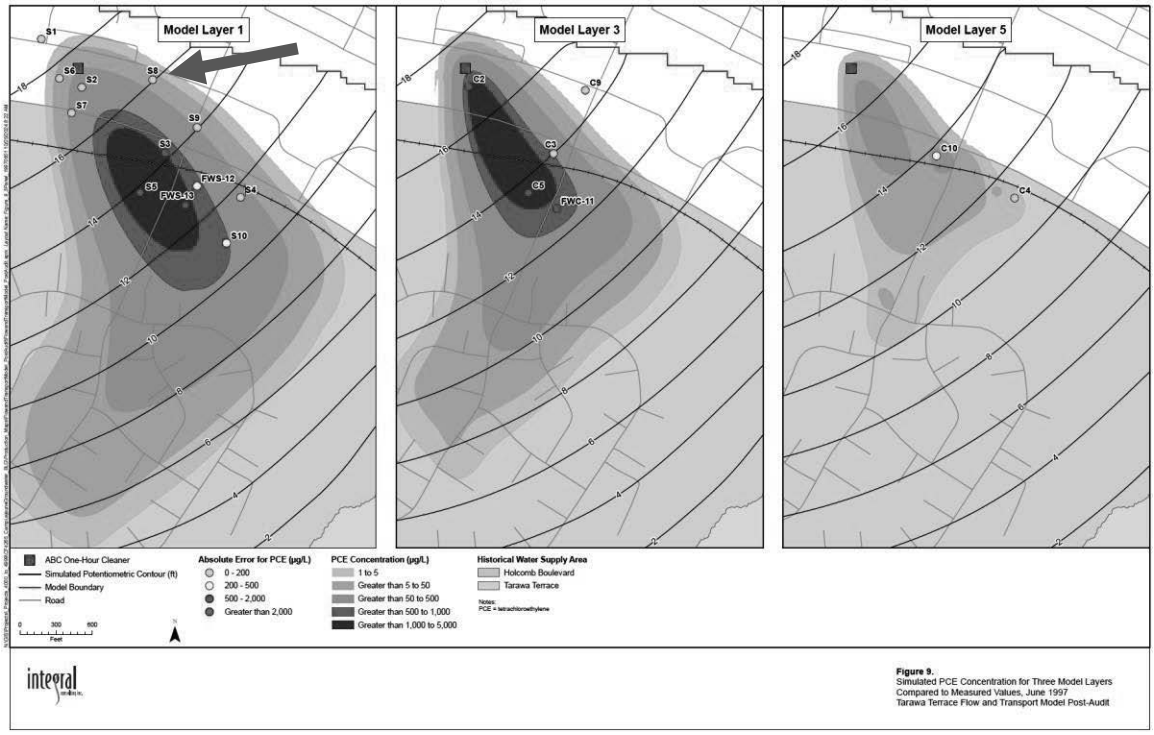



**Figure 22: Simulated Plume Maps, Well Locations, and Comparison to Observed Values – June 1997 (Jones & Davis, 2024)**

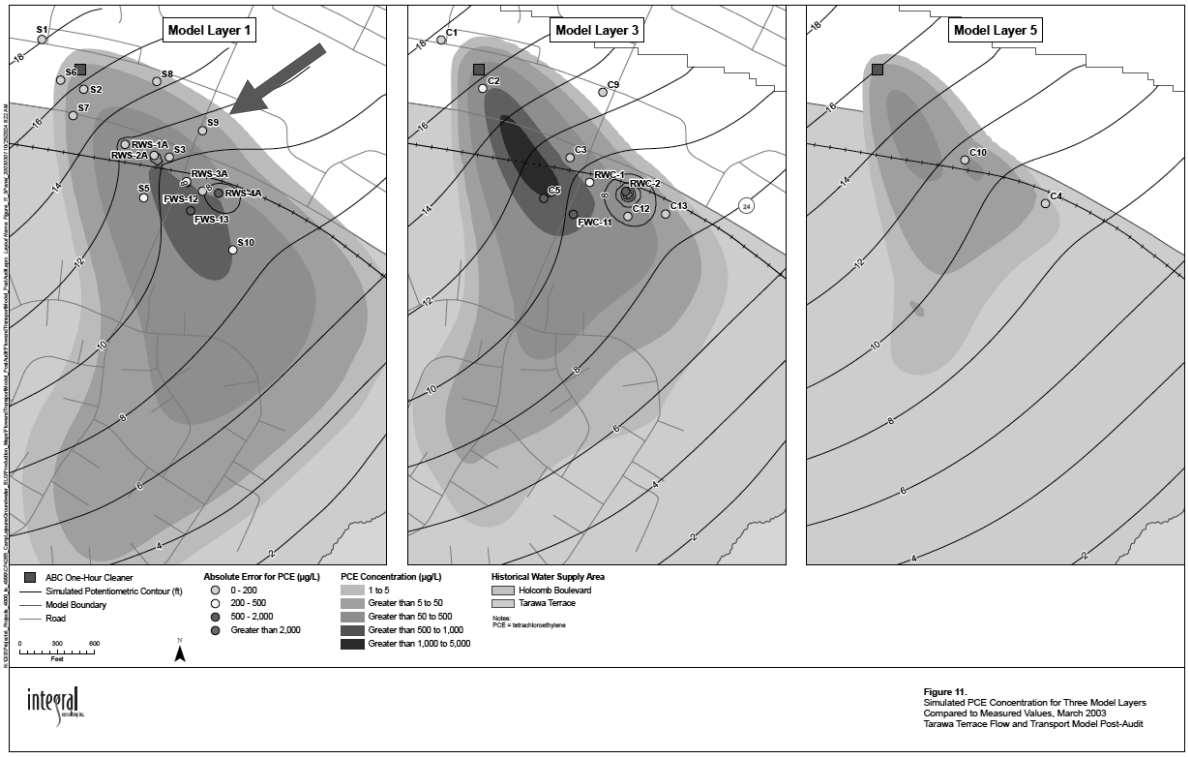



**Figure 23: Simulated Plume Maps, Well Locations, and Comparison to Observed Values – March 2003 (Jones & Davis, 2024)**

I post-processed the model results to confirm the simulated values for well S9, reported by Jones & Davis. Figure 24 shows my post-processed simulated concentrations at this location (black line) and the equivalent values reported by Jones & Davis (blue line). The simulated concentration at that well did not fall below 5 µg/L until after January 2006 and, therefore, Jones & Davis incorrectly reported the simulated concentration on 3/1/2003, 3/1/2004, and 3/1/2005 as "<DL," assuming that 5 µg/L was the threshold to consider a simulated value as non-detection.

Figure 24 also highlights the same issue of the questionable calculation of simulated values by Jones & Davis, which appear to be constant over different periods when the actual model results indicate otherwise. However, the reported concentrations by Jones & Davis (blue line in Figure 24) do not reflect that variability but, instead, appear to be constant between 1997-2002 and 2003-2008, as indicated above. This is highly unlikely, if not impossible, in a transient model simulation.

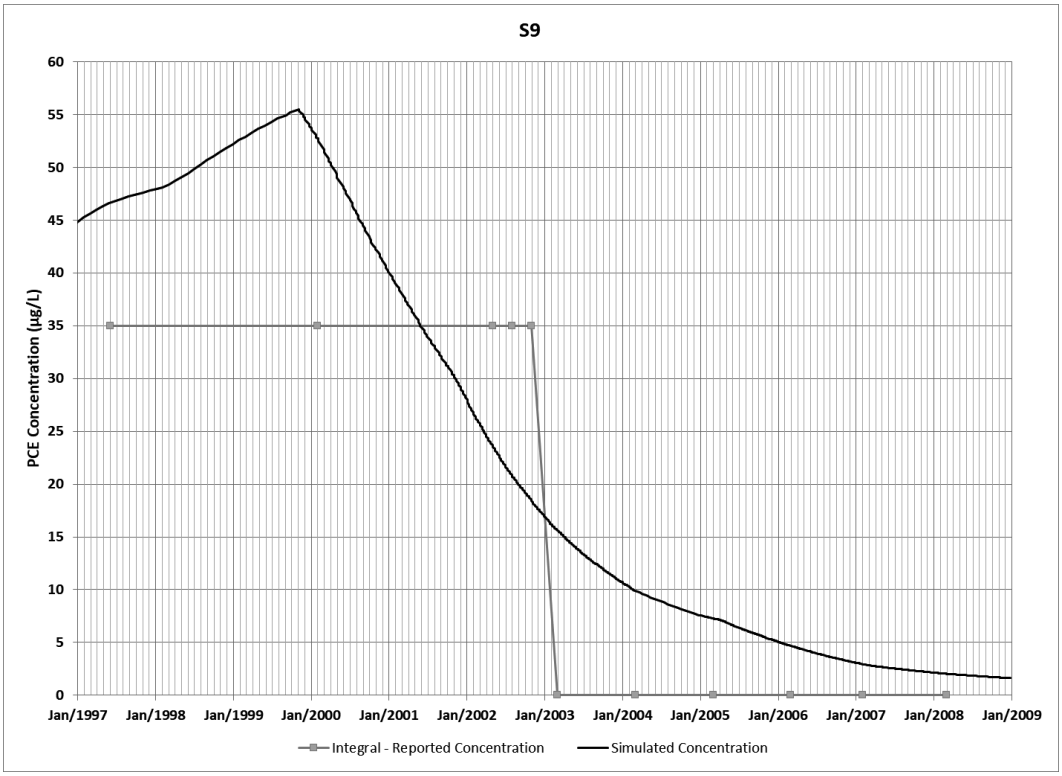



**Figure 24: Observed versus Simulated PCE Concentrations from the Extended Model for Well S9**

## 4.2 Hadnot Point – Holcomb Boulevard Area

Hadnot Point and Holcomb Boulevard are water distribution systems at Camp Lejeune served by individual water treatment plants. Hadnot Point began operations in 1942. The Holcomb Boulevard area was served by Hadnot Point until 1972, at which point it opened its own water distribution system and water treatment plant separate from Hadnot Point. For further discussion of the history of the water infrastructure at Camp Lejeune, see the expert report of Dr. Brigham.

Water quality samples taken at Camp Lejeune in the 1980s revealed contamination of VOCs. Because there were no VOC data prior to the 1980s, ATSDR attempted to use mathematical modeling to reconstruct historical concentrations of contaminants in water supply wells and at the WTPs in the absence of measured data.

ATSDR used a model to simulate historical groundwater flow and contaminant transport at Hadnot Point and Holcomb Boulevard. To construct their model, ATSDR first developed a conceptual model for groundwater flow and contaminant transport in the subsurface. To do this, they relied on past investigations at Camp Lejeune.

The groundwater flow model was created with limited available data. As with Tarawa Terrace, ATSDR also created a hypothetical well pumping schedule for Hadnot Point and Holcomb Boulevard using limited to no data. The groundwater flow model was used to create a contaminant fate and transport model, which also relied on limited data. Unlike the Tarawa Terrace model, ATSDR did not know the precise location of all contamination sources and the magnitude of contamination each source contributed. Therefore, they made arbitrary and highly uncertain assumptions to locate and quantify the contribution of these sources.

These uncertainties were highlighted in NRC's report: "*The contamination of the Hadnot Point system was more complex than Tarawa Terrace. There were multiple sources of pollutants, including an industrial area, a drum dump, a transformer storage lot, an industrial fly ash dump, an open storage pit, a former fire training area, a site of a former on-base dry cleaner, a liquids disposal area, a former burn dump, a fuel-tank sludge area, and the site of the original base dump*.."[234]

The Hadnot Point and Holcomb Boulevard areas of the base separately provided water to consumers using different water distribution networks. However, the Holcomb Boulevard and Hadnot Point water distribution networks could be connected if and when necessary to address water supply needs in Holcomb Boulevard. Usually, this occurred during the summer months when water demand at Holcomb Boulevard was high. On one occasion, Hadnot Point provided all water to the Holcomb Boulevard water distribution system for ten days between January 27, 1985, and February 7, 1985. This was because the Holcomb Boulevard system had to be flushed due to the presence of benzene (see details in Hennet, 2024).

For Hadnot Point, as with Tarawa Terrace, ATSDR assumed concentrations of contaminants in the influent to the WTP were equal to the concentrations of contaminants in the "finished water" that was delivered to consumers.[235] This assumption is incorrect, as treatment of the influent to the treatment plant

[234] NRC (2009), p. 5

[235] ATSDR stated that "*for this study, finished water is defined as groundwater that has undergone treatment at a water treatment plant and was subsequently delivered to a family housing unit or other facility. Throughout this report and the Hadnot Point–Holcomb Boulevard report series, the term finished water is used in place of terms such as finished drinking water, drinking water, treated water, or tap water*." (ATSDR-HP, Chapter A, Supplement 6, p. S6.21) However, ATSDR used simulated contaminant concentrations in the influent to the WTP to calculate concentrations in the water delivered to a family housing or other facility, without considering any contaminant losses during treatment. This was an important assumption of significant impacts, as discussed by Hennet (2024). Therefore, references to historical reconstruction of VOC concentrations hereafter are associated

resulted in evaporative and other losses, reducing contaminant concentrations in the "finished" water. Unlike Hadnot Point and Tarawa Terrace, the Holcomb Boulevard water distribution system itself was not contaminated. However, water quality in the Holcomb Boulevard water distribution network was impacted by the addition of contaminated water from Hadnot Point during interconnection events.

To account for contamination entering the Holcomb Boulevard water distribution network during interconnection events, ATSDR developed a model to simulate water flow in the piping network and the resulting migration of contamination throughout.

Based on my professional judgment, there was insufficient data to conduct groundwater flow and contaminant transport model calibration and uncertainty analysis. In fact, ATSDR admitted that *"[f]or the HPHB study area, data were extracted to compile operational chronologies for nearly 100 supply wells compared to only 16 water-supply well operational chronologies for the TT study area. The substantive increase in the numbers of data values for the HPHB study area compared to the TT study area (Table A2) are indicative of the increase in complexity and difficulty of reconstructing historical contaminant concentrations for the HPHB study area. This point is further highlighted given the multiple source contaminants (3) and numerous contaminant source areas (23) requiring identification and characterization for the HPHB study area as described in Faye et al. (2010, 2012) and discussed in subsequent sections of this report.*"[236]

Given the fact that prior to 1982, no water quality data were available, the resulting calibrated model was highly uncertain. ATSDR's sensitivity and uncertainty analysis evaluated a range of parameter values, some of which, when compared to site-specific data, did not reflect the site conditions. In addition, ATSDR used extreme values for some parameters in their sensitivity analysis. ATSDR then used the results of this sensitivity analysis to draw conclusions on the range of historical concentrations at the influent to the HP WTP.

Additionally, ATSDR's calibrated model is highly uncertain with regard to the start date and magnitude for mass loading from the different contamination sources. As ATSDR indicated in the Hadnot Point–Holcomb Boulevard reports, the model is sensitive to the start date for the release of contamination at Hadnot Point, which could have varied by several years.[237] This would significantly impact the timing and magnitude of concentrations at the water supply wells, and therefore, the water treatment plant. ATSDR focused on the period of interest to the epidemiological studies (1968-1975) but ignored the impact of this uncertainty for years prior to 1968[238].

An uncertainty analysis should provide a range of potential model outcomes that envelops the calibrated model. The calibrated model should generally sit in the middle of the uncertainty range. ATSDR's calibrated model sits at the top of or above the uncertainty range when the potential variability of historical pumping operations was evaluated. This demonstrates that the calibrated model was biased high.

NRC provided recommendations to address modeling hurdles: "*Because any groundwater modeling of the Hadnot Point system will be fraught with considerable difficulties and uncertainties, simpler modeling approaches should be used to assess exposures from the Hadnot Point water system.*

---

with concentrations in the influent to the treatment plant, and not after-treatment "finished" water that entered the water distribution network.

[236] ATSDR-HP, Chapter A, p. A10

[237] "Variations in source-release dates of ±9 years show MCL exceedance-date variations of about 5 years earlier to 14 years later than the calibrated TCE MCL exceedance date (August 1953)." ATSDR-HP, Chapter A, p. A84

[238] "In terms of historical reconstruction results of interest to the ATSDR epidemiological studies (finished-water concentrations of TCE during the period 1968–1985), the variation (and uncertainty due to a lack of data) in source-release dates does not appear to have a substantial effect." ATSDR-HP, Chapter A, p. A84

*Simpler modeling will not reduce the uncertainty associated with the estimates, but they have the advantage of providing a broad picture of the timeframe and magnitude of exposure encountered by people who used water from that system more quickly and with less resources than complex modeling exercises.*"[239] However, as will be shown in the following sections:

- ATSDR implemented the same complex modeling approach as in Tarawa Terrace for PCE and TCE, and only simplified their approach for modeling the VOC degradation by-products;
- The resulting calibrated model was riddled with uncertainties; and
- ATSDR performed limited sensitivity and uncertainty analyses that did not provide any confidence in the calibrated model results or their uncertainty range.

Similar concerns exist for the ATSDR's treatment of the degradation by-products of PCE and TCE (1,2-DCE and VC) and benzene.

### 4.2.1 Available Data are Limited or Non-Existent

To construct the groundwater flow model, ATSDR used available data, which included:

- Horizontal hydraulic conductivities from more than 200 aquifer and slug test analyses;[240]
- Aquifer specific yield and storativity values, based on data from the Tarawa Terrace model;[241] and
- Precipitation data from the Maysville-Hoffman Forest station with records from 1951-1994.[242]

Pumpage information at individual supply wells was not available for the study period. ATSDR developed assumed well pumping schedules and flow rates through a complex process. To do that, they relied on ancillary data.[243]

To construct the contaminant transport model, ATSDR used model parameters that were based on a literature review and the professional judgment of the modelers.

Contaminant concentration data at water supply wells were available in 1984-1985 and up to 1991. Eight samples were collected from water-supply wells after 1991, and up to 2005.[244] Similar to Tarawa Terrace, observed data from the historical period are unavailable prior to 1982. The HP WTP was built in 1942.[245] This means there was a forty-year period for which there is no historical water quality data that could be used to inform the model calibration. Figure 25 depicts ATSDR's Figure 18[246] with an added, yellow-highlighted area to illustrate the historical period of no available data. Appendix E lists the sampling data from the water supply wells and WTP available to ATSDR.

[239] NRC (2009), p. 5

[240] ATSDR-HP, Chapter A, Supplement 4, p. S4.5

[241] ATSDR-HP, Chapter A, Supplement 4, p. S4.18

[242] ATSDR-HP, Chapter A, Supplement 4, p. S4.18

[243] ATSDR-HP, Chapter A, Supplement 2, p. S2.2

[244] ATSDR-HP, Chapter A, pp. A21-22

[245] ATSDR-HP, Chapter A, p. A10

[246] ATSDR-HP, Chapter A, p. A46

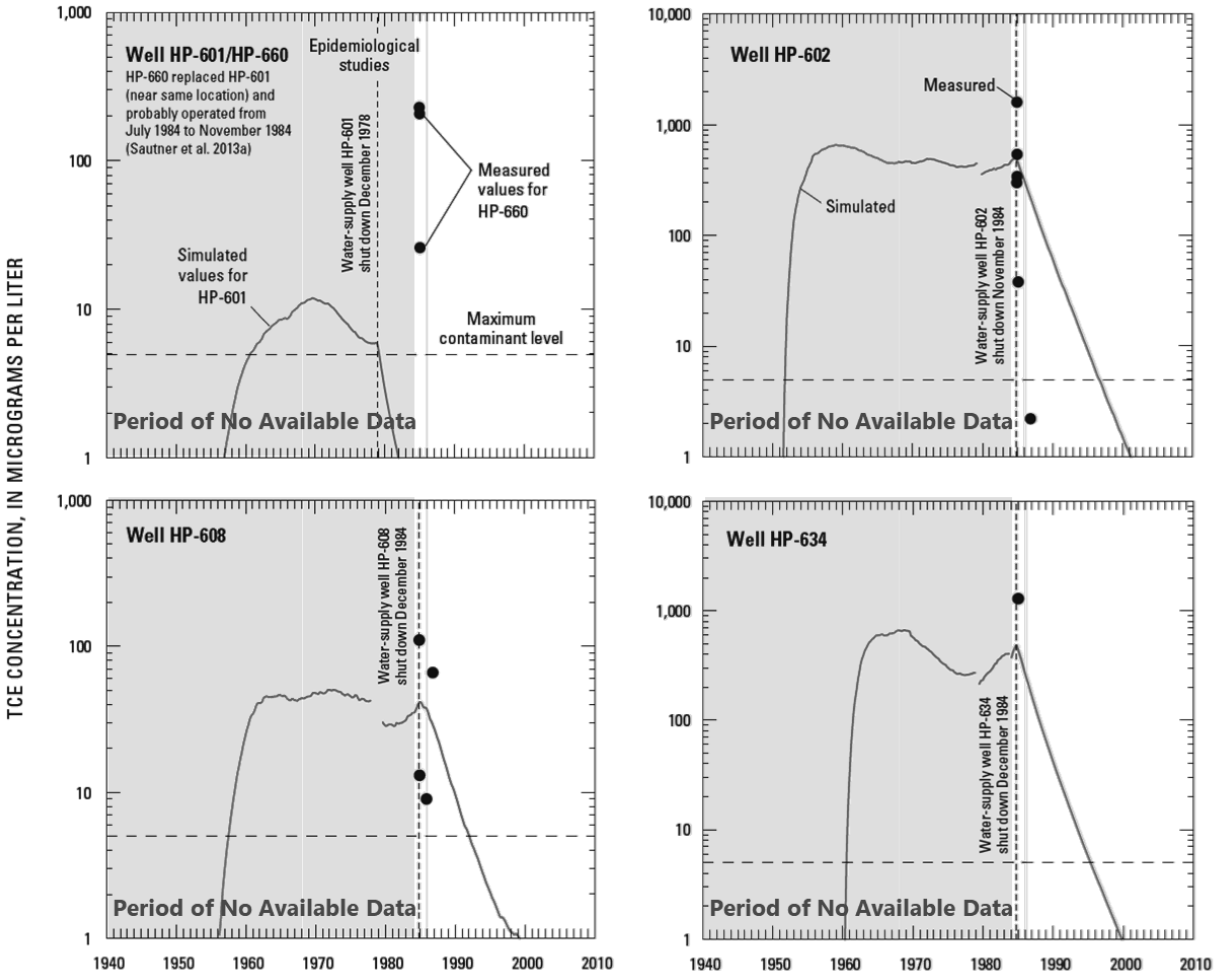



**Figure A18.** Reconstructed (simulated) and measured concentrations of trichloroethylene (TCE) at selected water-supply wells within the Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. Groundwater-flow simulation using MODFLOW (Harbaugh 2005) and contaminant fate and transport simulation using MT3DMS (Zheng and Wang 1999). (See Figure A13 for well locations.)

**Figure 25: Period of No Available Data for ATSDR's Model Reconstruction in Hadnot Point**

**In Summary (Opinion 14): ATSDR relied on very limited data for constructing the groundwater, fate, and transport models for dose reconstruction in Hadnot Point. Selection of model parameters was based, primarily, on professional judgment.**

### 4.2.2 Pumping Reconstruction is Highly Uncertain

As part of its historical reconstruction analysis, ATSDR had to generate an input file for the groundwater flow model to incorporate the historical operation of water supply wells. This is important because well operation impacts groundwater flow and contaminant transport. The model simulates monthly average conditions. Therefore, to develop this input, operational patterns (including hours of operation and associated pumping rates) would be necessary to calculate monthly-average pumping rates for all wells in the HPHB area for the historical period. However, no such data were available.

ATSDR made arbitrary assumptions to reconstruct the pumping history for each well. ATSDR provided the following discussion regarding data availability:

- "*Detailed daily data pertaining to the pumping schedule of the wells are available subsequent to January 1998 (Scott R. Williams, U.S. Marine Corps Base Camp Lejeune, written communication, December 2008).*
- *Prior to 1998, data pertaining to well operations are limited or unavailable.*
- *Similarly, daily WTP raw-water volumes are available after December 1994.*
- *Between 1980 and 1994, monthly raw-water volumes are available;*
- *[Y]early volumes are available for some years prior to 1980. A trendline was used to estimate raw-water flows for years prior to 1980 when no data exist.*"[247]

This information informed ATSDR's assumptions on monthly flows for the period 1980 to 2004. Based on that, ATSDR implemented a complex procedure for calculating monthly flows for the period prior to 1980. ATSDR provided the following discussion regarding this process:

- "*Monthly raw-water flow percentages were then calculated using known monthly data for the period 1980–2004.*
- *These values were used to estimate monthly raw-water flows prior to 1980. This methodology is based on two assumptions:*
- *(1) similar characteristics of the operational patterns of the wells and WTPs for the periods of time before and after January 1998, and*
- *(2) equality between total water volume delivered to the WTP from the operating wells and the WTP raw-water volume data at all times*."[248]

Hence, for the historical period, ATSDR developed uncertain estimates of water flows to the treatment plant based on sparse data and assumptions riddled with uncertainty.

Once ATSDR developed arbitrary and uncertain estimates of WTP raw-water flows for the period 1942 to 1980, they proceeded with developing a complex process for reconstructing a similarly arbitrary and uncertain operation of pumping wells in the HPHB area for the historical period 1942 to 1997. As part of this process, ATSDR had to rely on the following ancillary data: "*(1) daily operational records, January 1998–June 2008 (Scott R. Williams, U.S. Marine Corps Base Camp Lejeune, written communication, December 2008), (2) Camp Lejeune Historic Drinking Water Consolidated Document Repository records (CLHDW CDR 2011), (3) Camp Lejeune Water Documents (CLW 2007), and (4) U.S. Geological Survey (USGS) well inventory documents (USGS, well inventory, written communication, March 2004).*"[249] The ancillary data they used did not include information specific to the well operation and associated pumping rates.

As part of the reconstruction process, ATSDR used data and assumptions from the period 1998 to 2008 (the "training period") to construct operational patterns for the water supply wells that were active during that period. This assumed operational pattern during the "training period" informed ATSDR's complex reconstruction process for the historical period 1942-1997. Thus, it was assumed that a well would

[247] ATSDR-HP, Chapter A, Supplement 2, p. S2.2

[248] ATSDR-HP, Chapter A, Supplement 2, p. S2.2

[249] ATSDR-HP, Chapter A, Supplement 2, p. S2.2

be operated in the historical period based on a pattern similar to the more recent "training period," with further adjustments to account for information on the varying capacity[250] of the wells, where available.

However, to further complicate the process, several wells from the historical period (1942-1998) were not in service during the "training period." For those wells, historical reconstruction of their operational patterns was based on other "surrogate"[251] wells with characteristics that ATSDR considered similar to those wells without available data. The wells not in service during the training period were assumed to have operated in the historical period under the same operational patterns[251] as their corresponding surrogate wells. This is yet another significant assumption, as the historical operational patterns were unknown and "surrogate" well operation introduced additional uncertainty to the historical reconstruction.

Figure 26 lists the pumping wells not in service during the training period, and their corresponding surrogate wells identified by ATSDR. In this figure, select groups of wells are indicated for which operational patterns for the historical period were based on the same surrogate well, to illustrate how extensive this process was and the limited amount of information that was available to reconstruct historical well operations. For example, the operation of well HP-634 for the period 1942-1998 was based on well HP-606, as was the case for wells HP-601, HP-603, HP-608, and HP-660. The operation of another 8 wells (HP-602, HP-604, HP-605, HP-607 (old), HP-630, HP-635, HP-636, and HP-637) was based on well HP-642. Similarly, HP-633 was used as a surrogate for the operation of wells HP-610, HP-651, and HP-653.

The operation during the training and historical period for the three surrogate wells HP-606, HP-633, and HP-642 is illustrated in Figure 27, Figure 28, and Figure 29, respectively. These figures demonstrate how limited information was available for reconstructing past operations. They also demonstrate how arbitrary this reconstruction was, considering that only limited data were available for any individual well. Yet, ATSDR estimated monthly operational histories for each well based on several highly uncertain assumptions. It is also important to note that well operation during the training period addressed different requirements for raw-water delivery to the WTP compared to the historical period and, therefore, "lessons-learned" from one period cannot be directly transferred to another.

ATSDR developed this complex reconstruction process for defining monthly pumping rates of all wells in the HPHB area, based on arbitrary assumptions for schedules of operation, well conditions, and operator choices for which wells to operate at any given time. This injects a high degree of uncertainty into the HPHB model.

[250] The capacity of a well varies with time, due to clogging of the well screen (accumulation of sediments, mineral deposits, or growth of microorganisms), infrastructure issues (pump efficiency), among other (Glotfelty, 2019)

[251] ATSDR-HP, Chapter A, Supplement 2, p. S2.13

**Table S2.2.** Identification of surrogate water-supply wells used to represent untrained wells, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[Refer to Figure S2.1 for water-supply well locations and Figure S2.2 for operational chronologies]

| Water-supply wells | |
|---|---|
| **Untrained** | **Surrogate** |
| **Holcomb Boulevard water treatment plant service area** | |
| HP-645 | HP-644 |
| HP-649 | HP-648 |
| HP-706 | HP-705 |
| HP-707 | HP-704 |
| **Hadnot Point water treatment plant service area** | |
| HP-601 | HP-606 |
| HP-602 | HP-642 |
| HP-603 | HP-606 |
| HP-604 | HP-642 |
| HP-605 | HP-642 |
| HP-607 (old) | HP-642 |
| HP-608 | HP-606 |
| HP-609 | HP-628 (new) |
| HP-610 | HP-633 |
| HP-611 (old) | HP-623 |
| HP-612 (old) | HP-607 (new) |
| HP-614 (old) | HP-622 |
| HP-615 | HP-616 |
| HP-617 (old) | HP-654 |
| HP-618 (old) | HP-641 |
| HP-619 (old) | HP-620 |
| HP-621 (old) | HP-629 (new) |
| HP-624 | HP-628 (new) |
| HP-625 | HP-662 |
| HP-626 | HP-628 (new) |
| HP-627 (old) | HP-661 |
| HP-628 (old) | HP-662 |
| HP-629 (old) | HP-640 |
| HP-630 | HP-642 |
| HP-631 | HP-652 |
| HP-634 | HP-606 |
| HP-635 | HP-642 |
| HP-636 | HP-642 |
| HP-637 | HP-642 |
| HP-638 | HP-628 (new) |
| HP-639 (new) | HP-662 |
| HP-639 (old) | HP-662 |
| HP-651 | HP-633 |
| HP-653 | HP-633 |
| HP-655 | HP-662 |
| HP-660 | HP-606 |
| LCH-4006 | LCH-4009 |
| M-1 | LCH-4009 |
| M-2 | LCH-4007 |

**Figure 26: ATSDR Surrogate Water-Supply Wells**

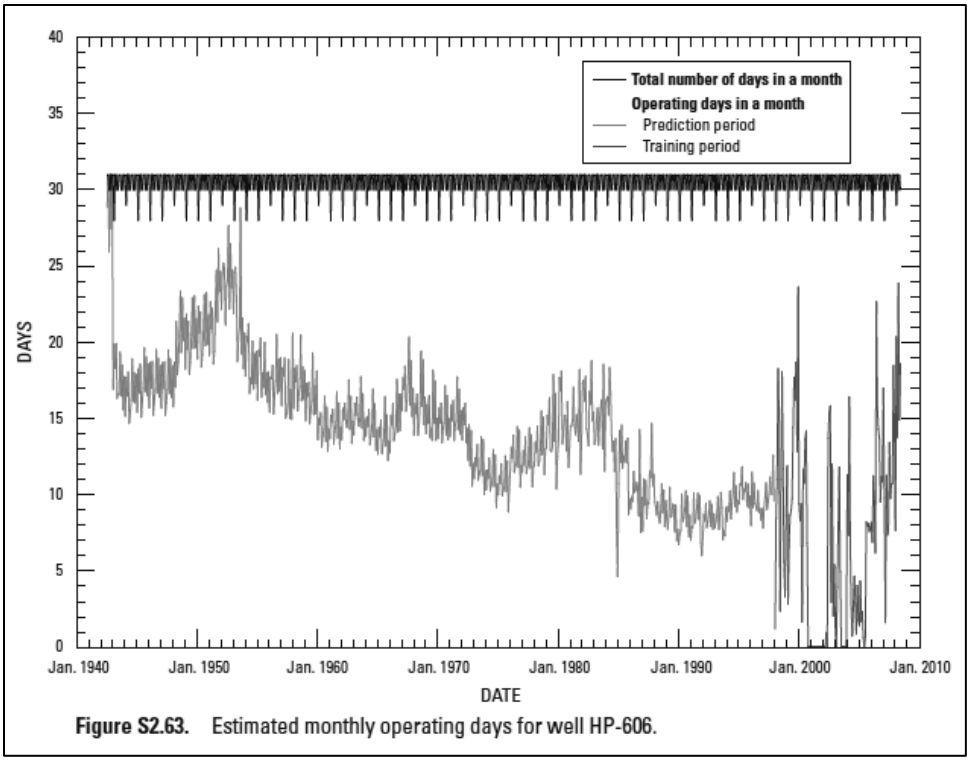



**Figure 27: Training and Prediction Period Operation of Surrogate Water-Supply Well HP-606**

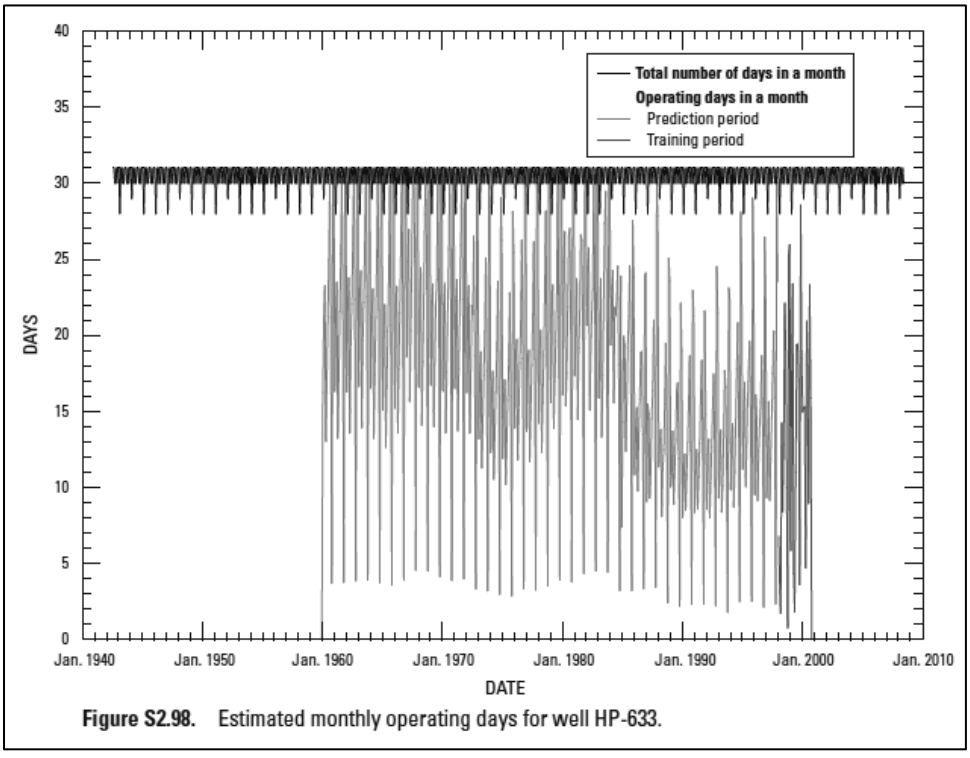



**Figure 28: Training and Prediction Period Operation of Surrogate Water-Supply Well HP-633**

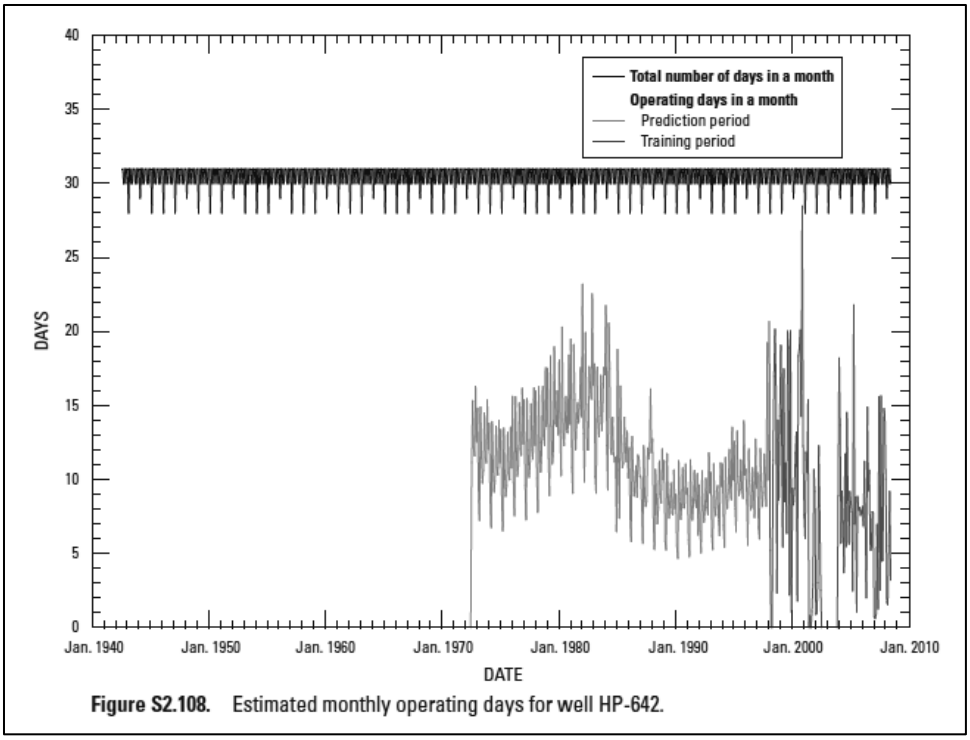


Figure S2.108. Estimated monthly operating days for well HP-642.

**Figure 29: Training and Prediction Period Operation of Surrogate Water-Supply Well HP-642**

**In Summary (Opinion 14): ATSDR relied on very limited data for constructing its model for Hadnot Point. Selection of model parameters was based, primarily, on professional judgment. ATSDR made arbitrary assumptions and implemented a complex methodology with significant inherent uncertainty to reconstruct the pumping history for each well.**

### 4.2.3 ATSDR's Model Calibration was Based on Limited Data and was Biased High

ATSDR conducted its calibration of the HPHB transient groundwater flow model relying on a very limited data set. As ATSDR admitted, "*only a few monitor wells in the study area contained continuous water-level data useful for assessment and calibration of the transient model*."[252] In addition, the variability in hydrogeologic features in the subsurface of the model was identified by ATSDR as a limitation.[253] as it was based on limited geophysical data. As a result, the variability in aquifer stratigraphy was consolidated in the model layer structure, simplifying aquifer complexity.

Recall that the monthly pumping rates of all wells in the model were developed using a complex reconstruction process based on arbitrary assumptions. These rates were fixed but uncertain, and underpinned model performance. Aquifer parameters were adjusted during model calibration to fit changes in water-level data caused by changes in pumping rates, among other factors.

The contaminant transport model was constructed based on numerous assumptions on parameter values as site specific data were limited or nonexistent. This problem was exacerbated by the fact that the assignment of source-release location, timing, and mass loading were unknown.[254] These quantities were

[252] ATSDR-HP, Chapter A, Supplement 4, p. S4-24

[253] ATSDR-HP, Chapter A, Supplement 4, p. S4-34

[254] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

arbitrarily assigned to the model. As a result, forty years of aquifer conditions and potential contamination, after 1942, were calibrated to limited water quality data available starting in 1982. Therefore, a statistical evaluation of the contaminant transport model calibration could not be performed due to insufficient water quality data.

In one instance, model calibration was improperly influenced by the interpretation of sampling data. Erroneous concentrations reported for well HP-634 were used in the calibration, while non-detections were ignored.

A discussion on ATSDR's calibration of the groundwater flow and contaminant transport models is provided below.

#### 4.2.3.1 The Groundwater Flow Model has Significant Limitations in the Absence of Data for Calibration

ATSDR calibrated its groundwater flow model combining a trial-and-error approach with automated parameter estimation.[255] The steady-state model, constructed for simulating pre-development conditions (i.e., ambient groundwater flow in the absence of pumping), was calibrated using more than 700 water-level measurements.[256] The transient-state model simulated conditions from January 1942 to June 2008, and was calibrated using a much smaller dataset as "*only a few monitor wells in the study area contained continuous water-level data useful for assessment and calibration of the transient model*"[257]

For the calibration of the groundwater flow model, ATSDR provided a discussion[258] addressing key issues related to the available data and model limitations. In the introductory paragraph of the discussion, ATSDR stated the following: "*Analyses and interpretations of the groundwater-flow model results should be considered in the context of model limitations and accuracy of water-level data. Results from the calibrated groundwater-flow model are used to estimate contaminant concentrations in groundwater; therefore, it is also important to consider the accuracy of the flow model results in the context of contaminant fate and transport results*."[259]

Recall that the subsurface is composed of stratified units, each with different characteristics that must be accounted for in the model. The variability in hydrogeologic features in the subsurface of the model was identified by ATSDR as a limitation, as it was based on limited geophysical data: "*the thickness of hydrogeologic units should be considered an approximation.*"[260] ATSDR continued, stating that "*multiple hydrogeologic units were combined into multiple layers. For example, layers 1 and 5 contain multiple hydrogeologic units (Table S4.1). However, contaminant transport model results typically are more sensitive than groundwater-flow model results to the combination of multiple hydrogeologic units in a model layer.*"[261] This means that ATSDR consolidated multiple geologic features into single layers of the model. This impacts the simulation of contaminant transport in the aquifer, making it inherently uncertain.

ATSDR identifies additional model limitations associated with model features such as drains, specified head boundaries, or no-flow boundaries, given that no historical data were available to properly represent these features in the model, adding to model uncertainty.[262]

---

[255] ATSDR-HP, Chapter A, Supplement 4, p. S4.21

[256] ATSDR-HP, Chapter A, Supplement 4, p. S4-24

[257] ATSDR-HP, Chapter A, Supplement 4, p. S4.24

[258] ATSDR-HP, Chapter A, Supplement 4, p. S4.34

[259] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

[260] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

[261] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

[262] ATSDR-HP, Chapter A, Supplement 4, p. S4.35

ATSDR also concluded that parameter estimation was successful in determining hydraulic conductivities in layers 1, 3, and 5.[263] However, ATSDR also stated that "*[m]ore rigorous sensitivity analyses could be conducted by computing the covariance matrix. However, initial simulations indicated that computing the covariance matrix using parameter estimation was time prohibited in terms of computational times using equipment available to authors at the time model calibration and sensitivity analyses were conducted.*"[264] This statement indicates that a more rigorous sensitivity analysis would be warranted to ensure that the estimated parameters were within reasonable bounds, but that it was never conducted.

**In Summary (Opinion 14): ATSDR relied on very limited data for calibrating its flow model for Hadnot Point. ATSDR identified significant model limitations associated with model features, and especially geologic representations. The lack of calibration data and the identified model limitations had substantial impacts on the quality of ATSDR's model calibration.**

#### 4.2.3.2 The Contaminant Transport Model is Constructed Using Uncertain Assumptions

For the calibrated contaminant transport model, ATSDR stated that "*insufficient water-quality data existed to conduct a statistical analysis for assessment of model calibration fit*."[265] ATSDR therefore admitted that it could not perform a quantitative assessment of the model calibration fit. This would require water-quality data from the historical period to constrain the calibration. As a result, only a qualitative assessment of the model calibration was performed.

This problem was further exacerbated by the following admission by ATSDR: "*specific data pertinent to the timing of initial deposition of contaminants to the ground or subsurface, chronologies of waste-disposal operations, such as dates and times when contaminants were deposited in the HPLF, or descriptions of the temporal variation of contaminant concentrations in the subsurface generally are not available*."[266] ATSDR therefore acknowledged that critical information on contaminant sources was unavailable. Recall NRC's critique that "*any groundwater modeling of the Hadnot Point system will be fraught with considerable difficulties and uncertainties.*"[267]

Despite this critical lack of data, ATSDR proceeded with model construction and calibration. According to ATSDR, *"Determining these types of source identification and characterization data became part of the historical reconstruction process, whereby the contaminate fate and transport model was used to test source locations, varying concentrations, and beginning and ending dates for leakage and migration of source contaminants to the subsurface and the underlying groundwater-flow system*."[268] ATSDR therefore admitted that source-release locations, timing, and mass loading were unknown, and these quantities were arbitrarily assigned to the model in order to fit the limited water-quality data available starting at 1982.

For example, ATSDR assigned the same, constant TCE concentration at all sources in the HP Industrial Area. Specifically, as illustrated in Figure 30, ATSDR assumed that contamination released from the source at Building 1601 resulted in TCE concentrations across three layers in the aquifer at that location

---

[263] "*Therefore, parameter estimation was appropriate for the steady-state model calibration phase to determine recharge and hydraulic conductivity for layers 1, 3, and 5*." ATSDR-HP, Chapter A, Supplement 4, p. S4.35

[264] ATSDR-HP, Chapter A, Supplement 4, p. S4.35

[265] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

[266] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

[267] NRC (2009), p.5

[268] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

which were equal to 640,000 µg/L on a monthly basis for a period of 42 years.[269] This value is arbitrary and unverifiable, as no site-specific data are available to support reconstructing the history of releases or quantifying their associated magnitude. The assumption that a constant mass loading of the same magnitude occurred at all sources for more than 40 years is highly uncertain and indicates the type of assumptions that were made for the historical reconstruction.

**Table S6.5.** Calibrated contaminant fate and transport model parameter values used to describe contaminant sources in the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

| Source area[1] | Cell location (row, column, layer)[2] | Concentration, in milligrams per liter | Source duration |
|---|---|---|---|
| Trichloroethylene (TCE) | | | |
| Building 1601 | 165, 116, 1–3 | 640 | January 1951–June 1993 |
| Building 900 area | | | |
| Source 1 | 102, 178, 1–3 | 640 | January 1957–December 1994 |
| Source 2 | 108, 179, 1–3 | | |
| Source 3 | 113, 173, 1–3 | | |
| Building 1401 | 122, 138, 1–3 | 640 | January 1951–June 1993 |
| Building 1115 | 145, 121, 1–3 | 640 | January 1951–June 1993 |
| Landfill area | | | |
| Source 1 | 159, 156, 1–7 | 256–384 | January 1948–June 2008 |
| Source 2 | 154, 145, 1–7 | | |
| Tetrachloroethylene (PCE) | | | |
| Landfill area | | | |
| Source 1 | 159, 156, 1–5 | 16–105 | January 1948–June 2008 |
| Source 2 | 154, 145, 1–5 | 6–42 | |
| Benzene | | | |
| Building 1601 | | | |
| Source 1 | 168, 117, 1 | 1.7 | January 1951–June 1993 |
| Source 2 | 171, 113, 1 | | |

[1] Refer to Figures S6.2 and S6.3 for maps showing location

[2] Cell location corresponds to their respective models (i.e., HPIA or HPLF). Cell location with coordinates row 1, column 1 and layer 1 corresponds to the northwest corner and uppermost cell of the total model domain

**Figure 30: Contaminant Sources in the HPHB Transport Model (ATSDR, Table S6.5)**

ATSDR also assigned TCE sources at Buildings 1115 and 1401 (Figure 30). Unlike other sources, for which ATSDR provided supporting information regarding their location and nature, for these two buildings ATSDR indicated the following: "*TCE releases around Buildings 1115 and 1401 have been documented to a lesser degree*."[270] ATSDR continued indicating that "*[t]he presence of chlorinated alkenes around Building 1115 is documented by Faye et al. (2012, Table D5), and the concentrations varied from below detection limits to maximum values of 160 µg/L for TCE, 11 µg/L for PCE, 110 µg/L for total DCE, and 6 µg/L for VC. The chlorinated alkenes found around Building 1115 are presumably the result of natural attenuation of TCE*."[271] All this is to say that ATSDR relied on limited information about the presence and extent of contamination at those locations and assigned source releases of which the timing and magnitude were arbitrary.

[269] ATSDR-HP, Chapter A, Supplement 6, p. S6.17

[270] ATSDR-HP, Chapter A, Supplement 6, p. S6.6

[271] ATSDR-HP, Chapter A, Supplement 6, p. S6.6

With regard to transport parameters in the model, and particularly sorption, ATSDR stated that "*[s]orption in the HPHB study area is assumed to be similar to sorption in the TT study area of USMCB Camp Lejeune described in Faye (2008)*."[272] However, as indicated in the discussion for the Tarawa Terrace model, there are important differences in the calculation of the sorption-related parameters between the two models. In the HPHB model, the value of bulk density was substantially different than the value used in the TT model. ATSDR used a bulk density value of 1.65 g/cm$^3$ for Hadnot Point and Holcomb Boulevard. This is significantly lower than the 2.7 g/cm$^3$ used in the Tarawa Terrace model.

Additionally, ATSDR selected a $K_d$ value of 0.30 mL/g[273] for PCE, which was different than the Tarawa Terrace value of 0.14 mL/g, even though the same soil characteristics are encountered in both areas.[274] Using these values for bulk density and $K_d$, the resulting retardation factor for PCE in Hadnot Point was 3.5. This value is much higher than the retardation factor of 2.93 that ATSDR used in the Tarawa Terrace model. Recall that a higher retardation factor means slower contaminant migration in groundwater.

**In Summary (Opinion 14): ATSDR relied on very limited data for calibrating its fate and transport model for Hadnot Point. ATSDR admitted that they could not perform a rigorous evaluation of the model calibration, due to insufficient water-quality data. ATSDR made several arbitrary assumptions for assigning source-release locations, timing, and mass loading, to fit the limited water-quality data. ATSDR assumed constant mass loading of the same magnitude at all sources for more than 40 years, which is highly uncertain, if not impossible. This is indicative of the type of assumptions that were made by ATSDR for constructing its historical reconstruction model. ATSDR assigned model parameter values that were not based on site-specific data and were inconsistent with the values they used for the Tarawa Terrace model.**

#### 4.2.3.3 HP-634 Concentration Data were Incorrectly Interpreted

ATSDR's interpretation of the available sampling data at well HP-634 is incorrect. When reviewing the sampling data and the operation of well HP-634 during the period encompassing these sampling events, it is unlikely that this well was ever contaminated with elevated TCE concentrations, as ATSDR assumed.

A sample collected from well HP-634 on December 4, 1984, while the well was in operation, was a non-detection. The well ceased operations on December 6, 1984.[275] Another sample collected on December 10, 1984 was a non-detection.[276] However, a sample from January 16, 1985, when the well had been out of service for more than a month, had a reported concentration of 1,300 µg/L.[276] Two more samples collected in 1986 and 1991 were also non-detections.[276]

ATSDR assigned two sources in the model near well HP-634.[277] However, well HP-634 is located upgradient of these source locations and, therefore, contamination could not have reached that well when it was not operational. But even when the well was operational, the December 4, 1984, sample was a non-detection. Therefore, the reported concentration of 1,300 µg/L from the sample collected on January 16, 1984, when the well was not in service, should be considered erroneous. See Dr. Hennet's expert report for a more detailed discussion of this issue.[278]

---

[272] ATSDR-HP, Chapter A, Supplement 6, p. S6.14

[273] ATSDR-HP, Chapter A, Supplement 6, p. S6.14

[274] See geohydrologic section A-A' in Hadnot Point-Holcomb Boulevard study area (ATSDR-HP, Chapter B, p. B12

[275] CLW0000006590

[276] ATSDR-HP, Chapter A, Table A4, p. A21

[277] Sources 1 & 2 in the HPIA

[278] Hennet (2024), Expert Report

However, ATSDR ignored the non-detections at HP-634 during model calibration and assigned a constant TCE concentration of 640,000 µg/L in layers 1, 2 and 3 for Sources 1 and 2, so that the historical reconstruction of concentrations at HP-634 would be close to the highest value reported (1,300 µg/L). Based on the rationale presented above, the source strength at those locations is substantially exaggerated and not supported by data. See more details in the discussion provided in Dr. Hennet's expert report.

If, instead, a lower mass loading at Sources 1 and 2 were considered, reconstruction of TCE concentrations at well HP-634 and the influent to the HP WTP would be lower. Such an adjustment would not fully eliminate the source in that area. The source adjustment would acknowledge some uncertainty in the sampling data and history of contamination at that well, given the findings in the soils near ground surface (see Hennet, 2024). For example, reducing the mass loading to 10% of the value specified in the ATSDR model, model simulated concentrations would be only a fraction of those calculated by ATSDR at well HP-634, but much closer to the non-detections observed at that well. This would also result in lower concentrations at influent to the treatment plant over the period 1962-1972. Figure 31 depicts the historical reconstruction of TCE concentrations at well HP-634 when such a reduction in mass loading is implemented.[279] The historical reconstruction of TCE concentrations in the influent to the treatment plant is depicted in Figure 32.

However, the Hadnot Point model is riddled with uncertainties and, therefore, the correction implemented in the model should not be considered as the only possible adjustment to the model inputs. These graphical representations serve only to demonstrate how variable the model outputs are to changes in parameters. They should not be interpreted as definitive, mean monthly concentrations of contaminants in the influent to the WTP.

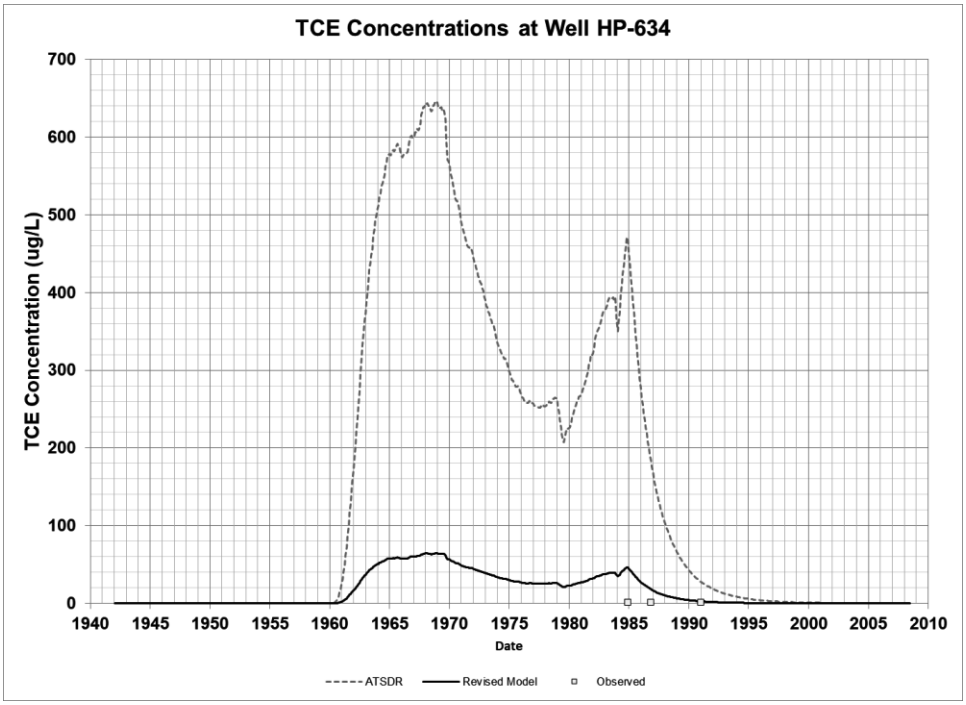



**Figure 31: Changes in Model Simulated TCE Concentrations at Water-Supply Well HP-634 After Source Mass-Loading Correction**

[279] The erroneous concentration of 1,300 µg/L is not depicted in this plot.

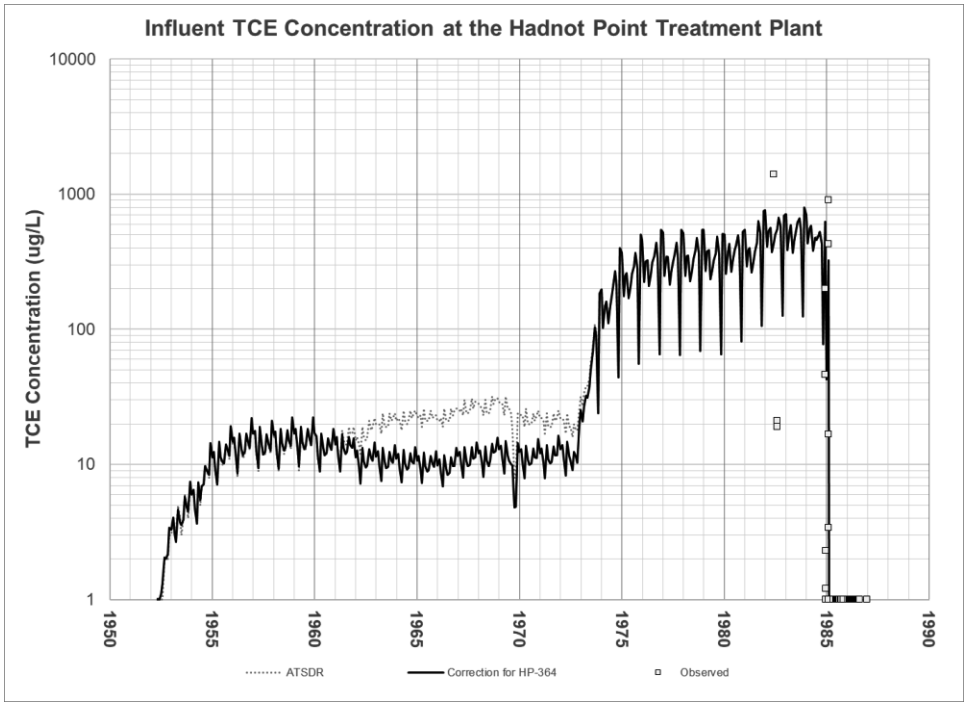



**Figure 32: Changes in Model Simulated Historical Reconstruction of TCE Concentrations in the Influent to the HP WTP after Source Mass-Loading Correction**

**In Summary (Opinion 14 and 15): ATSDR incorrectly interpreted field sampling data. ATSDR focused on an elevated, but likely erroneous, concentration value, and ignored multiple non-detections reported for that well. Hence, ATSDR assumed presence of contamination in an area where the available data indicated either the absence or presence of only traces of contamination. ATSDR included the erroneous, elevated concentration value in its model calibration and ignored the non-detections, resulting in conservative and biased-high simulated concentrations, not representative of aquifer conditions.**

### 4.2.4 VOC Degradation By-Products

ATSDR used the Linear Control Model (LCM), an alternative methodology for reconstructing the historical concentrations of the VOC degradation by-products. Unlike MODFLOW and MT3DMS, the LCM does not simulate the physical and chemical processes in the aquifer. As ATSDR indicated, the LCM "*does not require site-specific knowledge of the spatial distribution of aquifer and transport properties (e.g., hydraulic conductivity, porosity, contaminant source concentration).*"[280] Instead, the method "*characterizes the aquifer, contaminant sources, and the dynamics of contaminant migration as a 'black box.*"[281]

ATSDR applied this methodology to reconstruct concentrations at well HP-651 and then used a simple mixing model to calculate the blended concentration at the HP WTP. Application of this methodology relied on the same limited set of observed data, available after 1985. As illustrated in Figure 33, the historical reconstruction prior to 1985 cannot be verified, due to lack of observed data for the period.

[280] ATSDR-HP, Chapter A, p. A37

[281] ATSDR-HP, Chapter A, p. A37

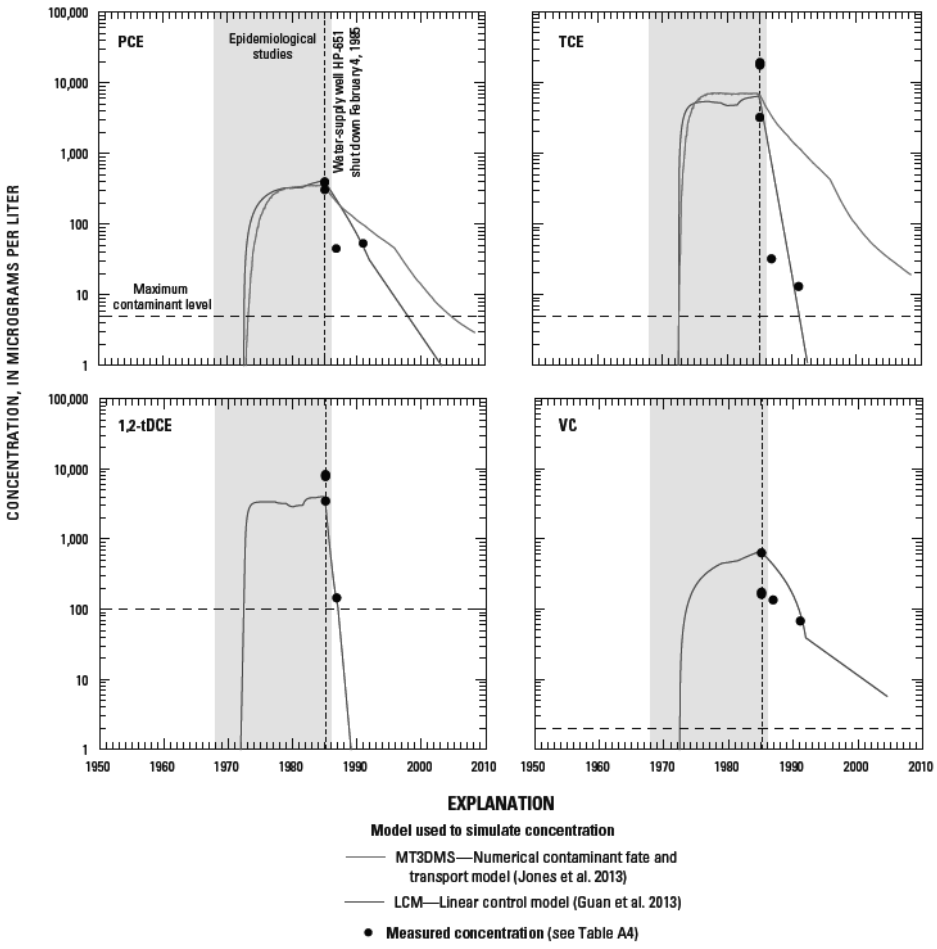



**Figure A25.** Reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at water-supply well HP-651 using numerical (MT3DMS) and linear control methodology (TechControl) models, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A14 for well location.)

**Figure 33: ATSDR's Model Simulated Concentrations of PCE, TCE, and their Degradation By-Products at Well HP-651**

**In Summary (Opinion 16): ATSDR used a "black box" for the historical reconstruction of VOC degradation by-products in Hadnot Point. However, the simulated historical reconstruction was not calibrated to historical data, as such data were not available prior to December 1984. Therefore, the estimated monthly contaminant concentrations cannot be verified.**

#### 4.2.5 Sensitivity and Uncertainty Analyses

ATSDR conducted a sensitivity analysis to evaluate the effect of variation of model input parameter values on model outputs. According to ATSDR, "*the results from all sensitivity analyses were used to define a range of finished-water concentrations at the HPWTP*." [282]

ATSDR also performed an uncertainty analysis of limited scope and magnitude, focusing on the "*effect of uncertainty in the pumping schedules of water-supply wells.*"[283]

Important aspects and conclusions of the sensitivity and uncertainty analyses are discussed below.

##### 4.2.5.1 Sensitivity Analysis Results are Incorrectly Presented as Uncertainty Ranges

A discussion on key aspects of the sensitivity analysis conducted by ATSDR is provided in the sections below.

###### 4.2.5.1.1 The Start Date of Source Releases is Highly Uncertain

As mentioned above, ATSDR admitted that "*specific data pertinent to the timing of initial deposition of contaminants to the ground or subsurface, chronologies of waste-disposal operations, such as dates and times when contaminants were deposited in the HPLF, or descriptions of the temporal variation of contaminant concentrations in the subsurface generally are not available.*"[284] In the absence of this critical information, reconstruction of historical conditions is highly uncertain. The timing and magnitude of contaminant releases in the soils at Camp Lejeune, their downward migration to the aquifers below, and ultimately their travel in groundwater before reaching the pumping wells, are unknown.

One type of contaminant source that ATSDR considered in the Hadnot Point model is underground storage tanks (USTs). Historical records for the start date of releases from UST systems were not available.[285] ATSDR formulated a rationale for delineating the start date of such releases from USTs, considering probable installation dates and data from a U.S. Environmental Protection Agency (EPA) study of UST releases.[286] The EPA report published in 1986 included an analysis of 12,444 leak incident reports across the United States.[287] These results indicated that the mean and median time of UST leaks was 11 and 9 years, respectively.[286] ATSDR used the median value of 9 years from the assumed installation date of the USTs to assign contaminant release start dates in the calibrated model.[286] The empirical data for UST releases may or may not be applicable to the USTs installed at Camp Lejeune and, therefore, assignment of timing and magnitude for these sources is arbitrary and uncertain.

ATSDR selected a source-release timeframe of 7 years for the landfill area based on the following rationale: "*given the lack of historical information, a similar source-release time frame, in this case 7 years from site development, was applied to HPLF-area sources within the model. The shorter source-release time frame acknowledges that landfill disposal likely encompassed a range of contained and uncontained source materials, in contrast to the engineered tank and piping system sources discussed previously*."[288]

---

[282] ATSDR-HP, Chapter A, Supplement 6, p. S6.32

[283] ATSDR-HP, Chapter A, Supplement 6, p. S6.44

[284] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

[285] ATSDR-HP, Chapter A, Supplement 6, p. S6.16

[286] ATSDR-HP, Chapter A, Supplement 6, p. S6.16

[287] The number of leak incident reports analyzed by USEPA (1,244) and the associated referenced document are incorrectly stated in ATSDR's report (Chapter A, Supplement 6, p. S6.16). The correct number is 12,444 (USEPA, 1986, "*Summary of State Reports on Releases from Underground Storage Tanks*," EPA/600/M-86/020, August 1986)

[288] ATSDR-HP, Chapter A, Supplement 6, p. S6.42

This statement further reinforces the argument regarding the arbitrary and uncertain timing and magnitude of contaminant source releases implemented in the model.

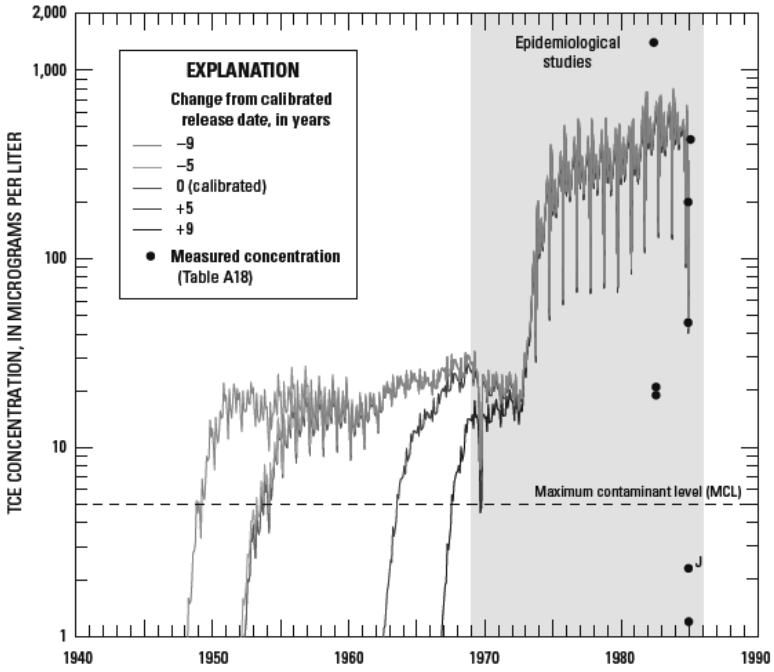
ATSDR proceeded to assess the model sensitivity to source-release dates by simulating scenarios where the start date was modified by ±5 and ±9 years.[289] This means ATSDR compared the calibrated model to models where the contamination release at each source began:

- 9 years before the calibrated model;
- 5 years before the calibrated model;
- 5 years after the calibrated model; and
- 9 years after the calibrated model.

The results of the corresponding calculations are depicted in Figure 34. ATSDR's sensitivity analysis results for these scenarios demonstrated the impacts of the arbitrary and uncertain assignment of source release timeframe and magnitude. Depending on when ATSDR assumed source releases began, contamination could have arrived at the pumping wells as early as 1948 or as late as 1967. This is a very wide timeframe, over which groundwater may or may not have been contaminated. It is also important to recall that, according to ATSDR "*[t]he core period of interest for the epidemiological studies is 1968–1985.*"[238]

The timing and magnitude of contaminant releases to the soils in Camp Lejeune are some of the most important parameters in the historical reconstruction of contaminant concentrations in the influent to the WTP. Without this critical information, any calculation on the arrival of contamination to the pumping wells is highly uncertain**.** ATSDR's sensitivity analysis on the source-release start date illustrates that it is impossible to know when such releases occurred, and there are no data to confirm or reject any hypothesis on those dates. Hence, it is not possible to validate the results of the calibrated model or any of the other sensitivity or uncertainty analyses performed by ATSDR and, therefore, the historical reconstruction of contamination in HPHB is arbitrary and uncertain.

[289] ATSDR-HP, Chapter A, Supplement 6, p. S6.42




| [1]Change from calibrated release date, in years | First month exceeding MCL | Concentration at start of epidemiological study (January 1968), in micrograms per liter | Maximum concentration during epidemiological study period (January 1968–December 1985), in micrograms per liter |
|---|---|---|---|
| –9 | November 1948 | 26 | 800 |
| –5 | April 1953 | 26 | 798 |
| 0 (calibrated) | August 1953 | 27 | 783 |
| +5 | August 1963 | 23 | 748 |
| +9 | August 1967 | 7 | 740 |

[1]Calibrated release date varies by source location (Table A13)

Note:
–9 years means 9 years earlier than calibrated-source release date
+9 years means 9 years after calibrated-source release date

**Figure A37.** Reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived from variations in contaminant-source release dates, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [J, estimated]

**Figure 34: Results of Sensitivity Analysis on Source Release Start Date**

**In Summary (Opinion 17): ATSDR conducted a sensitivity analysis to assess the impact of different source-release start dates on groundwater contamination. This is because there are no observed data about the actual time when USTs or other sources started to release contamination in the soil. As a result, it is not possible to confidently determine the actual period of groundwater contamination and, therefore, ATSDR's historical reconstruction is highly uncertain.**

#### 4.2.5.1.2 Sensitivity Analysis Scenarios Considered Extreme Parameter Values, and the Biased-High Results were Incorrectly Presented as Uncertainty Bounds

ATSDR constructed three scenarios to explore parameter sensitivity for the historical reconstruction of PCE and TCE concentrations.[290] In each scenario, the values of select hydraulic, fate, and transport model parameters were varied, and the resulting PCE and TCE concentrations in the influent to the WTP were calculated from the corresponding model results. The scenarios that ATSDR evaluated were the following:

- Scenario 1: Kxx, C, n, and $\alpha_L$
- Scenario 2: Kxx, I, C, $K_d$, and $\lambda$
- Scenario 3: Kxx, I, C, n, $\alpha_L$, $K_d$, and $\lambda$

where:

Kxx: horizontal hydraulic conductivity in Layer 3 (the most sensitive layer to hydraulic conductivity variability)

I: infiltration (areal recharge)

C: contaminant source concentration

n: porosity (effective; not total)

$a_L$: longitudinal dispersivity

$K_d$: distribution coefficient

$\lambda$: biodegradation rate

In these scenarios, ATSDR conducted an ensemble of model simulations that were part of a sensitivity analysis but essentially resembled a form of uncertainty analysis. Unlike a sensitivity analysis, which explores model response to parameter variability, uncertainty analysis is used to construct a range of possible outcomes. ATSDR claimed that they performed a sensitivity analysis, but presented the results as if it provided an uncertainty range. As will be illustrated below, the resulting range is not a reliable estimate of the possible uncertainty of model results, as the assumptions underpinning this analysis are not consistent with assumptions built into the calibrated flow and transport model. In fact, by doing so ATSDR conflated the sensitivity and uncertainty analyses.

In order to construct these sensitivity scenarios, ATSDR selected, for each parameter, the two extremes of the range of values for this parameter and ran the model twice, one using the minimum value of the parameter and one with the maximum value. For example, the two values selected for the hydraulic conductivity in Layer 3 were equal to 0.1 and 10 times the calibrated value.[291] Thus, if the horizontal hydraulic conductivity in the HPIA varies between 1 to 50 ft/d,[292] the values used in the sensitivity scenario would be as low as 0.1 ft/d, or as high as 500 ft/d.

To understand the importance of this assumption, recall that, for the Tarawa Terrace uncertainty analysis, ATSDR defined reasonable ranges for the calibrated parameter values. Regarding the variability in hydraulic conductivity, uncertainty realizations with hydraulic conductivity values that would exceed an acceptable range of model calibration were excluded from the analysis. No such caution was applied in the sensitivity analysis for Hadnot Point and Holcomb Boulevard. The values used in the HPHB sensitivity

[290] ATSDR-HP, Chapter A, p. A79

[291] ATSDR-HP, Chapter A, p. A79

[292] ATSDR-HP, Chapter A, p. A41

analysis represented two extremes of the range. Recall that for the uncertainty analysis in Tarawa Terrace, ATSDR implemented filtering criteria to reject implausible realizations that would violate calibration criteria for the groundwater flow model. In the HPHB sensitivity analysis such criteria were not implemented.

The implication of this choice is ATSDR used the calibrated model for this analysis, but then they varied parameter values to extremes, without evaluating how that would impact model calibration. Thus, either the model was reasonably calibrated (and, therefore, such wide range of parameter values was not warranted), or the model was not reasonably calibrated (and, therefore, a wide range of parameter values was warranted).

This issue is further exacerbated by ATSDR's use of extreme values for fate and transport simulations in Hadnot Point. The discussion below illustrates the implications of this approach.

Recall that in the Tarawa Terrace model, ATSDR defined a range of values for transport parameters based on literature sources and professional judgment. ATSDR proceeded with defining probabilistic distributions of these parameters, to calculate parameter value ranges for the uncertainty analysis (Section 4.1.2.2). The probabilistic distributions forced parameter ranges to vary closely around the mean value of the parameter, which was determined during model calibration.

For the Hadnot Point model, ATSDR did not conduct such an analysis for defining appropriate parameter ranges. Instead, ATSDR selected extreme values for the fate and transport parameters, corresponding to the 2.5 and 97.5 percentile of the parameter range. Table 2 lists the parameter values that ATSDR used for calculating the retardation factor for their sensitivity analysis.

It is important to understand the impact of selecting such extreme parameter values, and especially the maxima of these ranges. For example, a porosity value of 0.11 means that groundwater velocities can be double the mean, calibrated value. Recall that for the Tarawa Terrace analysis (Section 4.1.3.2), ATSDR used a porosity value that, on average, was equal to the calibrated value of 0.2. In other words, in Tarawa Terrace the uncertainty analysis included 840 realizations for which porosity was, on average, unchanged from the calibrated value. However, in Hadnot Point, the sensitivity analysis was presented in lieu of an uncertainty analysis, and calculations used values 50% higher or lower than those ATSDR deemed reasonable for the Tarawa Terrace uncertainty analysis.

**Table 2. ATSDR's Sensitivity Analysis Range of Parameter Values for Calculating the Retardation Factor for PCE and TCE in Hadnot Point[a]**

| Contaminant | Statistic | $K_d$ (mL/g)[b] | Porosity | Bulk Density ($g/cm^3$)[c] |
|---|---|---|---|---|
| PCE | Mean | 0.31 | 0.20 | 1.66 |
| | Minimum (2.5 Percentile) | **0.15** | **0.11** | 1.62 |
| | Maximum (97.5 Percentile) | **0.45** | **0.29** | 1.70 |
| TCE | Mean | 0.15 | 0.2 | 1.66 |
| | Minimum (2.5 Percentile) | **0.08** | **0.11** | 1.62 |
| | Maximum (97.5 Percentile) | **0.22** | **0.29** | 1.70 |

[a] Values from ATSDR's Table S6.8 (ATSDR-HP, Chapter A, Supplement 6, p. S6.35)

[b] Value converted from $ft^3/g$

[c] Value converted from $g/ft^3$

By considering such a wide range of parameter values and simulating groundwater flow and contaminant transport using extreme parameter values, the results of the sensitivity analysis would

unsurprisingly be wide, but not reasonable. Certain combinations of parameter values would include those extreme values that would result in the highest groundwater velocities (maximum hydraulic conductivity), highest contaminant source (maximum source concentration), and fastest contaminant migration (minimum $K_d$, minimum porosity, minimum biodegradation rate). Such combinations would result in the earliest arrivals and highest concentrations of the ranges shown in Figure 35. However, the minima and maxima for these parameters are not within a reasonable range that is consistent with site-specific data, or even the calibrated model parameter values. Hence, the calculated concentration ranges are not indicative of the potential variability of contaminant concentrations in the influent to the WTP.

It is also important to highlight that in the uncertainty analysis for Tarawa Terrace, ATSDR discarded "*physically implausible realizations*" for the groundwater flow model (Section 4.1.3.2), i.e., did not violate acceptance criteria for fitting observed water-level data. By doing so, ATSDR acknowledged the importance of generating realizations that would "calibrate" the model and replicating observed conditions. In the analysis for Hadnot Point such criteria for determining implausible realizations were not applied.

Nonetheless, Mr. Maslia said in his expert report: "*Based on these results, it is scientifically defensible to conclude that during the period of the 1950s to the mid-1980s, contaminant concentration levels would have occurred within this range of values (the shaded region) at HPWTP, with the average (most likely) values being the solid line in the interior*."[293]

**In Summary (Opinion 18): ATSDR conducted a sensitivity analysis of their calibrated model by selecting extreme values for model parameters. These extreme values were not supported by site-specific data. Model simulations were performed for combinations of these extreme values. Paticular combinations of these extreme parameter values resulted in conservative and biased-high estimates of monthly concentrations. Although a sensitivity analysis is designed to determine the impact of parameter value changes to model outcomes, ATSDR presented the results of this analysis as indicative of the expected range of reconstructed monthly contaminant concentrations. This is not correct.**

[293] Maslia (2024), Expert Report, p.88

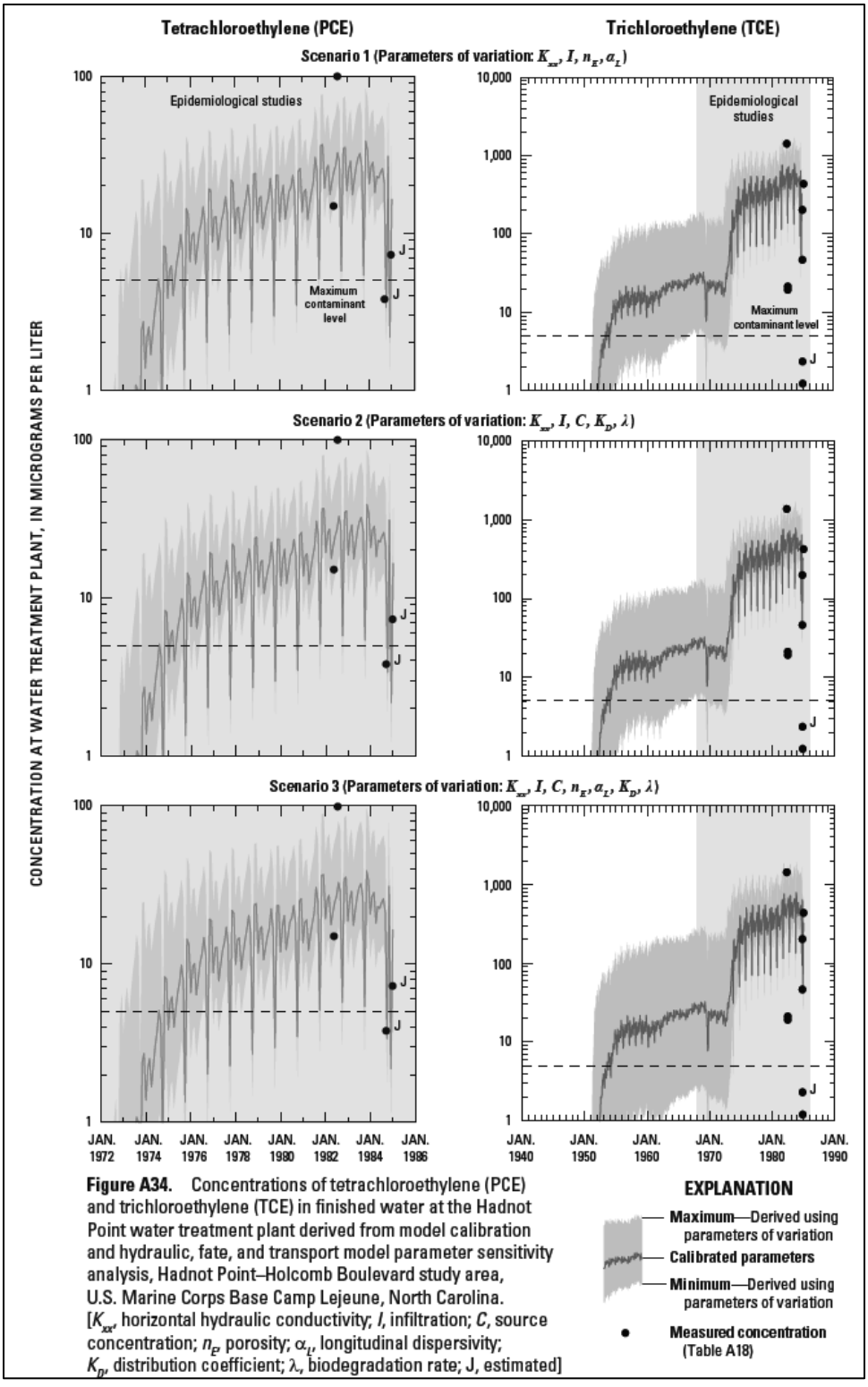



**Figure A34.** Concentrations of tetrachloroethylene (PCE) and trichloroethylene (TCE) in finished water at the Hadnot Point water treatment plant derived from model calibration and hydraulic, fate, and transport model parameter sensitivity analysis, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [$K_{xx}$, horizontal hydraulic conductivity; $I$, infiltration; $C$, source concentration; $n_E$, porosity; $\alpha_L$, longitudinal dispersivity; $K_D$, distribution coefficient; $\lambda$, biodegradation rate; J, estimated]

**Figure 35: ATSDR's Sensitivity Analysis of PCE and TCE Concentrations in the Influent to the HPHB WTP**

#### 4.2.5.2 Uncertainty Analysis Is Incomplete

The uncertainty analysis conducted by ATSDR focused solely on the uncertainty of the pumping schedules of water supply wells.[283] ATSDR implemented a Latin Hypercube Sampling (LHS) methodology, an approach that generates a limited number of scenarios to be evaluated. The reason for this choice is that a rigorous uncertainty analysis using, for example, a Monte Carlo approach, would require tens of thousands of realizations.[283] Such an approach would be computationally infeasible and, therefore, the simplified approach using LHS was selected instead.

However, ATSDR considered a small number of only 10 uncertainty scenarios. For each scenario of historical pumping schedule, a new input to the calibrated model was constructed to incorporate this pumping schedule, and the model was run to calculate the historical concentrations in the influent to the WTP. The simulation results of these scenarios were aggregated to the plot shown in Figure 36.

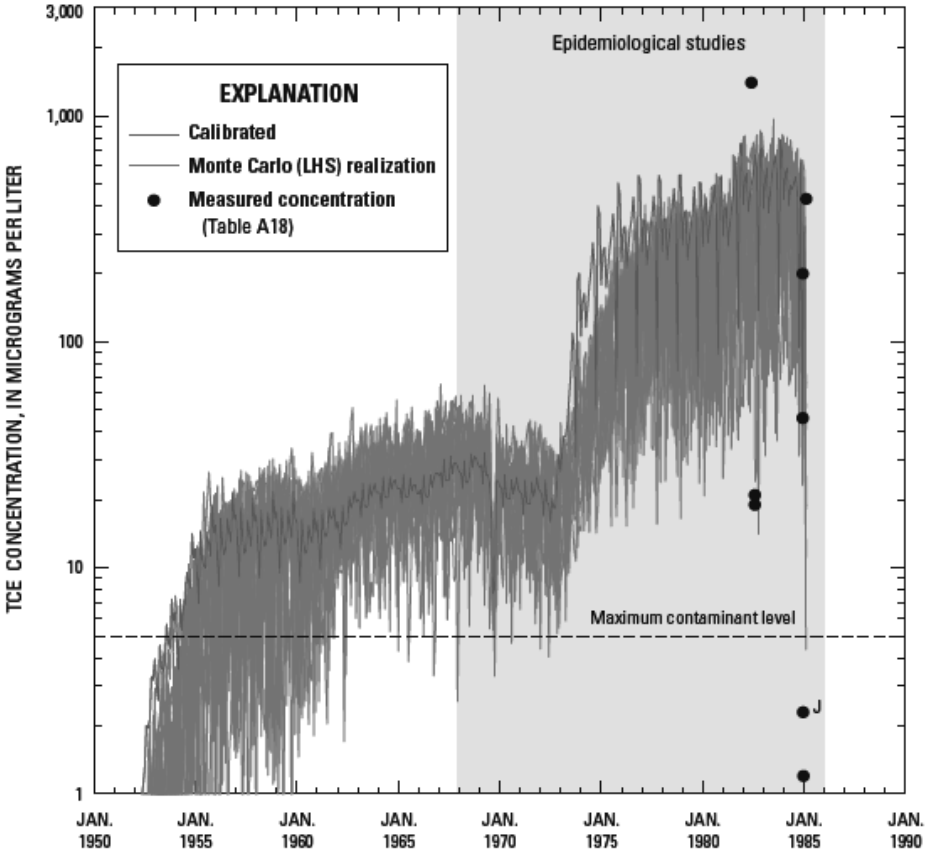



**Figure S6.23.** Variations in reconstructed (simulated) finished-water concentrations of trichloroethylene (TCE) derived using Latin hypercube sampling (LHS) methodology on water-supply well monthly operational schedules, Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. [J, estimated]

**Figure 36: TCE Variation due to Pumping Schedule Uncertainty**

Recall the discussion in Section 3.1.5 about the general rule for the calibrated model output (prediction): "*[i]deally, the value of that prediction should lie somewhere near the centre of the uncertainty band of the prediction. In this way, the potential for predictive error is minimized*."[294] Inspection of Figure 36 indicates that the calibrated model fails to conform with this rule at two critical times: (a) in the early 1950s, when the model estimates the arrival of TCE at the pumping wells and, thus, the influent to the WTP, and (b) after 1972, when pumping well HP-651 was put in service.

In both cases, the calibrated model is at or above the upper bound of the uncertainty range calculated by ATSDR. This clearly indicates that, with respect to pumping variability, the contaminant migration timeframe calculated by ATSDR's calibrated model is biased high. The model estimates faster arrival of contaminants to the pumping wells and, therefore, the WTP, than the uncertainty analysis indicates.

Figure 36 also indicates that the reconstructed historical concentrations calculated by ATSDR's calibrated model are biased high, as they are not near the center of the uncertainty range but, instead, at or near the upper bound of the uncertainty range.

ATSDR's analysis only partially addressed model uncertainty.The upper and lower bounds of uncertainty, shown in Figure 36, represent 95% of Monte Carlo simulations for evaluating only the effects of pumping schedule uncertainty,[295] are therefore the resulting range of uncertainty is unreliable.

**In Summary (Opinion 19): ATSDR conducted a limited uncertainty analysis, focusing solely on the effects of historical pumping variability on estimated monthly contaminant concentrations. This analysis only partially addressed the model uncertainty. Even this limited uncertainty analysis indicated that the calibrated model is conservative and biased high, as it is either at or above the upper bound of the calculated uncertainty range.**

#### 4.2.5.3 Concluding Remarks

As discussed above, the inherent shortcomings of ATSDR's model calibration, sensitivity analysis, and uncertainty analysis, limit the validity of the associated conclusions that ATSDR attempted to draw regarding the history of groundwater contamination in HPHB. The lack of site-specific data to confidently assign model parameters within reasonable ranges prevents a reliable model calibration. This is further exacerbated by the lack of historical observation data to constrain the calibration and ensure that historical patterns of contamination are reliably reproduced by the model. As Sepulveda and Doherty (2015) stated, the "*model should replicate observed system behavior."* The ATSDR model results did not meet this requirement. Similarly to Tarawa Terrace, there is no "observed system behavior" (i.e. historical data from the entire period of interest) to support a reasonable and accurate model calibration and, therefore, an accurate historical reconstruction of contaminant concentrations in the influent to the WTP.

But even the sensitivity and uncertainty analyses presented by ATSDR failed to quantify the uncertainty range reliably. In its own admission, ATSDR stated that *"the ranges of values presented in the sensitivity analysis section of this report assess a limited number of input and output model parameters. The results (i.e., range of concentration) presented in the sensitivity analysis reported herein should not be considered or interpreted as the results of a robust and comprehensive uncertainty analysis, but do provide insight into parameter sensitivity and uncertainty in a qualitative sense*."[296] This contradicts Mr. Maslia's statement about the results of the sensitivity analysis in his expert report, which was that "*it is scientifically defensible to conclude that during the period of the 1950s to the mid-1980s, contaminant concentration levels would have occurred within this range of values (the shaded region) at HPWTP, with the average*

[294] Doherty (2015), p. 52

[295] 2.5 and 97.5 percentile.

[296] ATSDR-HP, Chapter A, Supplement 6, p. S6.45

*(most likely) values being the solid line in the interior*."[293] If parameter sensitivity and uncertainty can only be evaluated in a qualitative sense, it is not scientifically defensible to conclude that contaminant concentration levels would have been within the range indicated by the sensitivity analysis performed by ATSDR. It is also not scientifically defensible to conclude that the most likely values of contamination were those calculated by the calibrated model.

# Section 5
# References

ATSDR-TT

Maslia, M.L., J.B. Sautner, R.E. Faye, R.J. Suárez-Soto, M.M. Aral, W.M. Grayman, W. Jang, J. Wang, F.J. Bove, P.Z. Ruckart, C. Valenzuela, J. Green, and A.L. Krueger. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions - Executive Summary*. Agency for Toxic Substances and Disease Registry. June.

Maslia, M.L., J.B. Sautner, R.E. Faye, R.J. Suárez-Soto, M.M. Aral, W.M. Grayman, W. Jang, J. Wang, F.J. Bove, P.Z. Ruckart, C. Valenzuela, J.W. Green Jr., and A.L. Krueger. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter A: Summary of Findings*. Agency for Toxic Substances and Disease Registry. July.

Faye, R.E. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter B: Geohydrologic Framework of the Castle Hayne Aquifer System*. Agency for Toxic Substances and Disease Registry. September.

Faye, R.E., and C. Valenzuela. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter C: Simulation of Groundwater Flow*. Agency for Toxic Substances and Disease Registry. November.

Maslia, M.L., J.B. Sautner, R.E. Faye, R.J. Suárez-Soto, M.M. Aral, W.M. Grayman, W. Jang, J. Wang, F.J. Bove, P.Z. Ruckart, C. Valenzuela, J.W. Green Jr, and A.L. Krueger. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions, Chapter C: Simulation of Groundwater Flow, Plate 1 - Location of Wells and Boreholes, Groundwater-Flow Model Boundary, and Present-Day (2004) Water-Distribution Systems Serving Tarawa Terrace, Holcomb Boulevard, and Hadnot Point and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina*. Agency for Toxic Substances and Disease Registry.

Lawrence, S.J. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter D: Properties and Degradation Pathways of Common Organic Compounds in Groundwater*. Agency for Toxic Substances and Disease Registry. September.

Faye, R.E., and J.W. Green Jr. 2007. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter E: Occurrence of Contaminants in Groundwater*. Agency for Toxic Substances and Disease Registry. December.

Faye, R.E. 2008. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE)*. Agency for Toxic Substances and Disease Registry. February.

Jang, W., and M.M. Aral. 2008. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products*. Agency for Toxic Substances and Disease Registry. April.

Wang, J., and M.M. Aral. 2008. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant*. Agency for Toxic Substances and Disease Registry. February.

Maslia, M.L., R.J. Suárez-Soto, J. Wang, M.M. Aral, R.E. Faye, J.B. Sautner, C. Valenzuela, and W.M. Grayman. 2009. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water*. Agency for Toxic Substances and Disease Registry. February.

Sautner, J.B., C. Valenzuela, M.L. Maslia, and W.M. Grayman. 2010. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-day Conditions Chapter J: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water*. Agency for Toxic Substances and Disease Registry. December.

Maslia, M.L., J.B. Sautner, R.E. Faye, R.J. Suárez-Soto, M.M. Aral, W.M. Grayman, W. Jang, J. Wang, F.J. Bove, P.Z. Ruckart, C. Valenzuela, J.W. Green Jr., and A.L. Krueger. 2008. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions Chapter K: Supplemental Information*. Agency for Toxic Substances and Disease Registry. July.

ATSDR-HP:

Maslia, M.L., R.J. Suárez-Soto, J.B. Sautner, B.A. Anderson, L.E. Jones, R.E. Faye, M.M. Aral, J. Guan, W. Jang, I.T. Telci, W.M. Grayman, F.J. Bove, P.Z. Ruckart, and S.M. Moore. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A: Summary and Findings*. Agency for Toxic Substances and Disease Registry. March.

Maslia, M.L., B.A. Anderson, R.J. Suárez-Soto, J.B. Sautner, F.J. Bove, P.Z. Ruckart, R.E. Faye, M.M. Aral, J. Guan, W. Jang, B. Chang, I.T. Telci, A. Zhang, and L.E. Jones. 2010. *Plate 1 - Location of Wells and Boreholes, Installation Restoration Program Site Areas, Above-Ground and Underground Storage Tank Sites, and Water-Distribution Systems (2004), Hadnot Point, Holcomb Boulevard, and Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina*. Agency for Toxic Substances and Disease Registry.

Sautner, J.B., B.A. Anderson, R.J. Suárez-Soto, and M.L. Maslia. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 1: Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations*. Agency for Toxic Substances and Disease Registry.

Telci, I.T., J.B. Sautner, R.J. Suárez-Soto, B.A. Anderson, M.L. Maslia, and M.M. Aral. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 2: Development and Application of a Methodology to Characterize Present-Day and Historical Water-Supply Well Operations*. Agency for Toxic Substances and Disease Registry.

Faye, R.E., L.E. Jones, and R.J. Suárez-Soto. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 3: Descriptions and Characterizations of Water-Level Data and Groundwater Flow for the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer*. Agency for Toxic Substances and Disease Registry.

Suárez-Soto, R.J., L.E. Jones, and M.L. Maslia. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 4: Simulation of Three-Dimensional Groundwater Flow*. Agency for Toxic Substances and Disease Registry.

Guan, J., B.A. Anderson, M.M. Aral, and M.L. Maslia. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 5: Theory, Development, and Application of Linear Control Model Methodology to Reconstruct Historical Contaminant Concentrations at Selected Water-Supply Wells*. Agency for Toxic Substances and Disease Registry.

Jones, L.E., R.J. Suárez-Soto, B.A. Anderson, and M.L. Maslia. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina Chapter A-Supplement 6: Characterization and Simulation of Fate and Transport of Selected Volatile Organic Compounds in the Vicinities of the Hadnot Point Industrial Area and Landfill*. Agency for Toxic Substances and Disease Registry.

Jang, W., B.A. Anderson, R.J. Suárez-Soto, M.M. Aral, and M.L. Maslia. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 7: Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area*. Agency for Toxic Substances and Disease Registry.

Sautner, J.B., I.T. Telci, W.M. Grayman, M.L. Maslia, and M.M. Aral. 2013. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter A-Supplement 8: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water with Emphasis on Intermittent Transfers of Drinking Water Between the Hadnot Point and Holcomb Boulevard Water-Distribution Systems*. Agency for Toxic Substances and Disease Registry.

Faye, R.E. 2012. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter B: Geohydrologic Framework of the Brewster Boulevard and Castle Hayne Aquifer Systems and the Tarawa Terrace Aquifer*. Agency for Toxic Substances and Disease Registry. January.

Faye, R.E., B.A. Anderson, R.J. Suárez-Soto, and J.B. Sautner. 2010. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter C: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites*. Agency for Toxic Substances and Disease Registry. October.

Maslia, M.L., B.A. Anderson, R.J. Suárez-Soto, J.B. Sautner, F.J. Bove, P.Z. Ruckart, R.E. Faye, M.M. Aral, J. Guan, W. Jang, B. Chang, l. Telci, and A. Zhang. 2009. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina, Chapter C: Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites, Draft Plate 1 - Location of Wells and Boreholes and Present-Day (2004) Water-Distribution Systems Serving Hadnot Point, Holcomb Boulevard, and Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina*. Agency for Toxic Substances and Disease Registry.

Faye, R.E., R.J. Suárez-Soto, and M.L. Maslia. 2012. *Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina Chapter D: Occurrence of Selected Contaminants in Groundwater at Above-Ground and Underground Storage Tank Sites*. Agency for Toxic Substances and Disease Registry. December.

2023 PEST Conference – The Path from Data to Decisions, March 5-10, 2023, La Jolla, CA

Agency for Toxic Substances and Disease Registry. 1997. Public Health Assessment for U.S. Marine Corps Camp Lejeune Military Reservation, Camp Lejeune, Onslow County, North Carolina, EPA Facility ID: NC6170022580, August 4.

Agency for Toxic Substances and Disease Registry. 2005. Expert Per Review Panel Evaluating ATSDR's Water-Modeling Activities in Support of the Current Study of Childhood Birth Defects and cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina. March 28-29.

Agency for Toxic Substances and Disease Registry. 2009. *Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions. Response to the Department of the Navy's Letter on: Assessment of ATSDR Water Modeling for Tarawa Terrace*. March.

Agency for Toxic Substances and Disease Registry. 2013. CLJA_WATERMODELING_01-0000076158 to CLJA_WATERMODELING_01-0000076159

Ahlfeld, D.P., J.M. Mulvey, G.F. Pinder, and E.F. Wood. 1988. Contaminated Groundwater Remediation Design Using Simulation, Optimization, and Sensitivity Theory: 1. Model Development: *Water Resources Research* 24, no. 3: 431-441.

American Society for Testing and Materials. 2016. *Standard Guide for Conducting a Sensitivity Analysis for a Groundwater Flow Model Application*. ASTM D5611-94(2016).

American Society for Testing and Materials. 2018. *Standard Guide for Calibrating a Ground-Water Flow Model Application*. ASTM D5981/D5981M-18.

Anderson, M.P., W.W. Woessner, and R.J. Hunt. 2015. *Applied Groundwater Modeling: Simulation of Advective Flow and Transport* (2nd ed.): Academic Press.

Aral, M.M. 2024. Expert Report

Black & Veatch. 2018. Focused Remedial Investigation Report, Revision 1, ABC One-Hour Cleaners OU3 Site Jacksonville, Onslow County, North Carolina.

Bove, F. 2024. Deposition. October 18.

Brigham, M.A. 2024. Expert Report

Clement, T.P. 2011. "Complexities in Hindcasting Models – When Should we Say Enough is Enough: *Groundwater* 49, no. 5: 620-629

CLJA_WATERMODELING_01-0000075306: Email from R.E. Faye to M. Maslia, Saturday, January 13, 2007, 5:14:51 PM.

CLW0000006590

Costas, K., R.S. Knorr, and S. Condon. 2002. A case–control study of childhood leukemia in Woburn, Massachusetts: the relationship between leukemia incidence and exposure to public drinking water: ESCTTE Vol. 300, No. 1-3, pp. 23-35. 1-3 23-35.

Department of the Navy. 2008. CLJA_2019ATSDR04-0000002375 and CLJA_2019ATSDR04-0000002377

Doherty, J. 2015. *Calibration and Uncertainty Analysis for Complex Environmental Models*. PEST: Complete Theory and What it Means for Modelling the Real World. Brisbane, Australia: Watermark Numerical Computing.

Doherty, J. and C. Moore. 2021. *Decision Support Modelling Viewed through the Lens of Model Complexity. A GMDSI Monograph*. National Centre for Groundwater Research and Training, Flinders University, South Australia.

Eastern Research Group Inc. 2009. *Expert Panel Assessing ATSDR's Methods and Analyses for Historical Reconstruction of Groundwater Resources and Distribution of Drinking Water at Hadnot Point, Holcomb Boulevard, and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, April 29-30, 2009*. Agency for Toxic Substances and Disease Registry. December.

Fienen, M.N., J. Luo, and P.K. Kitanidis. 2006. A Bayesian Geostatistical Transfer Function Approach to Tracer Test Analysis: *Water Resources Research* 42, no. 7: W07426.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Glotfelty, M.F. 2019. *The Art of Water Wells: Technical and Economic Considerations for Water Well Siting, Design, and Installation*. Westerville, OH: NGWA Press.

Grayman, W.M., R.M. Clark, B.L. Harding, M. Maslia, and J. Aramini. 2004. Chapter 10: Reconstructing Historical Contamination Events. In: Mays, L.W. editor. *Water Supply Systems Security*. McGraw-Hill, New York, pp. 10.1-10.55

Harbaugh AW, and M.G. McDonald. 1996. User's Documentation of MODFLOW-96, an Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. Reston, VA: U.S. Geological Survey Open-File Report 96-458.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process. Reston, VA: U.S. Geological Survey Open-File Report 00-92.

Harbaugh, A.W. 2005. MODFLOW-2005: The U.S. Geological Survey Modular Ground-Water Model - The Ground-Water Flow Process. U.S. Geological Survey Techniques and Methods 6-A16.

Harter, T., T. Moran, and E. Wildman. 2018. *Adjudicating Groundwater: A Judge's Guide to Understanding Groundwater and Modeling*. Reno, NV: National Judicial College.

Helsel, D.R., R.M. Hirsch, K.R. Ryberg, S.A. Archfield, and E.J. Gilroy. 2020. *Statistical Methods in Water Resources*. Chapter 3 of Section A, Statistical Analysis, Book 4, Hydrologic Analysis and Interpretation, USGS, Techniques and Methods 4-A3.

Hennet, R. 2024. Expert Report

Hill, M.C., and C.R. Tiedeman. 2007. *Effective Groundwater Model Calibration with Analysis of Data, Sensitivities, Predictions, and Uncertainty*. Hoboken, NJ: John Wiley & Sons, Inc.

Jones, N.L. and R.J. Davis. 2024. Expert Report: Tarawa Terrace Flow and Transport Model Post-Audit

Lagakos, S.W., B.J. Wessen, and M. Zenlen. 1986. An Analysis of Contaminated Wellwater and Health Effects in Woburn, Massachusetts: JASA, Vol. 81, No.78J, pp.583-614.

Maslia, M.L. 2010. Deposition, June 30

Maslia, M.L. 2024. Deposition, September 26

Maslia, M.L. 2024. Expert Report

Maslia, M.L., M.M. Aral, R.J. Suarez-Soto, J.B. Sautner, B.A. Anderson, F.J. Bove, P.Z. Ruckart, and S.M. Moore. 2012. Comment on "Complexities in Hindcasting Models – When Should we Say Enough is Enough: *Groundwater* 50, no. 1: 10-16

Meyer, P.D. and S. Orr. 2002. *Evaluation of Hydrologic Uncertainty Assessments for Decommissioning Sites Using Complex and Simplified Models*. PNNL-13831, NUREG/CR-6767, Pacific Northwest National Laboratory, Richland, WA 99352

Morris, D.A. and A.I. Johnson. 1967. *Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948-60*. U.S. Geological Survey Water-Supply Paper 1839-D.

National Judicial College and Dividing the Waters. 2010. Hydrologic Modeling Benchbook.

National Research Council. 1990. *Ground Water Models: Scientific and Regulatory Applications*. Washington, DC: The National Academies Press.

National Research Council. 2009. *Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects*. National Academies Press.

Reilly, T.E. and A.W. Harbaugh. 2004. *Guidelines for Evaluating Ground-Water Flow Models*, U.S. Geological Survey Scientific Investigations Report 2004-5038—Version 1.01.

Ruckart, P.Z., J. Bove, and M. Maslia. 2013. Evaluation of Exposure to Contaminated Drinking Water andSpecific Birth Defects and Childhood Cancers at Marine Corps Base Camp Lejeune, North Carolina: a Case-Control Study: Environmental Health, 12:104.

Sepúlveda, N., and J. Doherty. 2015. Uncertainty Analysis of a Groundwater Flow Model in East-Central Florida: *Groundwater* 53, no. 3: 464-474.

Tonkin, M., and J. Doherty. 2009. Calibration-Constrained Monte Carlo Analysis of Highly Parameterized Models Using Subspace Techniques: *Water Resources Research* 45, no. 12: W00B10.

U.S. Department of Navy. 2009. Navy Position on Tarawa Terrace Water Modeling. April.

U.S. Environmental Protection Agency. 1986. *Summary of State Reports on Releases from Underground Storage Tanks*. EPA/600/M-86/020.

U.S. Environmental Protection Agency. 1993. *EPA Superfund Record of Decision: ABC One Hour Cleaners, EPA ID: NCD024644494, OU 01, Jacksonville, NC*. EPA/ROD/R04-93/128. January 26.

U.S. Government Accountability Office. 2007. DEFENSE HEALTH CARE Activities Related to Past Drinking Water Contamination at Marine Corps Base Camp Lejeune. GAO-07-276. May.

Waddill, D. 2024. Deposition, August 6.

Wagner, B.J. 1995. Recent Advances in Simulation-Optimization Groundwater Management Modeling: *Reviews of Geophysics* 33, no. S2: 1021-1028.

Wiedemeier, T.H., H.S. Rifai, C.J. Newell, and J.T. Wilson. 1999. *Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface*. New York: John Wiley & Sons, Inc.

Zheng C, and P.P. Wang. 1999. MT3DMS: A Modular Three-Dimensional Multi-Species Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems: Documentation and User's Guide. Vicksburg, MS: U.S. Army Engineer Research and Development Center; Report No.: SERDP-99.

Zheng, C., and G.D. Bennett. 2002. *Applied Contaminant Transport Modeling* (Second ed.). New York: John Wiley & Sons.

# APPENDICES

# Appendix A: Site-Specific Data for $K_d$

## Table A-1. Site-Specific Data for $K_d$

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| BLDG902-SB03-100-101-07B | 5/20/2007 | 100.5 | 28,000 | 0.028000 | 234.42 | 6.5638 | 6.5638 | | CLJA_WATERMODELING_07-0001380126 |
| BLDG902-SB03-10-11-07B | 5/19/2007 | 10.5 | 810 | 0.000810 | 234.42 | 0.1899 | 0.1899 | | CLJA_WATERMODELING_07-0001380120 |
| BLDG902-SB03-120-121-07B | 5/20/2007 | 120.5 | 2,600 | 0.002600 | 234.42 | 0.6095 | 0.6095 | | CLJA_WATERMODELING_07-0001380127 |
| BLDG902-SB03-25-26-07B | 5/19/2007 | 25.5 | 210 | 0.000210 | 234.42 | 0.0492 | 0.0492 | | CLJA_WATERMODELING_07-0001380121 |
| BLDG902-SB03-43-44-07B | 5/20/2007 | 43.5 | 300 | 0.000300 | 234.42 | 0.0703 | 0.0703 | | CLJA_WATERMODELING_07-0001380122 |
| BLDG902-SB03-46-47-07B | 5/20/2007 | 46.5 | 24,000 | 0.024000 | 234.42 | 5.6261 | 5.6261 | | CLJA_WATERMODELING_07-0001380123 |
| BLDG902-SB03-55-56-07B | 5/20/2007 | 55.5 | 1,300 | 0.001300 | 234.42 | 0.3047 | 0.3047 | | CLJA_WATERMODELING_07-0001380124 |
| BLDG902-SB03-83-84-07B | 5/20/2007 | 83.5 | 1,200 | 0.001200 | 234.42 | 0.2813 | 0.2813 | | CLJA_WATERMODELING_07-0001380125 |
| IR84-DP27 | 7/19/2001 | 0.5 | 13 | 0.000013 | 234.42 | 0.0030 | 0.0030 | | CLJA_WATERMODELING_05-0000408229; CLJA_WATERMODELING_05-0000408591; CLJA_WATERMODELING_07-0001379092 |
| IR84-DP36 | 7/20/2001 | 0.5 | 3 | 0.000003 | 234.42 | 0.0007 | | Excluded; inconsistent with the two other samples | CLJA_WATERMODELING_05-0000408232; CLJA_WATERMODELING_05-0000408600; CLJA_WATERMODELING_07-0001379092 |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | from the same date | |
| IR84-DP36 | 7/20/2001 | 0.5 | 220 | 0.000220 | 234.42 | 0.0516 | 0.0527 | Average of two samples | CLJA_WATERMODELING_07-0001379092 |
| IR84-DP36 | 7/20/2001 | 0.5 | 230 | 0.000230 | 234.42 | 0.0539 | | | CLJA_WATERMODELING_07-0001379092 |
| IS26-04 | 11/21/1997 | 16.5 | 1,510 | 0.001510 | 234.42 | 0.3540 | 0.3540 | | CLJA_WATERMODELING_01-0000283421; CLJA_WATERMODELING_01-0000283606 |
| IS26-05 | 11/21/1997 | 18 | 5,560 | 0.005560 | 234.42 | 1.3034 | 1.3034 | | CLJA_WATERMODELING_01-0000283421; CLJA_WATERMODELING_01-0000283607 |
| IS26-06 | 11/21/1997 | 19 | 6,420 | 0.006420 | 234.42 | 1.5050 | 1.5050 | | CLJA_WATERMODELING_01-0000283421; CLJA_WATERMODELING_01-0000283608 |
| SWMU253-TW02 | 3/22/2002 | 10 | 2,005 | 0.002005 | 234.42 | 0.4700 | 0.4700 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045499; CLJA_WATERMODELING_07-0001379091 |
| SWMU254-SS01 | 7/18/2000 | 10 | 2,500 | 0.002500 | 234.42 | 0.5861 | 0.7173 | Average of two samples | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259590; CLJA_WATERMODELING_07-0001379091 |
| SWMU254-SS01 | 7/18/2000 | 10 | 3,620 | 0.003620 | 234.42 | 0.8486 | | | CLJA_WATERMODELING_01-0000259216; |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | CLJA_WATERMODELING_01-0000259588; CLJA_WATERMODELING_07-0001379091 |
| SWMU254-TW02 | 3/22/2002 | 8 | 2,084 | 0.002084 | 234.42 | 0.4885 | 0.4885 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045509; CLJA_WATERMODELING_07-0001379091 |
| SWMU255-GW01 | 3/21/2002 | 8 | 824 | 0.000824 | 234.42 | 0.1932 | 0.1932 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045522; CLJA_WATERMODELING_07-0001379091 |
| SWMU255-SS01 | 7/18/2000 | 8 | 444 | 0.000444 | 234.42 | 0.1041 | 0.1041 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259591; CLJA_WATERMODELING_07-0001379091 |
| SWMU256-GW02 | 7/18/2000 | 2 | 2,470 | 0.002470 | 234.42 | 0.5790 | 0.5790 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259592; CLJA_WATERMODELING_07-0001379091 |
| SWMU256-GW03 | 7/18/2000 | 2 | 3,460 | 0.003460 | 234.42 | 0.8111 | 0.8111 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259593; |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | CLJA_WATERMODELING_07-0001379091 |
| SWMU258-GW01 | 3/22/2002 | 4 | 1,916 | 0.001916 | 234.42 | 0.4492 | 0.4492 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045538; CLJA_WATERMODELING_07-0001379091 |
| SWMU258-GW02 | 7/18/2000 | 14 | 30,400 | 0.030400 | 234.42 | 7.1265 | 7.1265 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_07-0001379091 |
| SWMU258-IS05 | 7/17/2000 | 2 | 1,820 | 0.001820 | 234.42 | 0.4266 | 0.4266 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259595; CLJA_WATERMODELING_07-0001379091 |
| SWMU261-GW02 | 7/18/2000 | 14 | 3,930 | 0.003930 | 234.42 | 0.9213 | 0.9213 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259597; CLJA_WATERMODELING_07-0001379091 |
| SWMU264-GW01 | 3/24/2002 | 8 | 4,167 | 0.004167 | 234.42 | 0.9768 | 0.9768 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045568; CLJA_WATERMODELING_07-0001379092 |
| SWMU264-SS01 | 7/17/2000 | 8 | 578 | 0.000578 | 234.42 | 0.1355 | | Excluded; the two samples | CLJA_WATERMODELING_01-0000259216; |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | are inconsistent | CLJA_WATERMODELING_01-0000259599; CLJA_WATERMODELING_07-0001379092 |
| SWMU264-SS01 | 7/17/2000 | 8 | 9,800 | 0.009800 | 234.42 | 2.2973 | | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259598; CLJA_WATERMODELING_07-0001379092 |
| SWMU265-GW02 | 3/24/2002 | 10 | 976 | 0.000976 | 234.42 | 0.2288 | 0.2288 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045576; CLJA_WATERMODELING_07-0001379092 |
| SWMU285-GW01 | 3/26/2002 | 4 | 11,350 | 0.011350 | 234.42 | 2.6607 | 2.6607 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045613; CLJA_WATERMODELING_07-0001379091 |
| SWMU285-GW03 | 7/19/2000 | 8 | 784 | 0.000784 | 234.42 | 0.1838 | 0.1838 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259604; CLJA_WATERMODELING_07-0001379091 |
| SWMU294-GW01 | 3/22/2002 | 8 | 1,559 | 0.001559 | 234.42 | 0.3655 | 0.3655 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045644; |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | CLJA_WATERMODELING_07-0001379091 |
| SWMU295-GW01 | 3/22/2002 | 8 | 1,966 | 0.001966 | 234.42 | 0.4609 | 0.4609 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045680; CLJA_WATERMODELING_07-0001379091 |
| SWMU311-GW03 | 3/25/2002 | 6 | 1,364 | 0.001364 | 234.42 | 0.3198 | 0.3198 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045826; CLJA_WATERMODELING_07-0001379091 |
| SWMU312-GW01 | 3/21/2002 | 4 | 2,005 | 0.002005 | 234.42 | 0.4700 | 0.4700 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045840; CLJA_WATERMODELING_07-0001379091 |
| SWMU360-TW04 | 3/25/2002 | 12 | 875 | 0.000875 | 234.42 | 0.2051 | 0.2051 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002046015; CLJA_WATERMODELING_07-0001379091 |
| SWMU361-TW01 | 3/24/2002 | 4 | 1,216 | 0.001216 | 234.42 | 0.2851 | 0.2851 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002046030; CLJA_WATERMODELING_07-0001379091 |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| SWMU362-SB01 | 3/26/2002 | 2 | 13,670 | 0.013670 | 234.42 | 3.2046 | 3.2046 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002046032; CLJA_WATERMODELING_07-0001379091 |
| SWMU43-GW01 | 7/18/2000 | 14 | 589 | 0.000589 | 234.42 | 0.1381 | 0.1381 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259586; CLJA_WATERMODELING_07-0001379092 |
| SWMU43-GW02 | 3/25/2002 | 12 | 719 | 0.000719 | 234.42 | 0.1686 | 0.1686 | | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259580; CLJA_WATERMODELING_07-0001379092 |
| SWMU43-GW02 | 7/17/2000 | 14 | 341 | 0.000341 | 234.42 | 0.0799 | 0.0799 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045472; CLJA_WATERMODELING_07-0001379092 |
| SWMU43-GW03 | 7/17/2000 | 14 | 239 | 0.000239 | 234.42 | 0.0560 | 0.0897 | Average of two samples | CLJA_WATERMODELING_01-0000259216; CLJA_WATERMODELING_01-0000259582; CLJA_WATERMODELING_07-0001379092 |
| SWMU43-GW03 | 7/18/2000 | 14 | 526 | 0.000526 | 234.42 | 0.1233 | | | CLJA_WATERMODELING_07-0001379092 |

**Table A-1. Site-Specific Data for $K_d$**

| Sample | Date Sampled | Depth (ft) | TOC (mg/kg) | $f_{oc}$ | $K_{oc}$ | $K_d$ (mL/g) All Values | $K_d$ (mL/g) Final | Comments | Reference Citation |
|---|---|---|---|---|---|---|---|---|---|
| SWMU53-GW01 | 3/21/2002 | 6 | 21,150 | 0.021150 | 234.42 | 4.9580 | 4.9580 | | CLJA_WATERMODELING_07-0002047135; CLJA_WATERMODELING_07-0002045493; CLJA_WATERMODELING_07-0001379091 |

# Appendix B: Discussion on Site-Specific $K_d$ Values

According to the published data referenced by ATSDR, the range of $K_d$ values for sands was 0.25-0.76 mL/g, averaging 0.39 mL/g; the referenced range of values for silts was 0.21-0.71 mL/g, averaging 0.40 mL/g. ATSDR used the mean value of 0.40 mL/g as the starting value in the model calibration process. However, the value determined by ATSDR through model calibration was 0.14 mL/g. This value is out of range for the soils in the aquifer at Camp Lejeune, as discussed below.

In addition, this value is more than two times lower than the value used by ATSDR for the Hadnot Point model, despite ATSDR's statement that the same aquifers are encountered in both models.[297] ATSDR ultimately defined a $K_d$ value of 0.30 mL/g for PCE, through "refinement during the model calibration process."[298]

Site-specific Total Organic Carbon (TOC) data were available when the Tarawa Terrace and Hadnot Point models were constructed, which ATSDR did not consider. Table A-1 in Appendix A lists available TOC data. These data provide site-specific estimates of fraction organic carbon ($f_{oc}$) which, multiplied by the chemical-specific $K_{oc}$, provide $K_d$ estimates for the Tarawa Terrace aquifers.

Based on Table A-1 in Appendix A, site-specific estimates of fraction organic carbon ($f_{oc}$) can be calculated by dividing the TOC data by $10^{+6}$, to express the values in percentages of mg/mg. The resulting $f_{oc}$ values vary between 0.000003 and 0.0304. Corresponding $K_d$ values are calculated using a PCE-specific $K_{oc}$ value of 234.42.[299]

The $K_d$ range calculated using site-specific data is consistent with the range provided by ATSDR, with an upper bound lower than the maximum of the ATSDR-cited range. However, the site-specific data provide a distribution of $K_d$ values that reflects actual conditions in the Castle Hayne aquifer, and that can be used for calculating site-specific statistics for this parameter.

When duplicate samples are replaced by their average and extreme values are removed, the mean value is 1.0999 mL/g. The corresponding geometric mean and median values are 0.3998 and 0.3961 mL/g, respectively. When samples from depths greater than 10 ft are considered, the mean $K_d$ value is actually higher (1.2858 mL/g). The corresponding geometric mean and median values are 0.4244 and 0.3047 mL/g, respectively.

These values are two to three times greater than the value used by ATSDR in the Tarawa Terrace model (0.14 mL/g). They are also greater than the value used by ATSDR in the Hadnot Point model (0.30 mL/g), except for the median value for samples from depths greater than 10 ft.

The implications of using a $K_d$ that is substantially lower than the mean value derived from measured data are important, as the corresponding retardation coefficients can be significantly underestimated, resulting in faster plume migration and, therefore, erroneously shorter contaminant arrival times at the pumping wells.

---

[297] "*Because field data describing contaminant fate and transport parameters is lacking for the HPHB study area and the TT study area is adjacent to the HPHB study area, the probability density functions described by Maslia et al. (2009) were used to generate a range of transport parameters values for the analyses reported herein*." (ATSDR-HP, Chapter A, Supplement 6, p. S6.34)

[298] ATSDR assumed an $f_{oc}$ value of 0.002, and a range of $K_{oc}$ values from the literature (ATSDR-HP, Chapter A, Supplement 6, Table S6.4, p. S6.14). In that same table, ATSDR provided the corresponding calculated range of $K_d$ values for PCE, varying between 0.03 and 21.43 mL/g (the $K_d$ value is the same when units of L/kg are used).

[299] Value derived from logKoc = 2.37 (ATSDR-TT, Chapter D, Table D12, p. D15)

# Appendix C: Discussion on ATSDR's Retardation Factor Calculations

Below is a detailed discussion on: (a) ATSDR's probabilistic distributions and ranges for the parameters used for calculating the retardation factor, and (b) the resulting spatial distribution of $K_d$ in the model cells and the resulting implication in the calculation of the retardation factor.

## C-1. Probabilistic distributions and associated ranges

ATSDR conducted uncertainty analysis of the Tarawa Terrace historical reconstruction of contaminant concentrations in the finished water produced by the treatment plant. The uncertainty analysis assessed the range of model outputs due to variability in model parameter values. ATSDR defined model parameter uncertainty by constructing probabilistic distributions of those parameters, based on published ranges of the parameter values.

For the distribution coefficient ($K_d$) for PCE, ATSDR selected a range of values to consider in its uncertainty analysis, corresponding to a reasonable range for silts and sands from comparable published data.[300] A probability density function was developed using a mean and standard deviation. The $K_d$ value used in the calibrated model ($5.0x10^{-6}$ $ft^3/g$, or 0.14 mL/g) was defined as the mean for the probabilistic distribution. The rationale for selecting the parameter standard deviation for generating the probability density function is not documented.

For one of the uncertainty scenarios, which excluded pumping uncertainty, ATSDR constructed 840 realizations. Using the selected mean and standard deviation values, ATSDR generated 840 $K_d$ sets, with values assigned on a cell-by-cell basis for each groundwater model realization. Statistics of the PDF illustrated on the graph in Figure 37, calculated from files generated by ATSDR[301]. The horizontal axis shows $K_d$ values in $ft^3/g$, and corresponding percentages of that value for the ensemble of the 840 distributions are shown on the vertical axis. A secondary horizontal axis at the top of the graph shows the same $K_d$ values but different units (mL/g) used interchangeably in ATDR's reports. The blue horizontal line at the top of the graph depicts the range of values corresponding to ATSDR's minimum and maximum value (blue dots at the edges of the blue line) for the statistical description of the probabilistic distribution. The middle blue dot on that line indicated the selected mean value of the probability distribution. As illustrated in this graph, the actual distribution of $K_d$ values that was generated by the algorithm when all 840 realizations are considered, spans only a fraction of the range that ATSDR indicated as representative for soils similar to those found at Camp Lejeune.

ATSDR's algorithm for generating random numbers was set to exclude values outside the prescribed range. However, based on the statistical description for $K_d$, only values below the prescribed minimum were omitted, as higher values never reached the upper bound of the range, further highlighting the reasons for the skewed range of values illustrated in Figure 37.

[300] ATSDR-TT, Chapter I, p. I37

[301] External Drive: EDRP03\Monte Carlo_No Pumping_April 2007\Simulation files and results-Used\

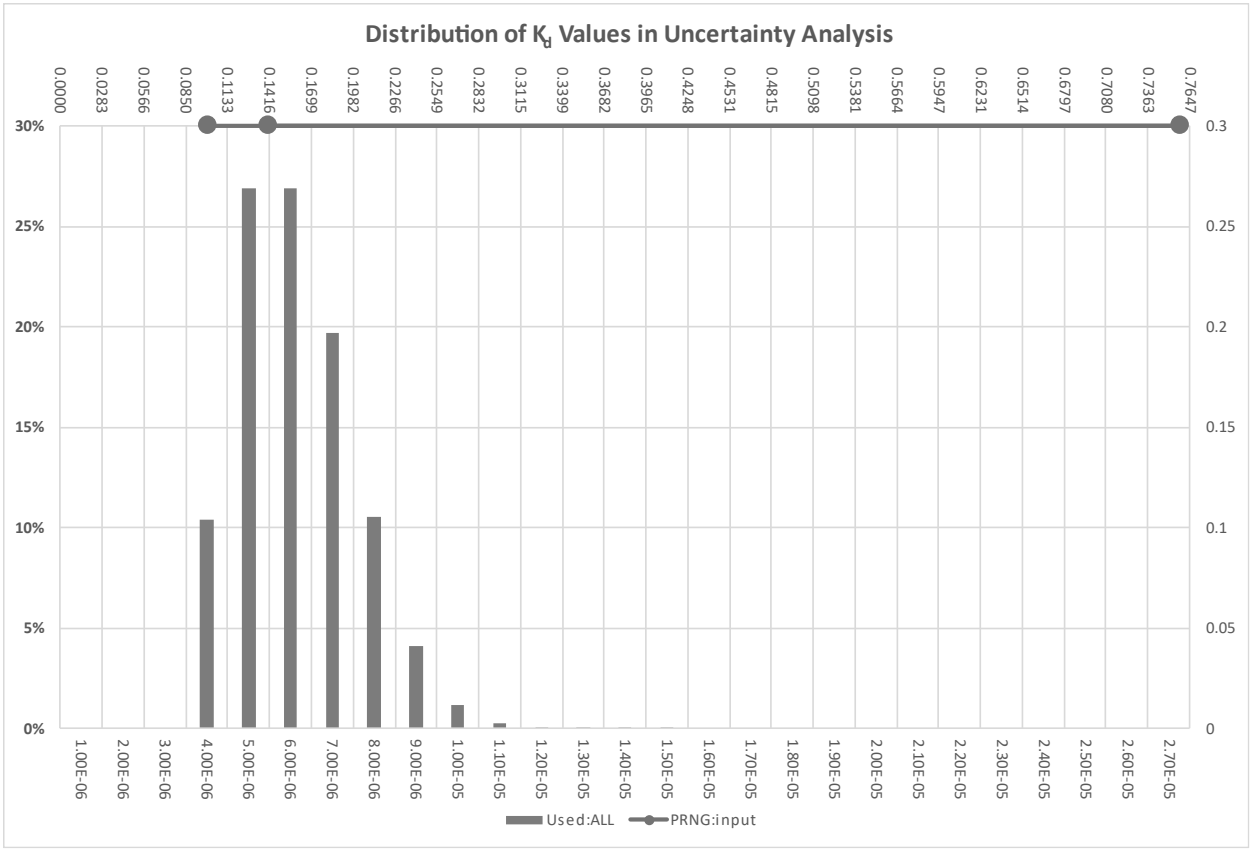



**Figure 37: Distribution of $K_d$ Values in ATSDR's Uncertainty Analysis**

ATSDR did not provide an explanation for their choice of statistical descriptions for the $K_d$ distribution, which inherently prevented the assessment of a wider range of possible $K_d$ values from the range ATSDR considered reasonable.

Similar conclusions can be drawn for the bulk density and porosity distributions used for generating model inputs for the Monte Carlo realizations.

## C-2. Statistical descriptions for the model parameters result in distributions closely resembling the mean values used in the calibrated model

Although there is cell-by-cell variability in the calculated parameter fields for each realization, the contaminant plume migrates based on average conditions along its path. The changes in parameter value from cell to cell would result in varying plume migration patterns from one realization to the next if the mean value of the parameter were to vary between realizations. However, in ATSDR's uncertainty analysis, the mean parameter values for $K_d$, bulk density, and porosity for all realizations are comparable to the corresponding calibrated-model value, and do not encompass the range of values that ATSDR indicated as reasonable, or even the narrower range that resulted from the probabilistic distributions.

The impact of selecting these statistical descriptions for assigning property values in each model cell is illustrated in Figure 38. This map depicts the $K_d$ values assigned to each model cell in Layer 3, within a focus area that encompasses the model-calculated plume footprint between the source area at well TT-26, for one of ATSDR's uncertainty analysis realizations. Per ATSDR's approach, $K_d$ values are assigned randomly in each cell, sampled from the distribution depicted in Figure 37.

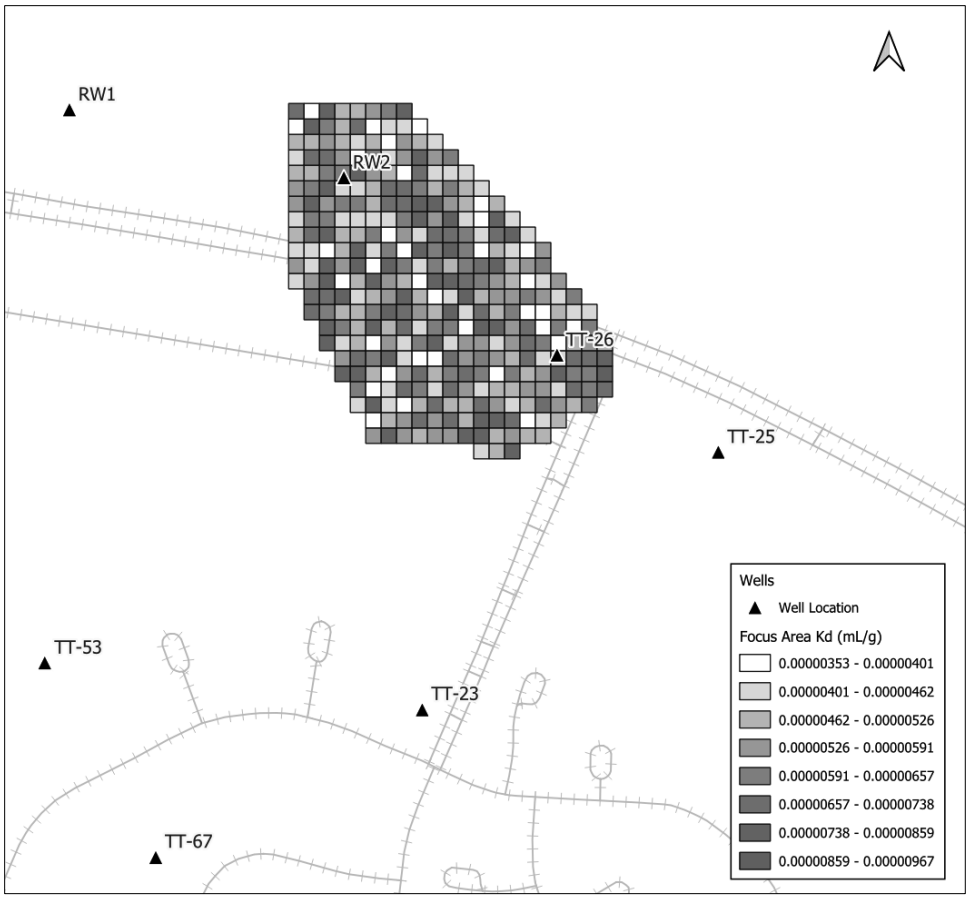



**Figure 38: Cell-by-Cell Distribution of $K_d$ Values in Focus Area of ATSDR's Model Layer 3**

The mapped spatial distribution of Figure 38 indeed encompasses $K_d$ values within the range indicated in the statistical description of Figure 37. However, when the mean and median $K_d$ values are calculated for the focus area in Layer 3, the corresponding values are 0.159 and 0.154 mL/g, respectively. The mean and median $K_d$ values for the focus area in Layer 1 for all 840 realizations are 0.159 and 0.154 mL/g, respectively.

These values confirm that (a) ATSDR implemented an approach that considered parameter variability within a fraction of the reasonable range of values to be evaluated; (b) this variability resulted in mean $K_d$ values over the entire model and, more importantly for the historical reconstruction, over the critical distance/area between the source and the pumping wells, that did not vary within even the narrow uncertainty range that ATSDR ultimately assessed; and (c) these mean values are very similar to the values used in the calibrated model, which should be expected considering the statistical descriptions ATSDR implemented for these parameters.

I also calculated mean and median values for bulk density and porosity for the cells in the focus area in Layers 1 and 3, indicating the same patterns as $K_d$. The same conclusions are drawn when values for $K_d$, bulk density and porosity are calculated for all model layers/cells and all 840 realizations.

Mean and median parameter values for the focus area from 840 realizations based on the defined probability distribution function:

| Parameter | Layer | Mean | Median |
|---|---|---|---|
| $K_d$ | 1 | 0.159 | 0.154 |
| | 3 | 0.159 | 0.154 |
| Porosity | 1 | 0.2 | 0.2 |
| | 3 | 0.2 | 0.2 |
| Bulk Density | 1 | 77,008 | 77,053 |
| | 3 | 77,008 | 77,053 |

Property values varied significantly from cell to cell in ATSDR's analysis, but the overall mean values did not vary. The cell-by-cell variability resulted in a very small variability in plume migration and contaminant arrival times at the water-supply wells, as plume migration patterns and timing are determined primarily by mean property values over the distance/area of interest and not the small-scale variability implemented in this analysis. Hence, ATSDR's uncertainty analysis evaluated only local-scale spatial variability and did not address large-scale variability or, more importantly, mean-value variability that would impact plume migration patterns.

# Appendix D: Sampling Data Available During the Historical Period in Tarawa Terrace

**Table F13.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply wells and calibration target range, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; J, estimated]

| Site name | Date | PCE concentration, in µg/L | | Calibrated target range, in µg/L |
|---|---|---|---|---|
| | | Observed | Simulated | |
| [1]RW1 | 7/12/1991 | ND | 0.0 | 0.0–2.0 |
| [1]RW2 | 7/12/1991 | 760 | 1,804 | 240–2,403 |
| [1]RW3 | 7/12/1991 | ND | 0.0 | 0.0–2.0 |
| [2]TT-23 | 1/16/1985 | 132 | 254 | 41.7–417 |
| | 2/12/1985 | 37.0 | 254 | 11.7–117 |
| | 2/19/1985 | 26.2 | 253 | 8.3–82.8 |
| | 2/19/1985 | ND | 253 | 0.0–10.0 |
| | 3/11/1985 | 14.9 | 253 | 4.7–47.1 |
| | 3/11/1985 | 16.0 | 253 | 5.2–52.5 |
| | 3/12/1985 | 40.6 | 253 | 12.8–128 |
| | 3/12/1985 | 48.0 | 253 | 15.4–154 |
| | 4/9/1985 | ND | 265 | 0.0–2.0 |
| | 9/25/1985 | 4.0 | 279 | 0.3–12.6 |
| | 7/11/1991 | ND | 193 | 0.0–5.0 |
| [2]TT-25 | 2/5/1985 | ND | 6.2 | 0.0–10.0 |
| | 4/9/1985 | ND | 8.6 | 0.0–2.0 |
| | 9/25/1985 | 0.43J | 18.1 | 0.14–1.4 |
| | 10/29/1985 | ND | 20.4 | 0.0–10.0 |
| | 11/4/1985 | ND | 20.4 | 0.0–10.0 |
| | 11/13/1985 | ND | 20.4 | 0.0–10.0 |
| | 12/3/1985 | ND | 22.8 | 0.0–10.0 |
| | 7/11/1991 | 23.0 | 72.6 | 7.3–72.7 |
| [2]TT-26 | 1/16/1985 | 1,580 | 804 | 500–5,000 |
| | 2/12/1985 | 3.8 | 804 | 1.2–12 |
| | 2/19/1985 | 55.2 | 798 | 17.5–175 |
| | 2/19/1985 | 64.0 | 798 | 20.2–202 |
| | 4/9/1985 | 630 | 801 | 199–1,999 |
| | 6/24/1985 | 1,160 | 732 | 367–3,668 |
| | 9/25/1985 | 1,100 | 788 | 348–3,478 |
| | 7/11/1991 | 340 | 670 | 111–1,107 |
| [2]TT-30 | 2/6/1985 | ND | 0.0 | 0.0–10.0 |
| [2]TT-31 | 2/6/1985 | ND | 0.15 | 0.0–10.0 |
| [2]TT-52 | 2/6/1985 | ND | 0.0 | 0.0–10.0 |
| [2]TT-54 | 2/6/1985 | ND | 5.8 | 0.0–10.0 |
| | 7/11/1991 | ND | 30.4 | 0.0–5.0 |
| [2]TT-67 | 2/6/1985 | ND | 3.9 | 0.0–10.0 |

[1]See Figure F6 for location

[2]See Figure F1 for location

Note: Calibration target ranges for analyses listed as not detected are detection limits noted in Table F2

**Figure 39: Simulated and Observed PCE Concentrations at Water Supply Wells in Tarawa Terrace (ATSDR, Table F13, Chapter F)**

**Table F14.** Computed and observed tetrachloroethylene (PCE) concentrations in water samples collected at the Tarawa Terrace water treatment plant and calibration target range, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; TTWTP, Tarawa Terrace water treatment plant; ND, not detected]

| Date | PCE concentration, in µg/L | | Calibration target range, in µg/L |
|---|---|---|---|
| | Computed[1] | Observed | |
| [2]TTWTP Building TT-38 | | | |
| 5/27/1982 | 148 | 180 | 25–253 |
| 7/28/1982 | 112 | [3]104 | 33–329 |
| 7/28/1982 | 112 | [3]76 | 24–240 |
| 7/28/1982 | 112 | [3]82 | 26–259 |
| 2/5/1985 | 176 | [3,4]80 | 25–253 |
| 2/13/1985 | 3.6 | [5]ND | 0–10 |
| 2/19/1985 | 3.6 | [6]ND | 0–2 |
| 2/22/1985 | 3.6 | [5]ND | 0–10 |
| 3/11/1985 | 8.7 | [6]ND | 0–2 |
| 3/12/1985 | 8.7 | [6,7]6.6 | 2.1–21 |
| 3/12/1985 | 8.7 | [6,8]21.3 | 6.7–67 |
| 4/22/1985 | 8.1 | [5]1 | 0.3–3.2 |
| 4/23/1985 | 8.1 | [5]ND | 0–10 |
| 4/29/1985 | 8.1 | [5]3.7 | 1.2–11.7 |
| 5/15/1985 | 4.8 | [5]ND | 0–10 |
| 7/1/1985 | 5.5 | [5]ND | 0–10 |
| 7/8/1985 | 5.5 | [5]ND | 0–10 |
| 7/23/1985 | 5.5 | [5]ND | 0–10 |
| 7/31/1985 | 5.5 | [5]ND | 0–10 |
| 8/19/1985 | 6.0 | [5]ND | 0–10 |
| 9/11/1985 | 6.0 | [5]ND | 0–10 |
| 9/17/1985 | 6.0 | [5]ND | 0–10 |
| 9/24/1985 | 6.0 | [5]ND | 0–10 |
| 10/29/1985 | 6.0 | [5]ND | 0–10 |
| [2]TTWTP Tank STT-39 | | | |
| 2/11/1985 | 176 | [5]215 | 0–10 |

[1] Weighted-average computation

[2] See Plate 1, Chapter A report, for location (Maslia et al. 2007)

[3] Detection limit is unknown

[4] Analysis of tap water sample for Tarawa Terrace, address unknown

[5] Detection limit = 10 µg/L

[6] Detection limit = 2 µg/L

[7] Sample collected downstream of TTWTP reservoir after operating well TT-23 for 24 hours

[8] Sample collected upstream of TTWTP reservoir after operating well TT-23 for 22 hours

**Figure 40: Simulated and Observed PCE Concentrations at the Tarawa Terrace WTP (ATSDR, Table F14, Chapter F)**

# Appendix E: Sampling Data Available During the Historical Period in Hadnot Point and Holcomb Boulevard

**Table A4.** Water-supply wells with reported detections of tetrachloroethylene (PCE), trichloroethylene (TCE), 1,1-dichloroethylene (1,1-DCE), *trans*-1,2-dichloroethylene (1,2-tDCE), *cis*-1,2-dichloroethylene (1,2-cDCE), total 1,2-dichloroethylene (total 1,2-DCE), or vinyl chloride (VC), Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[<, constituent is less than the detection limit. Number following the "<" is the detection limit; —, constituent concentration not determined in laboratory analysis; ND, constituent not detected; J, estimated concentration; D, sample diluted for analysis]

| Well name | Sample date | [2]Concentration, in micrograms per liter | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | PCE | TCE | 1,1-DCE | 1,2-tDCE | 1,2-cDCE | Total 1,2-DCE | VC |
| HP-602 | 7/6/1984 | <1.9 | <1.4 | <1.3 | 7.8 | — | — | <0.9 |
| | 11/30/1984 | 24 | 1,600 | 2.4J | 630 | — | — | 18 |
| | 12/10/1984 | <500 | 540 | <500 | 380 | — | — | <500 |
| | 12/13/1984 | 3.2 | 300 | — | 110 | — | — | — |
| | 12/14/1984 | <50 | 340 | <50 | 230 | — | — | <50 |
| | 2/4/1985 | 1.5J | 38 | <10 | 74 | — | — | <10 |
| | 11/12/1986 | <4.1 | 2.2 | <2.8 | 14 | — | — | <4.9 |
| | 1/22/1991 | <5.0 | 0.7J | <5.0 | — | — | 12 | <10 |
| HP-603 | 12/4/1984 | <10 | 4.6J | <10 | <10 | — | — | <10 |
| | 12/12/1984 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 1/16/1985 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 8/11/1988 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 6/26/1990 | <5.0 | <5.0 | <5.0 | — | — | — | <10 |
| | 1/22/1991 | <5.0 | 1.0J | <5.0 | — | — | <5.0 | <10 |
| | 9/20/1995 | <0.50 | 3.0 | <0.50 | <0.50 | 2.4 | — | <0.50 |
| HP-608 | 12/4/1984 | <10 | 110 | <10 | 5.4J | — | — | <10 |
| | 12/10/1984 | <10 | 13 | <10 | 2.4J | — | — | <10 |
| | 2/4/1985 | <10 | 9.0 | <10 | <10 | — | — | <10 |
| | 11/12/1986 | <4.1 | 66 | <2.8 | 8.5 | — | — | <4.9 |
| HP-610 | 2/4/1985 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 10/1/1992 | <1.0 | 37 | — | — | — | — | <2.0 |
| HP-634 | 12/4/1984 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 12/10/1984 | <10 | <10 | <10 | 2.3J | — | — | <10 |
| | 1/16/1985 | 10 | 1,300 | <10 | 700 | — | — | 6.8 |
| | 11/12/1986 | <4.1 | <1.9 | <2.8 | 2.9 | — | — | <4.9 |
| | 1/22/1991 | <5.0 | <5.0 | <5.0 | — | — | 1.0J | <10 |
| HP-637 | 12/4/1984 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 12/10/1984 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 1/16/1985 | <10 | <10 | <10 | <10 | — | — | <10 |
| | 1/22/1991 | <5.0 | 0.90J | <5.0 | — | — | <5.0 | <10 |
| | 8/26/1992 | <5.0 | <5.0 | <5.0 | <5.0 | <5.0 | — | <5.0 |
| HP-651 | 1/16/1985 | 386 | 3,200 | 187 | 3,400 | — | — | 655 |
| | 2/4/1985 | 307 | 17,600 | <200 | 8,070 | — | — | 179 |
| | 2/4/1985 | 400 | 18,900 | <200 | 7,580 | — | — | 168 |
| | 11/12/1986 | 45 | 32 | 7.0 | 140 | — | — | 140 |
| | 1/22/1991 | 53 | 13 | 2.0J | — | — | 75 | 70 |
| HP-652 | 1/16/1985 | <10 | 9.0 | <10 | <10 | — | — | <10 |
| | 11/12/1986 | <3.0 | <3.0 | <2.8 | <1.6 | — | — | <1.0 |
| | 1/22/1991 | <5.0 | <5.0 | <5.0 | — | — | <5.0 | <10 |
| | 9/20/1995 | <0.50 | <0.50 | <0.50 | <0.50 | <0.50 | — | <0.50 |
| | 12/11/2001 | <0.50 | <0.50 | <0.50 | <0.50 | <0.50 | — | <0.50 |
| HP-653 | 1/16/1985 | <10 | 5.5 | <10 | <10 | — | — | <10 |
| | 11/12/1986 | <4.1 | 2.6 | <2.8 | <1.6 | — | — | <4.9 |
| | 1/22/1991 | <5.0 | <5.0 | <5.0 | — | — | <5.0 | <10 |
| HP-660 | 12/4/1984 | 5.0J | 210 | <10 | 88 | — | — | <10 |
| | 12/10/1984 | 4.4J | 230 | <10 | 99 | — | — | <10 |
| | 1/16/1985 | <10 | 26 | <10 | 88 | — | — | <10 |
| | 11/12/1986 | <4.1 | <1.9 | <2.8 | <1.6 | — | — | <4.9 |
| | 1/22/1991 | <5.0 | 1.0J | <5.0 | — | — | 2.0J | <10 |

[1] See Faye et al. (2010) for a complete tabulation of contaminants in water samples collected at water-supply wells in the Hadnot Point–Holcomb Boulevard study area

[2] Concentrations above the detection limit are highlighted in red

**Figure 41: Concentration Data for PCE and its Degradation By-Products in HPHB Water Supply Wells (ATSDR, Table A4, Chapter A)**

**Table A5.** Water-supply wells with reported detections of benzene, toluene, ethylbenzene, or total xylenes, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[<, constituent is less than the detection limit. Number following the "<" is the detection limit; —, constituent concentration not determined in laboratory analysis; ND, constituent not detected; J, estimated concentration]

| Well name | Sample date | [2]Concentration, in micrograms per liter | | | |
|---|---|---|---|---|---|
| | | Benzene | Toluene | Ethylbenzene | Total xylenes |
| Hadnot Point Water Treatment Plant Service Area | | | | | |
| HP-602 | 7/6/1984 | 380 | 10 | 8.0 | — |
| | 11/30/1984 | 120 | 5.4J | <10 | — |
| | 12/10/1984 | 720 | <500 | <500 | — |
| | 12/13/1984 | <1.0 | <1.0 | <2.0 | — |
| | 12/14/1984 | 230 | 12J | <50 | — |
| | 2/4/1985 | <10 | <10 | <10 | — |
| | 11/12/1986 | 50 | <6.0 | <7.2 | <12 |
| | 1/22/1991 | 17 | <5.0 | <5.0 | <5.0 |
| HP-603 | 12/4/1984 | <10 | <10 | <10 | — |
| | 12/10/1984 | <10 | <10 | <10 | — |
| | 1/16/1985 | <10 | <10 | <10 | — |
| | 8/11/1988 | <10 | <10 | <10 | <10 |
| | 6/26/1990 | <5.0 | <5.0 | <5.0 | <5.0 |
| | 1/22/1991 | <5.0 | <5.0 | <5.0 | <5.0 |
| | 9/20/1995 | <0.50 | <0.50 | <0.50 | <0.50 |
| HP-608 | 12/4/1984 | 3.7J | <10 | <10 | — |
| | 12/10/1984 | 4.0J | <10 | <10 | — |
| | 2/4/1985 | 1.6 | <10 | <10 | — |
| | 11/12/1986 | <4.4 | <6.0 | <7.2 | <12 |
| HP-651 | 1/16/1985 | <10 | <10 | <10 | — |
| | 2/7/1985 | <10 | <10 | <10 | — |
| | 11/12/1986 | <4.4 | <6.0 | <7.2 | <12 |
| | 1/22/1991 | <5.0 | 0.9J | <0.5 | <0.5 |
| Holcomb Boulevard Water Treatment Plant Service Area | | | | | |
| HP-645 | 2/4/1985 | <10 | <10 | <10 | — |
| | 11/6/1986 | 20 | 7.5 | ND | ND |
| | 2/17/1987 | 290 | 15 | 38 | 36 |
| HP-706 | 9/19/1995 | 0.60 | <0.50 | <0.50 | <0.50 |
| | 1/13/1998 | 6.1 | — | — | — |

[1] See Faye et al. (2010) for a complete tabulation of contaminants in water samples collected at water-supply wells in the Hadnot Point–Holcomb Boulevard study area

[2] Concentrations above the detection limit are highlighted in red

**Figure 42: Concentration Data for Benzene, Toluene, Ethylbenzene, or Total Xylenes in HPHB Water Supply Wells (ATSDR, Table A5, Chapter A)**

**Table A18.** Selected measured and reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), vinyl chloride (VC), and benzene at the Hadnot Point water treatment plant, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; J, estimated]

| Contaminant | [1]Measured data | | [2]Reconstructed (simulated) | | [2]Reconstructed (maximum value) | |
|---|---|---|---|---|---|---|
| | Sample date | Concentration, in µg/L | Simulation date | Concentration, in µg/L | Simulation date | Concentration, in µg/L |
| PCE | 5/27/1982[3] | 15 | May 1982 | 21 | Nov. 1983 | 39 |
| | 7/27/1982[4] | 100 | July 1982 | 27 | | |
| | 12/4/1984[6] | 3.9J | Nov. 1984 | 31 | | |
| | 2/5/1985[7] | 7.5J | Jan. 1985 | 16 | | |
| TCE | 5/27/1982[3] | 1,400 | May 1982 | 438 | Nov. 1983 | 783 |
| | 7/27/1982[5] | 19 | Aug. 1982 | 670 | | |
| | 7/27/1982[6] | 21 | Aug. 1982 | 670 | | |
| | 12/4/1984[5] | 46 | Nov. 1984 | 639 | | |
| | 12/4/1984[6] | 200 | Nov. 1984 | 639 | | |
| | 12/12/1984[6] | 2.3J | Dec. 1984 | 43 | | |
| | 12/19/1984 | 1.2 | Dec. 1984 | 43 | | |
| | 2/5/1985[7] | 429 | Jan. 1985 | 324 | | |
| 1,2-tDCE | 12/4/1984[6] | 83 | Nov. 1984 | 358 | Nov. 1983 | 435 |
| | 12/4/1984[5] | 15 | Dec. 1984 | 26 | | |
| | 12/12/1984[6] | 2.3J | Dec. 1984 | 26 | | |
| | 2/5/1985[7] | 150 | Jan. 1985 | 163 | | |
| VC | 2/5/1985[7] | 2.9J | Jan. 1985 | 31 | Nov. 1983 | 67 |
| Benzene | 11/19/1985[7,8,9] | 2,500 | Nov. 1985 | 3 | Apr. 1984 | 12 |
| | 12/10/1985[7] | 38 | Dec. 1985 | 3 | | |
| | 12/18/1985[7] | 1.0 | Dec. 1985 | 3 | | |

[1]Data from Faye et al. (2010, Tables C11 and C12)

[2]Simulation results represent the last day of each month (e.g., May 31); results reported for simulation month nearest the sample date; refer to Appendix A7 for complete listing of reconstructed finished-water concentrations

[3]Water sample collected at Building NH-1; data reported as unreliable

[4]Water sample collected at Building FC-530

[5]Untreated water

[6]Treated water

[7]Treatment status unknown

[8]Laboratory analysis noted with: "Sample appears to have been contaminated with benzene, toluene, and methyl chloride" (JTC Environmental Consultants 1985)

[9]Data noted with: "Not Representative" (U.S. Marine Corp Base Camp Lejeune Water Document CLW #1356)

**Figure 43: Concentration Data for PCE, TCE, 1,2-tDCE, VC, and Benzene at the Hadnot Point WTP (ATSDR, Table A18, Chapter A)**

# Attachment

## Curriculum Vitae

# Alexandros Spiliotopoulos, Ph.D.

## Senior Associate, Senior Hydrogeologist

Dr. Spiliotopoulos' expertise is quantitative and qualitative analysis of environmental data to support water resources management. He develops and applies analytical and numerical groundwater models, develops novel methods for evaluating water quantity and quality data, and designs and optimizes multiscale remedial systems and monitoring programs. He brings extensive experience in the remediation of nuclear and Superfund sites, providing expert modeling support for RI/FS, RPO, and RD/RA Work Plans; design, performance assessment and optimization of remedial systems for fuel additives, metals, radionuclides and VOCs; as well as water-resource assessment for water-supply development, permitting, and adjudication.

### REPRESENTATIVE EXPERIENCE

***S.S. Papadopulos & Associates, Inc.*** *– Rockville, Maryland*

*GROUNDWATER REMEDY DESIGN & EVALUATION*

**U.S. Department of Energy, Hanford, Washington:** Technical Lead and Lead Modeler for the River Corridor Operable Units. Designed system alternatives for Remedial Process Optimization, Remedial Investigation/Feasibility Study, and Remedial Design/Remedial Action Work Plans, including the design and implementation of large-scale pump-and-treat systems and/or MNA and other in-situ treatment technologies, to meet short- and long-term goals for river protection and aquifer cleanup. Used in-house enhanced versions of MODFLOW, MODPATH, and MT3DMS to design, evaluate and optimize remedies to meet cleanup objectives. Examples of this work include:

- Developed strategies for implementing EPA's DQO process and statistical evaluations for site closure, considering MNA and/or in-/ex-situ treatment.
- Constructed and calibrated the 100 Areas 3D groundwater flow and reactive contaminant transport groundwater model, using the MODFLOW suite of codes. performed uncertainty analysis using Null Space Monte Carlo to evaluate aquifer restoration timeframe uncertainty.
- Constructed and calibrated groundwater flow and fate & transport models for all Operable Units in the River Corridor.
- Designed sampling and analysis plans and test designs for area-specific hexavalent chromium rebound studies to determine if groundwater remediation activities have met or are on track to meet cleanup goals.
- As part of annual reporting since 2012, conducted (a) site-wide multi-constituent plume delineation by developing/ implementing a systematic approach for data-selection and using in-house transformation-based kriging algorithms; (b) pump-and-treat system performance evaluations including flow and fate & transport modeling, statistical assessment of water-quality data (with covariates for seasonal, river, and pumping effects), monitoring network evaluation and recommendations.
- Contributor to the evaluation of the presence, extent, and mass loading from continuing sources, including analysis of batch tests
- Developed functional criteria and designed critical and optimal networks for monitoring wells equipped with pressure transducers and data loggers to collect continuous water-level data.
- Designed and performed reactive transport simulations using the MT3DMS dual-domain formulation and developing the CTS module for time-varying mass recirculation of extracted contaminants via injection wells.

### YEARS OF EXPERIENCE

20+

### EDUCATION

» **PhD**, Civil and Environmental Engineering, University of Vermont, 1999

» **BS**, Civil Engineering, University of Patras, Greece, 1994

### EXAMPLE AREAS OF EXPERTISE

» Groundwater Remedy Design and Evaluation

» Water Resource Evaluation and Management

» Environmental Data Analysis

» Groundwater Modeling

### PROFESSIONAL SOCIETIES

» National Ground Water Association (NGWA)

» American Geophysical Union (AGU)

### LANGUAGES

English, Greek

### PROFESSIONAL HISTORY

» S.S. Papadopulos & Associates, Inc.: 2004–present

» ADK Consulting Engineers S.A., Hydraulic Engineer: 2000–2004

» University of Vermont, Graduate Researcher in Research Center for Ground Water Remediation Design: 1994–1999

### EMAIL

alexs@sspa.com

- For groundwater monitoring under RCRA, developed tools and novel approaches in support of remedial action and contaminant migration pattern evaluations.
- Responsible manager for RCRA progress evaluations in 300 Area, including estimates of concentration trends, yearly mean concentrations, and confidence limits for groundwater wells for the MNA remedy for multiple constituents, and enhanced attenuation (EA) remedy for uranium.

**U.S. Environmental Protection Agency (EPA) Region 5:** Provides technical support to Region 5 EPA for evaluating groundwater flow, contaminant transport, and remedy performance at multiple Superfund sites. Authored and co-authored reports to support statutory Five-Year Reviews, including recommendations on remedy and monitoring program optimization. Remedial technologies evaluated included pump-and-treat (P&T), monitored natural attenuation (MNA), soil vapor extraction (SVE), air-sparge/biosparge (AS/B).

**Sparton Corporation, Albuquerque, New Mexico:** Technical Lead and Lead Modeler for performance evaluation and optimization of the remedial design, and assessment of groundwater quality data to evaluate plume migration patterns and effectiveness of remediation of VOCs and metals, including chromium. Constructed and calibrated 3D groundwater flow and contaminant transport for transient site conditions, in support of system performance evaluations. Responsible for all compliance/mitigation efforts and annual reporting to EPA/NMED. Expanded monitoring program to evaluate potential vapor intrusion issues and the presence and migration of 1,4-dioxane within and outside the hydraulic containment zone.

**New York Department of Environmental Conservation (NYSDEC), New York:** Consulted to the NYSDEC spills department, evaluating and simulating the fate and remediation of fuel spills. Provided hydrogeologic oversight and groundwater flow and fuel-component transport and fate analyses to design and optimize groundwater remedies and the associated monitoring systems to protect sole-source municipal supplies. Projects included:

- **New Hyde Park Site Characterization, Long Island:** Reviewed and supervised site characterization efforts in collaboration with NYSDEC. Developed and calibrated a three-dimensional flow and transport model for a robust pump-and-treat remedy evaluation to support the development of a cost-effective remedial system design to address a MTBE mega-plume.
- **Mineola Site Characterization and Monitoring Plan, Long Island:** Provided technical support for site characterization and design of a monitoring plan for a MTBE plume. Developed and calibrated a three-dimensional flow and transport model for the design of a remedial system to protect a downgradient public supply well. Implemented geostatistical and other methods to evaluate spatial and temporal variations of the magnitude and direction of the hydraulic gradient in support of additional remedy designs to address the MTBE plume.
- **Elmont Site Characterization, Long Island:** Reviewed and supervised site characterization efforts. Designed, coordinated, and performed a rapid mapping methodology for 3D site-characterization and expedited plume delineation. The designed mapping methodology combined direct-push sampling and Quantile-Kriging interpolation techniques. Developed a three-dimensional flow-and-transport model to assess the MTBE plume migration, to evaluate alternative remedial designs, and to monitor natural attenuation.
- **Ronkonkoma Groundwater Flow & Transport Model, Long Island:** Developed and calibrated a groundwater flow and transport model to analyze plume (MTBE, BTEX, TAME, and TBA) migration patterns for at the site, and to monitor the operation of the appropriate Interim Remedial Measure (IRM) system.
- **Uniondale Monitoring Plan, Long Island:** Developed a monitoring plan to delineate the contaminant plume and to assess plume migration characteristics to identify appropriate measures for protection of downgradient receptor wells.
- **Hampton Bays Flow & Transport Model, Long Island:** Applied a three-dimensional flow-and-transport model to assess MTBE-plume migration pathways over time, under varying regional hydraulic gradient conditions. Evaluated the effectiveness of the existing IRM system and recommended system enhancements.
- **West Hempstead Flow & Transport Model:** Developed a transient three-dimensional flow-and-transport model to analyze historical groundwater flow conditions at the site and to identify MTBE plume migration and recovery at the IRM wells. Evaluated system performance, recommended improvements for system operations, and assessed aquifer cleanup times.
- **Gloria Road Groundwater Monitoring Network, Nassau County:** Provided technical support and recommendations for the development of a monitoring network to determine the migration pattern of a MTBE and BTEX plume. Implemented an existing flow model to perform particle-tracking analysis and sensitivity analysis to provide bounding estimates on the lateral extent of the plume pathway and to evaluate whether a proposed monitoring well would intercept the plume.
- **East Patchogue Flow & Transport Model, Suffolk County:** Supervised the development of a three-dimensional flow and transport model to analyze the historical migration of a MTBE plume and to quantify its

relative discharge to a pond near the shoreline and the Long Island Sound. Performed a sensitivity analysis to incorporate variation in pond stage due to tidal effects.

**Onondaga Lake Parameter Estimation:** Reviewed and expanded parameter estimation efforts for a flow-and-transport model calibration. Evaluated the proposed remedial design and provided recommendations for appropriate design parameters.

**Far-Mar-Co Subsite, Hastings Site, Nebraska:** Calibration of the groundwater-flow and contaminant-transport model, applying advanced parameter estimation techniques, including regularization, using PEST.

*WATER RESOURCE EVALUATIONS*

**Mississippi vs. Tennessee, City of Memphis and Memphis Light, Gas, and Water Division:** Worked on groundwater modeling and ancillary evaluations in support of assessment of water-level declines throughout the aquifer in light of Mississippi's complaint that Tennessee is stealing its groundwater.

**North Penn Area 5 Superfund Site near Colmar, in Bucks and Montgomery Counties, Pennsylvania:** Compiled and analyzed historical water level data for vertical gradient and particle tracking evaluations in a highly fractured aquifer. Modified the groundwater flow model developed by the USGS, to include additional pumping wells and a former pond area. Developed and assessed various pumping scenarios, via groundwater modeling and particle tracking.

**Hanford Natural Resource Trustee Council (HNRTC), Hanford, Washington:** Technical lead to conduct a desktop survey to evaluate existing information incorporating a literature study, model outputs, conceptual site models (CSMs), plume maps, and data, to estimate the upwelling of contaminants to the Columbia River at the Hanford Site, in support of a Natural Resource Damage Assessment and Restoration (NRDAR) process undertaken by the Hanford Natural Resource Trustee Council (HNRTC). Developed a hybrid mapping-modeling method for integrating distributed plume information and historical groundwater model results, to provide bounding estimates of contaminant upwelling for the period 1980-2020. The assessment reviewed contaminants of interest (COIs) and produced sitewide plume depictions, hundreds of piecewise-continuous digital maps for the main COIs, mass upwelling graphs illustrating the annual and cumulative mass upwelling for each COI and area, heatmaps illustrating upwelling patterns for each COI and OU, concentration upwelling maps for the main COIs, and maps of annualized temperature distributions for each OU.

**Apalachicola-Chattahoochee-Flint River Basin, Florida vs. Georgia Water Dispute:** Provided technical support to Georgia's Counsel in reviewing material submitted for consideration in the conflict-resolution litigation at the U.S. Supreme Court. Reviewed model files, numerical and analytical evaluations, and historical data. Provided high-level assessment of current and projected water-resource management practices and plans, and of the impacts to inter-state water allocations.

**Confidential Client:** Technical Lead for the evaluation of groundwater as a large-scale potential water supply for an international site serving a population of more than 5 million people. Led and conducted hydrogeologic and geochemical evaluations, reviewed geophysical assessments to enhance hydrogeologic interpretations, and developed multiple conceptual models for hypotheses testing by constructing, calibrating and deploying groundwater flow and transport models in a highly fractured aquifer with transboundary considerations. Designed and performed uncertainty analyses using IES for calibrated realizations. Provided recommendations for short- and long-term aquifer testing and monitoring/characterization activities.

**U.S. Army Corps of Engineers (USACE), New England District:** Technical Lead for the construction and calibration of a MODFLOW-USG groundwater flow model and deployment of mod-PATH3DU to evaluate pumping effects on surface water bodies, assess contaminant migration pathways, areas of influence, and Zone II Wellhead Protection Area for the proposed well. The model will serve as the main tool for evaluating PFAS fate and transport, as part of the RI/FS effort at the site.

**Kansas Department of Agriculture Republican River Basin Model, Northwest Kansas:** Modified and re-calibrated the existing Republican River Compact Association flow model (focusing on the Northwest Kansas area) to provide an administrative tool for the prediction of impacts to the Republican River from varying future irrigation patterns. Provided technical support to Kansas Department of Agriculture to evaluate future resource allocation and compliance on the basis of a Tri-State water-use agreement.

**Kansas Department of Agriculture Solomon River Basin Groundwater Flow Model Evaluation:** Supervised and provided recommendations for the development and calibration of two groundwater flow models for the Solomon River basin, to be used as an administrative tool for the management of the available water resources for irrigation purposes.

**Montana vs. Wyoming and North Dakota, Tongue River Basin Technical Support:** Provided technical support in reviewing groundwater model parameters and results, historical stream flow and outfall data, and other analyses to evaluate aquifer response and stream depletions to irrigation pumping and coal bed methane (CBM) pumping.

**Rainelle Power Plant Water Supply Evaluation, West Virginia:** As part of the EIS for the construction and operation of this proposed power plant, developed and calibrated a three-dimensional flow model to simulate groundwater flow conditions to evaluate the availability of groundwater as a water source for cooling purposes and to evaluate potential impacts to local pumping wells and river flow. Performed aquifer test analyses to define hydraulic properties that were further refined during the model calibration process. Conducted baseflow analysis to estimate river flow that was attributed to groundwater and to evaluate river water depletions due to pumping. Developed pumping and recharge scenarios to assess the impact of pumping from existing and proposed wells that would supply the power plant, to local production wells and to river flow.

**Confidential Client, El Campo, Texas:** Performed statistical analyses of isotopes and other chemicals to examine origin of contaminants and plume migration for a site contaminated with TCE, DCE and other chemicals. Constructed, calibrated, and deployed numerical and semi-analytical methods for simulating groundwater flow and contaminant transport (MODFLOW/MT3D and ATRANS), to estimate the contaminant release history at the site, based on recent monitoring data.

### *ADK Consulting Engineers S.A. – Athens, Greece*

**Water distribution network, Corfu, Greece:** Designed and calibrated a model of the metropolitan water distribution network of the City of Corfu.

**Athens Water Supply and Sewerage Company, Greece:** Updated the numerical model for the principal mains of the water distribution network of the City of Athens and its suburbs, to simulate water demands associated with the 2004 Olympic Games. The assessment included all recent changes to the network and served as the primary management tool of the water distribution network. Developed a database and a GIS application for data management and interface with the hydraulic simulation model.

**Olympic Village, Athens, Greece:** Project engineer responsible for the design of the irrigation system of the Olympic Village, including four pumping stations and two storage ponds. Completed the preliminary and final design and tender document preparation for the irrigation system and a treated water storage tank. Evaluated the efficiency of the water distribution network design parameters, and performed complete fire-flow analysis.

**Municipality of Lamia, Greece:** Proposed an alternative design of the new treated-water storage tank for the City of Lamia for a total capacity of 2,500m³, and developed a GIS application interface for the management of the new treated-water aqueducts.

**Pan-Peloponnesian National Stadium of Patras, Greece, Ministry of Culture:** Designed the new stormwater management network as part of the stadium reconstruction for the 2004 Olympic Games.

### *Publications & Presentations*

Spiliotopoulos, A., Karanovic, M., Chowdhury, M., Ni, J., and Tonkin, M., 2025, *An Integrated Approach for Developing Contaminant Upwelling Estimates in the Hyporheic Zone*. Presentation at th Waste Management Conference, Phoenix, AZ, March 12, 2025 (in preparation)

Spiliotopoulos, A., Tonkin, M., DiFilippo, E., and Sorel, D., 2025, *Remedy Challenges, Novel Approaches and Lessons Learned from Superfund Waste Sites*. Presentation at th Waste Management Conference, Phoenix, AZ, March 10, 2025 (in preparation)

Muffels, C., S. Panday, C. Andrews, M. Tonkin, and A. Spiliotopoulos, 2022, *Simulating Groundwater Interaction with a Surface Water Network using Connected Linear Networks*. Groundwater, v. 60, no. 6 (November-December), pp. 801-807. doi: 10.1111/gwat.13202

Spiliotopoulos A., E.L. DiFilippo, P. Khambhammettu, D. Hayes, M.J. Tonkin, M. Hartman, K. Ivarson, and J. Hulstrom, 2019. *Web-Assisted Methods and Tools for Efficient Remedy Design and System Performance Evaluation at Hanford*. Presentation at the Waste Management Conference, Phoenix, AZ, March 7, 2019. Received "Superior" paper and "WM2019 Papers of Note Winner" awards. OSTI #23003084

DiFilippo E.L., M.J. Tonkin, A. Spiliotopoulos, W. Huber, and V. Rohay, 2019. *Evaluating Environmental Remediation Performance at Radwaste Sites Using Multiple, Censored Regression Analysis*. Presentation at the Waste Management Conference, Phoenix, AZ, March 7, 2019. IAEA #52043413

Spiliotopoulos, A., R. Shannon, M.J. Tonkin, and L.C. Swanson, 2011. *Evaluation of Temporal Variations in Hydraulic Capture due to Changing Flow Patterns Using Mapping and Modeling Techniques*. Presentation at MODFLOW and More 2011, Colorado School of Mines, Golden, CO. OSTI #1011435

Bedekar, V., M.J. Tonkin, and A. Spiliotopoulos, 2011. *Implementation of a Contaminant Treatment System (CTS) Module in MT3DMS*. Presentation at MODFLOW and More 2011, Colorado School of Mines, Golden, CO.

Khambhammettu, P., M.J. Tonkin, and A. Spiliotopoulos, 2011. *FIELDGEN_D – A Modified 2D Field Generator for Deterministic and Stochastic Groundwater Modeling*. Presentation at MODFLOW and More 2011, Colorado School of Mines, Golden, CO.

Shannon, R., A. Spiliotopoulos, and M.J. Tonkin, 2011. *Estimating Contaminant Migration Pathways Using a Time Sequence of Water Level Maps and Particle Tracking*. Presentation at the 2011 Ground Water Summit and 2011 Ground Water Protection Council Spring Meeting. National Ground Water Association, Baltimore, MD.

Smoot, J.L., F.H. Biebesheimer, J.A. Eluskie, T. Simpkin, M.J. Tonkin, and A. Spiliotopoulos, 2011. *Groundwater Remediation at the 100-HR-3 Operable Unit, Hanford Site, Washington*. Presentation at the Waste Management Conference, Phoenix, AZ. February 27– March 3, 2011. OSTI # 1004613

Spiliotopoulos, A., M.J. Tonkin, D. Shrimpton, J. Blount, T. Simpkin, and J. Hanson, 2010. *Groundwater Modeling in Support of Remedial Process Optimization: Implementing a Developing Conceptual Site Model into Comparative Remedy Analyses*. Presentation at the Waste Management Conference, Phoenix, AZ, March 7-11, 2010.

Spiliotopoulos, A., M. Karanovic, and S.P. Larson, 2008. *Development of Transient Flow Models for the Solomon River Basin*. Presentation at MODFLOW and More 2008, Colorado School of Mines, Golden, CO.

Spiliotopoulos, A., K. Krajenke, N. Hart, J. Haas, D. Cornacchiulo, D. Trego, and M. Tonkin, 2008. *Robust Pump-and-Treat Remedy Evaluation for an MTBE Mega-Plume*. Presentation at the National Ground Water Association (NGWA) Conference on Eastern Regional Ground Water Issues, Ronkonkoma, NY.

Spiliotopoulos, A., K. Krajenke, K. Salafrio, and J. Haas, 2008. *Rapid Mapping to Support Accelerated Site Assessments*. Presentation at NGWA Conference on Eastern Regional Ground Water Issues, Ronkonkoma, NY.

Spiliotopoulos, A., and C.B. Andrews, 2007. *Analysis of Aquifer Test Data – MODFLOW and PEST*. in Groundwater and Wells. (3rd ed.). Sterrett, R.J., ed. New Brighton, MN: Johnson Screens. 812 p. (also presented at MODFLOW and More 2006, Colorado School of Mines, Golden, CO).

Spiliotopoulos, A.A., G.P. Karatzas, and G.F. Pinder. 2004. *A Multi-period Approach to the Solution of Groundwater Management Problems Using an Outer Approximation Method*. European Journal of Operational Research, v. 157, no. 2 (September), pp. 514-525. doi: 10.1016/S0377-2217(03)00239-X

Matsouki, M., G. Germanopoulos, and A. Spiliotopoulos, 2003. *Geographical Information Systems (G.I.S.) Implementation in Water Supply Network Modeling*. Presentation at the XXX IAHR Congress, Thessaloniki, Greece. August 24-29, 2003.

Spiliotopoulos, A.A., G.P. Karatzas, and G.F. Pinder, 2000. *A Biconcave-Decomposition Method for the Optimal Design of Pump-and-Treat Remediation Systems Including the Treatment Plant*. Presentation at the 13th International Conference on Computational Methods in Water Resources, Calgary, Canada. June 2000.

Karatzas, G.P., and A.A. Spiliotopoulos, 1998. *Development of Two Optimization Models: (1) A Multi-period Approach to Solve Engineering Management Problems, and (2) Incorporating Uncertainty in the Decision-Making Process for Optimal Management Design. An Application to a Groundwater Management Problem*. Presentation at the Vermont EPSCoR (Experimental Program to Stimulate Competitive Research) Annual Conference on Science and Technology, University of Vermont, October 6, 1998.

# EXHIBIT 3

**U.S. Department of Justice**

Civil Division, Torts Branch
Environmental Tort Litigation

*Haroon Anwar, Trial Attorney*
*Telephone: 202-598-3946*
*Facsimile: (202) 616-4989*
*Email: Haroon.Anwar@usdoj.gov*

**VIA EMAIL** April 21, 2025

Laura J. Baughman
Weitz & Luxenberg
700 Broadway
New York, New York 10003
lbaughman@weitzlux.com

**Re:** ***Camp Lejeune Water Litigation***
***Documents related to Drs. Hennet and Spiliotopoulos***

Counsel:

I am writing in response to your April 16, 2025, letter regarding certain materials requested by document subpoenas accompanying the deposition notices directed to the United States' Phase I experts, Drs. Remy Hennet and Alex Spilitopoulous. I am also writing to follow-up about the status of outstanding materials that have yet to be produced from Mr. Maslia and Dr. Konikow.

**SSPA Billing Records Related to CLJA**

The United States disagrees that Plaintiffs are "entitled to billing records that identify the number of hours each testifying expert worked each day and describe the work that was performed, to the extent these records exist." Fed. R. Civ. P. 26(a)(2)(vi) & 26(b)(4)(C)(i) require the production of "a statement of the compensation to be paid for the study and testimony in the case" and communications that "relate to compensation for the expert's study or testimony." District courts within the Fourth Circuit have interpreted these provisions narrowly. *See*, *e.g.*, *Norman v. Leonard's Express, Inc.*, 2023 WL 3244002 at *6 (W.D. Va. May 4, 2023) ("Dispositively, it lists the hourly rates for Dr. Richmond's services. Because Rule 26 requires a statement of the compensation 'to be paid' to an expert—as opposed to the amount 'paid to date'—and the compensation disclosure is necessarily to be made at the time the expert's report is disclosed—as opposed to at the time of trial—the defendants have satisfied Rule 26 by producing to Norman the fee schedule.") (internal citations omitted); *Seaman v. Duke University*, 2018 WL 1441267, at *8 (M.D. N.C. Mar. 21, 2018) ("Here, based on the above authority, the Court finds Plaintiff's first two requests—for the total amount Analysis Group has billed in connection with this case

and a breakdown of the proportion of Analysis Group's bills that are attributed to Dr. Cremieux's work—are sufficiently narrow and consistent with the Rule's intent."); *Océ North America, Inc. v. MCS Services*, 2011 WL 13217472, at *8 (D. Md. Sept. 9, 2011) ("To the extent it has not done so already, Océ should produce for each of its named experts a statement of the total compensation paid for their 'study and testimony in the case.' The court finds, however, that DeFazio has not articulated a compelling need for production of every monthly invoice or other document describing or concerning fees. Disclosure of Océ's experts' total compensation will adequately enable defendants to explore the experts' financial interest in this case on cross-examination.").

Here, the United States has more than complied with Fed. R. Civ. P. 26(a)(2)(vi) & 26(b)(4)(C)(i) and Fourth Circuit case law interpreting these provisions. Specifically, the United States has produced (1) information about the hourly rates of Drs. Hennet and Spilitopoulous and (2) invoices that reflect total compensation paid to S.S. Papadopulos & Associates related to work performed by or at the direction of Drs. Hennet and Spilitopoulous in the CLJA litigation. The produced invoices identify the employee type or title of each SSPA billing professional, including Dr. Hennet as "Senior Principal" and Dr. Spilitopoulous as "Senior Hydrologist." However, to avoid an unnecessary discovery dispute, the United States is working to gather and produce more detailed, timekeeping records related to the invoices already produced.

**SSPA Billing Records Related to Past Camp Lejeune Litigation**

The United States disagrees with Plaintiffs' characterization of the United States' objections to producing "compensation records related to work performed by SSPA for DOJ prior to August 2022." The specific document requests at issue in Plaintiffs' subpoena were overly broad, unduly burdensome, and sought documents and information not proportional to the needs of the case. Specifically, Request No. 6 sought "[a]ll bills, invoices, or other documents relating to payments from the United States or any of its agencies to you, S.S. Papadopulos, or any principals or agents of S.S. Papadopulos relating in any way to Camp Lejeune water contamination, the CLJA litigation, remediation related to Camp Lejeune or any other water quality issues related to Camp Lejeune from 2004 through the present." Request No. 7 sought "[a]ll timekeeping and billing records related to time that you, S.S. Papadopulos, or any principals or agents of S.S. Papadopulos spent working on any projects related to Camp Lejeune and the CLJA litigation from the time you or your employer first were retained, hired or contracted." These Requests sought extensive documentation over a 20-year period dating back to 2005 related to past Camp Lejeune litigation involving distinct and separate issues.

Fed. R. Civ. P. 26(a)(2)(B)(vi) requires a retained testifying expert to disclose "a statement of the compensation to be paid for the study and testimony *in the case*," and district courts within the Fourth Circuit have interpreted this provision narrowly. Plaintiffs cite *Burris v. Ethicon, Inc.*, 2019 WL 13185497 (S.D. W.V. Nov. 7, 2019). In that case, the district court required production of "*basic documentation* reflecting the expert's income from acting as an expert witness [in prior related litigation]." *Id*. at *1 (emphasis added). Likewise, in *Bilenky v. Ryobi Ltd.*, the district court limited production of past expert compensation "to Mr. Nielsen's expert-

related income earned on behalf of Husqvarna *during the last three years*." 2014 WL 12591078, at *4 (E.D. Va. Oct. 22, 2014) (emphasis added). To avoid an unnecessary discovery dispute, the United States is working to determine if and to what extent compensation information or documents still exist related to SSPA's work for DOJ in past Camp Lejeune litigation. The United States will supplement its production with "basic" compensation information or documents related to SSPA's work for DOJ in past Camp Lejeune litigation to the extent it exists.

**2005 ATSDR Expert Panel Notes**

The United States disagrees that "Dr. Spiliotopoulos's notes, memoranda and any related documents regarding his attendance at the 2005 ATSDR Expert Panel meeting are not protected work product and must be produced." The work product doctrine protects "(1) documents or tangible things; (2) prepared in anticipation of litigation or trial; and (3) by or for the party or the party's representative." *U.S. v. Bertie Ambulance Service, Inc.*, 2015 WL 3932167, at *3 (E.D. N.C. June 15, 2015) (Jones, J.); *see also* Fed R. Civ. P. 26(b)(3)(A) ("Ordinarily, a party may not discover documents and tangible things that are prepared in anticipation of litigation or trial by or for another party or its representative… ."). Fed. R, Civ. P. 26(b)(4)(B) extends the work product doctrine to draft reports of retained experts. To overcome the work product protection, the discovering party must show that it "has substantial need for the materials to prepare its case and cannot, without undue hardship, obtain their substantial equivalent by other means." Fed. R. Civ. P. 26(b)(3)(A)(ii).

As you know, Dr. Spiliotopoulos testified that "In 2005 Gordon Bennet and Remy Hennet asked me to attend the meeting…and provide them with information about that." Spiliotopoulos Dep., 115:18-21. Furthermore, Dr. Hennet testified that "In 2005 I was involved in work for the Department of Justice on issues at Camp LeJeune that it had nothing to do with this case. It was a different case or different cases. And that's what I recall." Hennet Dep., 29:17-21. Contrary to Plaintiffs' assertion that "Dr. Spiliotopoulos had not been retained as an expert at that time…," Drs. Spiliotopoulos' and Hennet's testimony in this case make clear that Dr. Spiliotopoulos was working with, and under the direction of, the United States' retained experts at that time in anticipation of litigation. The United States has identified multiple prior cases in which Dr. Hennet went on to submit declarations or expert reports. Accordingly, the United States maintains that any notes taken by Dr. Spiliotopoulos in attending the 2005 ATSDR Expert Panel are protected by the work product doctrine. *Deangelis v. Corzine***,** 2016 WL 93862 at *4 (S.D. N.Y. Jan. 15, 2016) ("The CFTC's arguments as to why these documents are not drafts are unconvincing. First, its claim that 'notes, summaries, memoranda, and other materials created by an expert or the expert's assistants in connection with drafting a[n] expert report' cannot be considered 'drafts' proves too much."). Plaintiffs have failed to articulate a substantial need for these notes in light of the millions of pages of documents produced and dozens of depositions taken in the litigation.

**CLJA Site-Visit Notes from Dr. Spiliotopoulos**

The United States confirms that Dr. Spiliotopoulos searched his records and that he does not have any "interview notes" or "summaries" from his site-visit to Camp Lejeune.

**Morris Maslia's Supplemental Calculations & Notes**

During Mr. Maslia's March 14, 2025, deposition, he testified that he had performed additional calculations at some point after Dr. Konikow's rebuttal report was disclosed. Maslia Dep. (3/14/25), 38:2-42:1; 52:20-54:15. Mr. Maslia specifically testified to creating notes reflecting these calculations related to the geometric bias of ATSDR's water model for Tarawa Terrace. *Id*. The United States requested production of these notes at Mr. Maslia's deposition, but they have yet to be produced. The United States again requests production of these notes.

**Leonard Konikow's Invoices**

During Dr. Konikow's February 25, 2025, deposition, he testified that he had not yet submitted his invoice for January 2025. Konikow Dep., 66:22-67:15. The United States requested that when the invoice was completed and issued to Plaintiffs' counsel, a copy of the invoice be produced. *Id*. This invoice has yet to be produced. The United States again requests production of this invoice and any additional invoices issued since Dr. Konikow's deposition.

Very Truly Yours,

*/s/ Haroon Anwar*

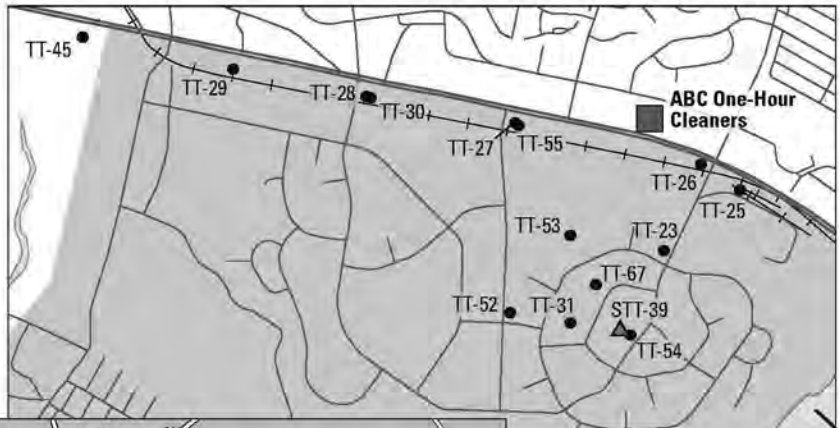
Haroon Anwar
Trial Attorney
U.S. Department of Justice
Environmental Tort Litigation

cc: Plaintiffs' Leadership Group

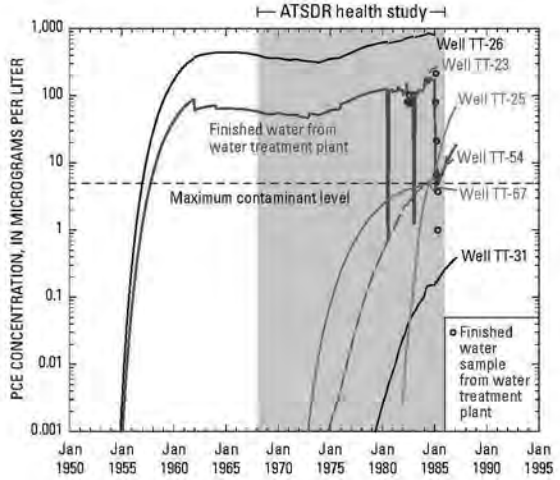
# EXHIBIT 4

# Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

## Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water









ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–February 2009

*Front cover:* Historical reconstruction process using data, information sources, and water-modeling techniques to estimate historical exposures

*Maps:* U.S. Marine Corps Base Camp Lejeune, North Carolina; Tarawa Terrace area showing historical water-supply wells and site of ABC One-Hour Cleaners

*Photographs on left:* Ground storage tank STT-39 and four high-lift pumps used to deliver finished water from tank STT-39 to Tarawa Terrace water-distribution system

*Photograph on right:* Equipment used to measure flow and pressure at a hydrant during field test of the present-day (2004) water-distribution system

*Graph:* Reconstructed historical concentrations of tetrachloroethylene (PCE) at selected water-supply wells and in finished water at Tarawa Terrace water treatment plant

# Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

## Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water

By Morris L. Maslia, René J. Suárez-Soto, Jinjun Wang, Mustafa M. Aral, Robert E. Faye, Jason B. Sautner, Claudia Valenzuela, and Walter M. Grayman

Agency for Toxic Substances and Disease Registry
U.S. Department of Health and Human Services
Atlanta, Georgia

February 2009


ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

## Authors

**Morris L. Maslia, MSCE, PE, D.WRE, DEE**
*Research Environmental Engineer and Project Officer*
Exposure-Dose Reconstruction Project
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

**René J. Suárez-Soto, MS EnvE, EIT**
*Environmental Health Scientist*
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

**Jinjun Wang, MSCE**
*Ph.D. Candidate*
Multimedia Environmental Simulations Laboratory
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia

**Mustafa M. Aral, PhD, PE**
*Director and Professor*
Multimedia Environmental Simulations Laboratory
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia

**Robert E. Faye, MSCE, PE**
*Civil Engineer/Hydrologist*
Robert E. Faye and Associates, Inc.
Consultant to Eastern Research Group, Inc.
Lexington, Massachusetts

**Jason B. Sautner, MSCE, EIT**
*Environmental Health Scientist*
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia

**Claudia Valenzuela, MSCE**
*Post Graduate Research Fellow*
Formerly, Oak Ridge Institute for Science and Education
Agency for Toxic Substances and Disease Registry
Atlanta, Georgia
Now, National Commission for the Environment
(CONAMA), Santiago, Chile

**Walter M. Grayman, PhD, PE**
*Consulting Engineer*
W.M. Grayman Consulting Engineer
Cincinnati, Ohio

For additional information write to:

Project Officer
Exposure-Dose Reconstruction Project
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry
4770 Buford Highway, N.E., Mail Stop F-59
Atlanta, Georgia 30341

Suggested citation:
Maslia ML, Suárez-Soto RJ, Wang J, Aral MM, Faye RE, Sautner JB, Valenzuela C, and Grayman WM. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2009.

# Foreword

The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to volatile organic compounds in contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at the base. During 2004, the study protocol received approval from the Centers for Disease Control and Prevention Institutional Review Board and the U.S. Office of Management and Budget.

Historical exposure data needed for the epidemiological case-control study are limited. To obtain estimates of historical exposure, ATSDR is using water-modeling techniques and the process of historical reconstruction. These methods are used to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water.

Final interpretive results for Tarawa Terrace and vicinity—based on information gathering, data interpretations, and water-modeling analyses—are presented as a series of ATSDR reports. These reports provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant levels in drinking water at Tarawa Terrace and vicinity. Each topical subject within the water-modeling analysis and historical reconstruction process is assigned a chapter letter. Specific topics for each chapter report are listed below:

- **Chapter A**: Summary of Findings
- **Chapter B**: Geohydrologic Framework of the Castle Hayne Aquifer System
- **Chapter C**: Simulation of Groundwater Flow
- **Chapter D**: Properties and Degradation Pathways of Common Organic Compounds in Groundwater
- **Chapter E**: Occurrence of Contaminants in Groundwater
- **Chapter F**: Simulation of the Fate and Transport of Tetrachloroethylene (PCE) in Groundwater
- **Chapter G**: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products
- **Chapter H**: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant
- **Chapter I**: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water
- **Chapter J**: Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water
- **Chapter K**: Supplemental Information

An electronic version of this report, *Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water*, will be made available on the ATSDR Camp Lejeune Web site at *http://www.atsdr.cdc.gov/sites/lejeune/index.html*. Readers interested solely in a summary of this report or any of the other reports should refer to *Chapter A: Summary of Findings* that also is available at the ATSDR Web site.

# Contents

## Figures

# Tables

## Conversion Factors

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| mile, nautical (nmi) | 1.852 | kilometer (km) |
| yard (yd) | 0.9144 | meter (m) |
| | Area | |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| | Volume | |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| million gallons (MG) | 3,785 | cubic meter ($m^3$) |
| | Flow rate | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| cubic foot per day ($ft^3$/d) | 0.02832 | cubic meter per day ($m^3$/d) |
| million gallons per day (MGD) | 0.04381 | cubic meter per second ($m^3$/s) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| | Density | |
| pound per cubic foot ($lb/ft^3$) | $1.602 \times 10^1$ | kilogram per cubic meter ($kg/m^3$) |
| | Hydraulic conductivity | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |

## Concentration Conversion Factors

| Unit | To convert to | Multiply by |
|---|---|---|
| microgram per liter (µg/L) | milligram per liter (mg/L) | 0.001 |
| microgram per liter (µg/L) | milligram per cubic meter ($mg/m^3$) | 1 |
| microgram per liter (µg/L) | microgram per cubic meter ($µg/m^3$) | 1,000 |
| parts per billion by volume (ppbv) | parts per million by volume (ppmv) | 1,000 |

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 1983).

Altitude, as used in this report refers to distance above the vertical datum.

# Glossary and Abbreviations

Definitions of terms and abbreviations used throughout this report are listed below.

| | |
|---|---|
| 2-COMP | a two-compartment storage-tank mixing model |
| ATSDR | Agency for Toxic Substances and Disease Registry |
| CD–ROM | compact disc, read-only memory |
| CI | cast iron |
| CLW | Camp Lejeune water document |
| CRWQME | continuous recording water-quality monitoring equipment |
| CSTR | continuous stirred-tank reactor, also referred to as a complete mixing storage-tank model |
| DCE | 1,1-DCE 1,1-dichloroethylene or 1,1-dichloroethene |
| | 1,2-DCE 1,2-dichloroethylene or 1,2-dichloroethene |
| | 1,2-cDCE *cis*-1,2- dichloroethylene or *cis*-1,2-dichloroethene |
| | 1,2-tDCE *trans*-1,2- dichloroethylene or *trans*-1,2-dichloroethene |
| DVD | digital video disc |
| EPANET 2 | a water-distribution system model developed by USEPA (Rossman 2000) |
| EPS | extended period simulation; a simulation method used to analyze a water-distribution system |
| FIFO | a first-in, first-out plug-flow storage-tank mixing model |
| FORTRAN | formula translation, a computer coding language for scientific and engineering computations and analyses |
| gal/min | gallons per minute |
| kriging | geostatistical techniques used to interpolate the value of random parameters (for example, porosity) at an unobserved location from observations of its value at nearby locations |
| LIFO | a last-in, first-out plug-flow storage-tank mixing model |
| MCL | maximum contaminant level; a legal threshold limit set by the USEPA on the amount of a hazardous substance that is allowed in drinking water under the Safe Drinking Water Act; usually expressed as a concentration in milligrams or micrograms per liter. Effective dates for MCLs are as follows: trichloroethylene (TCE) and vinyl chloride (VC), January 9, 1989; tetrachloroethylene (PCE) and *trans*-1,2-dichloroethylene (1,2-tDCE), July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.) |
| MC simulation | Monte Carlo simulation, also referred to as Monte Carlo analysis; a computer-based method of analysis that uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model (USEPA 1997) |
| MESL | Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia; an ATSDR cooperative agreement partner |
| mL | milliliter; 1/1000th of a liter |
| MODFLOW | a three-dimensional groundwater-flow model developed by the U.S. Geological Survey; versions of MODFLOW used for the Tarawa Terrace analyses are MODFLOW-96 (Harbaugh and McDonald 1996) and MODFLOW-2000 (Harbaugh et al. 2000) |
| MT3DMS | a three-dimensional mass transport, multispecies model developed by C. Zheng and P. Wang on behalf of the U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi |

| | |
|---|---|
| NPL | National Priorities List |
| PCE | tetrachloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK® |
| PDF | probability density function |
| PEST | a model-independent parameter estimation and uncertainty analysis tool developed by Watermark Numerical Computing (Doherty 2005) |
| PRNG | pseudo-random number generator; an algorithm for generating a sequence of numbers that approximates the properties of random numbers |
| probabilistic | an analysis in which frequency distributions are assigned to represent uncertainty analysis or variability in model parameters. The output of a probabilistic analysis is a distribution (Cullen and Frey 1999) |
| PVC | polyvinyl chloride |
| realization | a set of uncertain parameter values obtained by using a pseudo-random number generator; an MC simulation consists of multiple realizations |
| *RMS* | root-mean-square |
| SCADA | supervisory control and data acquisition |
| sensitivity analysis | an analysis method used to ascertain how a given model output (for example, concentration) depends upon the input parameters (for example, pumping rate, mass loading rate). Sensitivity analysis is an important method for checking the quality of a given model, as well as a powerful tool for checking the robustness and reliability of its analysis |
| SG simulation | sequential Gaussian simulation; a process in which a field of values (such as hydraulic conductivity) is obtained multiple times assuming the spatially interpolated values follow a Gaussian (normal) distribution |
| TCE | 1,1,2-trichloroethene, 1,1,2-trichloroethylene, or trichloroethylene |
| uncertainty | the lack of knowledge about specific factors, parameters, or models (for example, one is uncertain about the mean value of the concentration of PCE at the source) |
| uncertainty analysis | determination of the uncertainty (e.g., standard deviation) of the output variables' expected value (e.g., mean) due to uncertainty in model parameters, inputs, or initial state by stochastic modeling techniques (Schnoor 1996) |
| USEPA | U.S. Environmental Protection Agency |
| USGS | U.S. Geological Survey |
| variability | observed differences attributable to heterogeneity or diversity in a model parameter, an exposure parameter, or a population |
| variogram | also known as semivariogram; a statistically-based (geostatistical), quantitative description of the spatial continuity or roughness of a dataset (Barnes 2003) |
| VC | vinyl chloride or chloroethene |
| VOC | volatile organic compound |
| WTP | water treatment plant |

Use of trade names and commercial sources is for identification only and does not imply endorsement by the Agency for Toxic Substances and Disease Registry or the U.S. Department of Health and Human Services.

# Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

# Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water

By Morris L. Maslia,[1] René J. Suárez-Soto,[1] Jinjun Wang,[2] Mustafa M. Aral,[2] Robert E. Faye,[3] Jason B. Sautner,[1] Claudia Valenzuela,[4] and Walter M. Grayman[5]

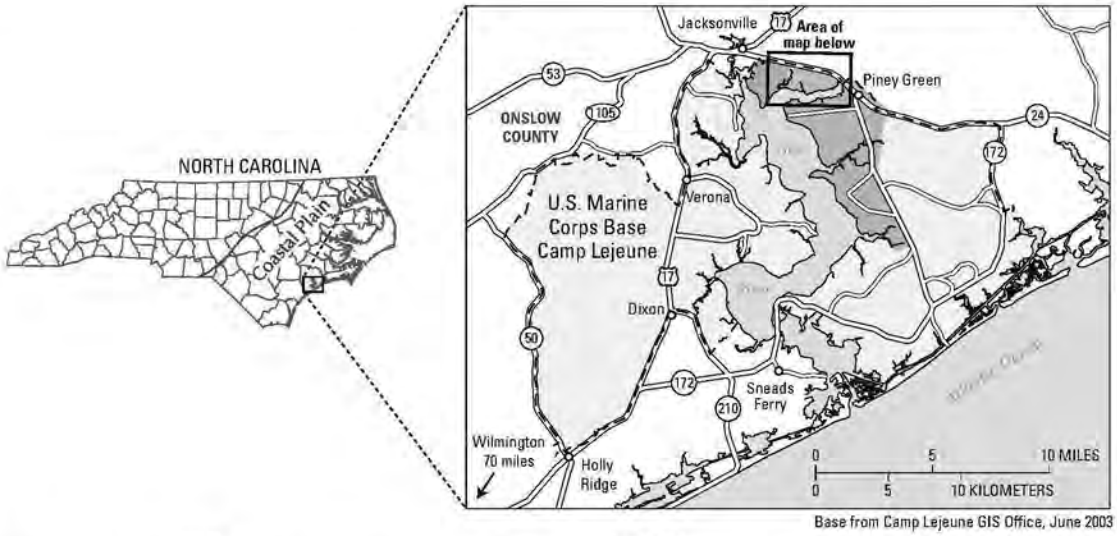
## Abstract

Two of three water-distribution systems that have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune, North Carolina, were contaminated with volatile organic compounds (VOCs). Tarawa Terrace was contaminated mostly with tetrachloroethylene concentrations up to 215 micrograms per liter (µg/L), and Hadnot Point was contaminated mostly with trichloroethylene concentrations up to 1,400 µg/L. Because scientific data relating to the harmful effects of VOCs on a child or fetus are limited, the Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate potential associations between in utero and infant (up to 1 year of age) exposures to VOCs in contaminated drinking water at Camp Lejeune and specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at Camp Lejeune. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using modeling techniques to reconstruct historical conditions of groundwater flow, contaminant fate and transport, and the distribution of drinking water contaminated with VOCs delivered to family housing areas. This report, Chapter I, provides detailed information and interpretations of parameter sensitivity, variability, and uncertainty associated with model simulations of groundwater flow, contaminant fate and transport, and distribution of drinking water at Tarawa Terrace and vicinity. It relies on information, data, and simulation results from calibrated models presented in previously published ATSDR reports on Tarawa Terrace—Chapters A, B, C, E, and F. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

## Background

The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to drinking water contaminated with volatile organic compounds (VOCs) at U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to pregnant women who resided in family housing at the base. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using water-modeling techniques to provide the epidemiological study with quantitative estimates of monthly contaminant levels in the drinking water. Results obtained by using water-modeling techniques, along with information from the mother on her water use, can be used by the epidemiological study to estimate the level and duration of exposures to the mother during her pregnancy and to the infant (up to 1 year of age). Using water-modeling techniques in such a process is referred to as historical reconstruction (Maslia et al. 2001). Calibrated models were developed for groundwater flow (Faye and Valenzuela 2007), contaminant fate and transport (Faye 2008), and the distribution of drinking water (Sautner et al. 2007, In press 2009) for Tarawa Terrace and vicinity (Figure I1). These models required data that are usually not readily

[1] Agency for Toxic Substances and Disease Registry, Atlanta, Georgia.
[2] Multimedia Environmental Simulations Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia.
[3] Consultant to Eastern Research Group, Inc., Lexington, Massachusetts.
[4] Formerly, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, now at National Commission for the Environment (CONAMA), Santiago, Chile.
[5] W.M. Grayman Consulting Engineer, Cincinnati, Ohio.



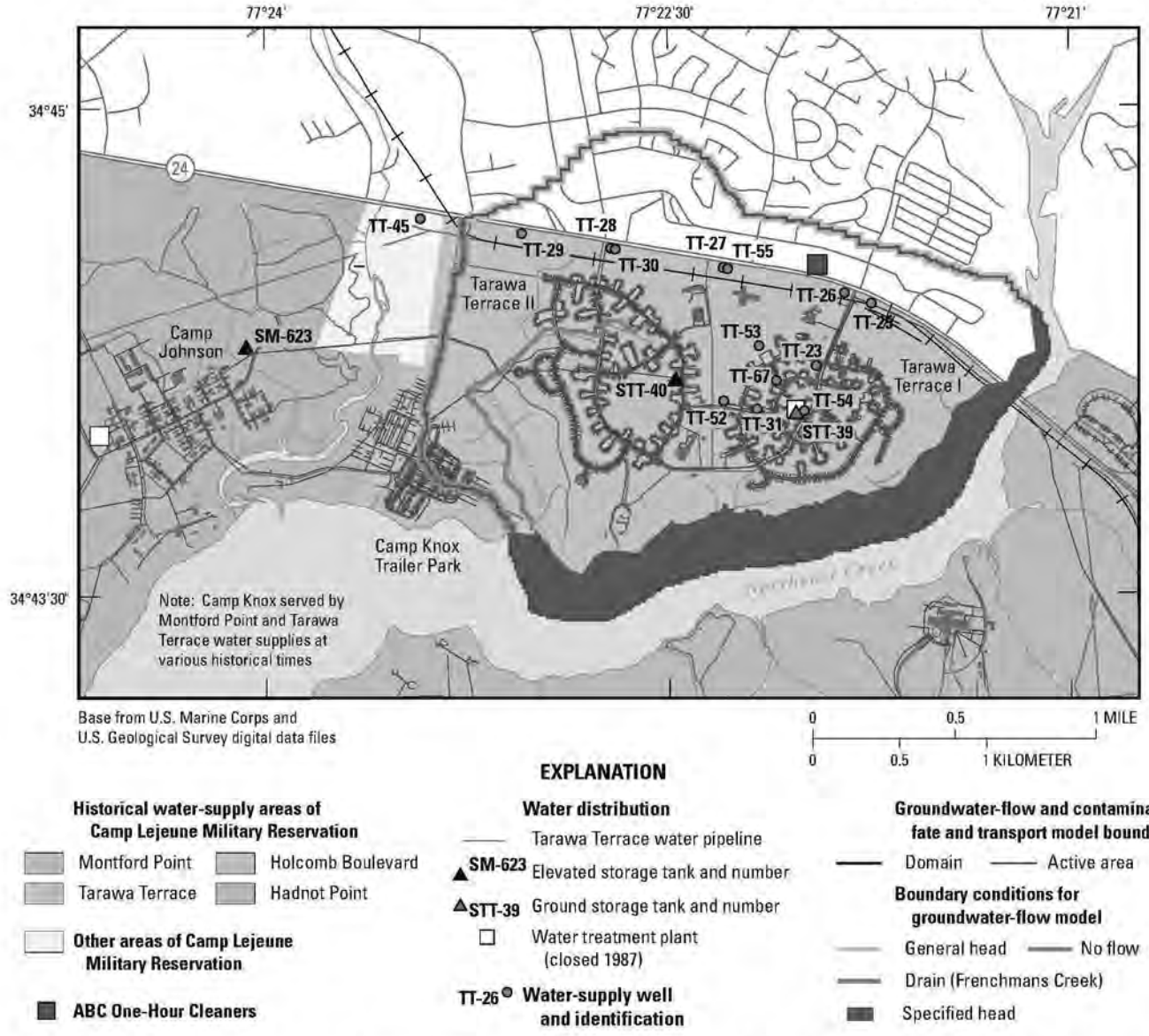




**Figure I1.** Location of groundwater-flow and contaminant fate and transport modeling domain and water-supply facilities used for historical reconstruction analyses, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

available and inherently contain errors of approximation and interpretation. Moreover, all models and associated parameters contain uncertainties—both in the approximation of solutions to mathematical equations and in parameter values. Analyses subsequent to model calibration are required to describe, understand, and quantify sources of variability and uncertainty resulting from the application of models. Descriptions of the Tarawa Terrace models, calibration procedures, and simulation results are summarized in the Chapter A report (Maslia et al. 2007). Comprehensive details pertaining to the development, calibration, and simulation results of the Tarawa Terrace models are provided in Chapter C for groundwater flow (Faye and Valenzuela 2007), Chapter F for contaminant fate and transport (Faye 2008), and Chapter J for the distribution of drinking water (Sautner et al. In press 2009).

## Purpose and Scope

The goal of the water-modeling analyses and the historical reconstruction process is to quantify the concentration of tetrachloroethylene (PCE) in groundwater, at Tarawa Terrace water-supply wells, and in finished drinking water[6] at the Tarawa Terrace water treatment plant (WTP) for the period 1951–1994. To achieve this goal, a number of models were used. Groundwater flow was simulated using the model code MODFLOW-96 (Harbaugh and McDonald 1996), contaminant fate and transport was simulated using the model code MT3DMS (Zheng and Wang 1999), the concentration of contaminants in finished water at the WTP was calculated using a flow-weighted materials mass balance model (Masters 1998, Maslia et al. 2007, Faye 2008), and the distribution of contaminated drinking water was simulated using the model code EPANET 2 (Rossman 2000). A discussion and description of all models used for the Tarawa Terrace analyses is presented in Chapter A of this report series (Maslia et al. 2007).

All models, including the aforementioned models, are subject to varying degrees of uncertainty which are associated with: (1) limited or lack of data, (2) erroneous data due to precision and accuracy limitations, and (3) simplifications of mathematical equations represented by the model. As defined by Schnoor (1996), an uncertainty analysis allows one to determine the uncertainty (standard deviation) of an output variable's expected value (mean) due to uncertainty in model parameters, inputs, or initial state by stochastic modeling techniques. Therefore, sensitivity and uncertainty analyses are a requisite of the model building and implementation process (Anderson and Woessner 1992). The purpose of this chapter report (Chapter I) is to characterize the uncertainty of model output (that is, simulated results) due to model input parameter uncertainty and variability. Several methods are frequently used to evaluate and quantify uncertainty. Two such methods are sensitivity and probabilistic analyses. Within the generalized classification of probabilistic analysis, Monte Carlo (MC) simulation is a particularly well-known numerical method. For this study, four types of sensitivity analyses and two sets of MC simulations were conducted using the calibrated Tarawa Terrace models (Faye and Valenzuela 2007, Faye 2008). The uncertainty methods discussed in this report are shown graphically in Figure I2 and are described below:

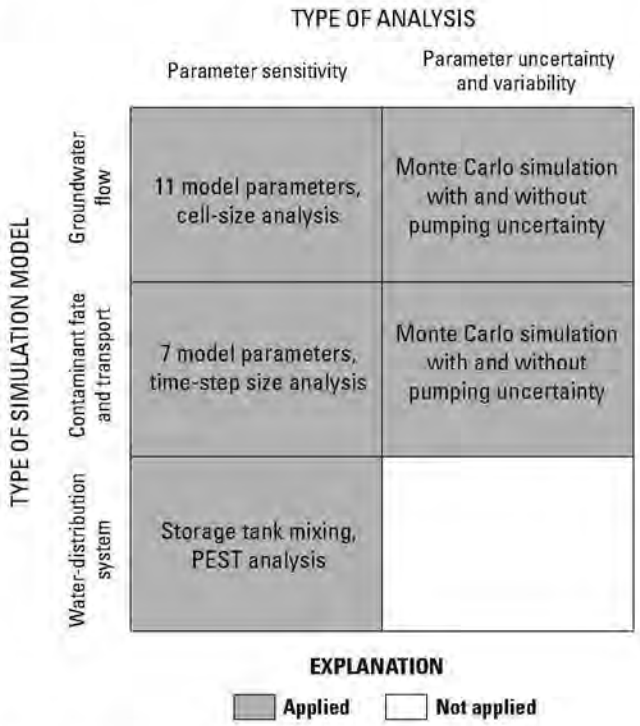



**Figure I2.** Types of uncertainty analyses applied to simulation models, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PEST, sensitivity analysis using PEST model code (Doherty 2005)]

1. a sensitivity analysis conducted using parameters of the groundwater-flow and contaminant fate and transport models. This sensitivity analysis included 11 parameters associated with the groundwater-flow model and 7 parameters associated with the contaminant fate and transport model;
2. a sensitivity analysis conducted to quantify the effect of the finite-difference grid cell size on groundwater-flow model output; [7]

[6] For the Tarawa Terrace study, finished drinking water is defined as groundwater that has undergone treatment at the WTP and delivered to a person's home. The concentration of contaminants in treated water at the WTP is considered the same as the concentration in the water delivered to a person's home. This assumption is tested and verified in the Chapter J report (Sautner et al. In press 2009). Hereafter, the term "finished water" will be used when referring to treated water.

[7] Refer to the Chapter C report (Faye and Valenzuela 2007) for details specific to the computational grid and model boundaries used to simulate groundwater flow.

3. a sensitivity analysis conducted to quantify the effect of time-step size on contaminant fate and transport model output; [8]
4. a sensitivity analysis conducted to quantify the relative importance of water-distribution system model parameters by conducting analyses of storage-tank mixing models and by utilizing the parameter estimation tool, PEST (Doherty 2005); [9]
5. a probabilistic analysis based on MC simulation using selected groundwater-flow model parameters with and without pumping uncertainty; and
6. a probabilistic analysis based on MC simulation using selected contaminant fate and transport model parameters, with and without pumping uncertainty.

The probabilistic analyses described in items 5 and 6 were conducted to determine the variability and uncertainty of model output caused by input parameter uncertainty. To quantify the variability and uncertainty of the model results, a series of MC simulations was conducted using the groundwater-flow and contaminant fate and transport models described in Faye and Valenzuela (2007) and Faye (2008), respectively. Two simulation scenarios were considered using MC simulations (Figure I2). Scenario 1 assumed no uncertainty associated with the allocation of groundwater pumping. Scenario 2 assumed uncertainty was associated with the allocation of groundwater pumping.[10]

# Description of Calibrated Models

Given the paucity of measured historical contaminant-specific data and the lack of historical exposure data during most of the period relevant to the epidemiological study (January 1968–December 1985), ATSDR decided to apply the concepts of historical reconstruction to synthesize and estimate the spatial and temporal distributions of contaminant-specific concentrations in the drinking-water supply at Tarawa Terrace. Historical reconstruction typically includes the application of simulation tools, such as models, to recreate (or synthesize) past conditions. For this study, historical reconstruction included the linking of contaminant fate and transport models with materials mass balance (simple mixing) and water-distribution system models. In a simulation approach, a calibration process is used so that the combination of various model parameters—regardless of whether a model is simple or complex—appropriately reproduces the behavior of real-world systems (for example, migration of PCE) as closely as possible. A hierarchical approach for model calibration was used to estimate concentrations of PCE in finished water at the Tarawa Terrace WTP. A description of this approach is provided in the Chapter A report (Maslia et al. 2007). Specific details relative to models used to simulate groundwater flow, contaminant fate and transport, and the distribution of drinking water are provided in the Chapter C report (Faye and Valenzuela 2007), the Chapter F report, (Faye 2008), and the Chapter J report (Sautner et al. In press 2009), respectively. In the following sections of this report, summaries are provided that describe each of the aforementioned calibrated models.

## Groundwater Flow

Steady-state and transient groundwater flow were simulated using the model code MODFLOW-96 (Harbaugh and McDonald 1996). The location of the model domain and active model area used for simulating groundwater flow are shown in Figure I1. The modeling grid consists of 7 layers, 200 rows, and 270 columns. Each cell represents an area of 250 square feet (ft$^2$)—50 feet (ft) per side—and every layer consists of 54,000 cells, of which 27,642 cells are within the active domain of the model. The following boundary conditions, described in Faye and Valenzuela (2007) are imposed on the modeled area.

1. A no-flow boundary is assigned to the eastern, western, and southern perimeters of the active model domain for all model layers.
2. A specified-head boundary with an assigned value of 0 ft, representing sea level, is assigned in layer 1 to Northeast Creek, extending east to the mid-channel line.
3. A general-head (head-dependent) boundary is used to represent the northern boundary for all layers and also generally conforms to a topographic divide. A general-head (head-dependent) boundary is assigned because of the proximity of water-supply wells to the boundary in the northwestern and north-central parts of the active model domain.
4. A drain is used to represent Frenchmans Creek in model layer 1 in the western part of the model domain.

Transient simulations were conducted using monthly stress periods of 28, 29, 30, or 31 days that corresponded to January 1951–December 1994 for a total of 528 stress periods. A listing of simulation stress periods and the corresponding month and year can be found in Appendix I1 of this report. The locations of water-supply wells used for the transient simulations are listed in Table I1. A complete listing of data pertaining to pumpage rates assigned to specific water-supply wells and the corresponding stress periods when the wells were operated in the model is provided in the Chapter C (Faye and Valenzuela 2007) and Chapter K (Maslia et al. In press 2009) reports. Calibrated groundwater-flow model parameter

[8] Refer to the Chapter F report (Faye 2008) for details specific to the computational time step used to simulate contaminant fate and transport analyses.

[9] Refer to the Chapter J report (Sautner et al. In press 2009) for details specific to the simulation of the distribution of water within the Tarawa Terrace water-distribution system.

[10] Refer to the Chapter H report (Wang and Aral 2008) for detailed analyses of the effect of groundwater pumping schedule variation on arrival of PCE at water-supply wells and at the Tarawa Terrace WTP.

**Table I1.** Locations of water-supply wells used for simulating groundwater flow and contaminant fate and transport, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft, feet]

| Well[1] | Groundwater-flow model location[2] | | | Location coordinates[3] | |
|---|---|---|---|---|---|
| | Layer | Row | Column | Easting (ft) | Northing (ft) |
| TT-23 | 3 | 84 | 175 | 2491015 | 363195 |
| TT-25 | 3 | 67 | 194 | 2491965 | 364045 |
| TT-26 | 3 | 61 | 184 | 2491465 | 364345 |
| TT-27 | 3 | 52 | 135 | 2489015 | 364795 |
| TT-28 | 3 | 47 | 96 | 2487065 | 365045 |
| TT-29 | 3 | 41 | 61 | 2485315 | 365345 |
| TT-30 | 3 | 47 | 97 | 2487115 | 365045 |
| TT-31 | 1 and 3 | 104 | 152 | 2489865 | 362195 |
| TT-52 | 1 and 3 | 101 | 136 | 2489065 | 362345 |
| TT-53 | 1 | 81 | 151 | 2489815 | 363345 |
| TT-54 | 1 and 3 | 106 | 167 | 2490615 | 362095 |
| TT-55 | 1 | 53 | 136 | 2489065 | 364745 |
| TT-67 | 3 | 93 | 158 | 2490165 | 362745 |

[1]Water-supply wells #6, #7, and TT-45 are located external to the model domain and are not included in groundwater-flow and contaminant fate and transport model simulations. They are included in computations of water volume supplied to the Tarawa Terrace water treatment plant (Maslia et al. 2007, Faye 2008)

[2]Refer to Faye and Valenzuela (2007) for details describing groundwater-flow model grid

[3]Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

values, reported by Faye and Valenzuela (2007) are listed in Table I2. Calibration statistics are summarized in the Chapter A report (Maslia et al. 2007) and are discussed in detail in the Chapter C report (Faye and Valenzuela 2007).

## Contaminant Fate and Transport

The contaminant fate and transport model uses simulated cell-by-cell specific discharge (Darcy velocities) derived from the calibrated groundwater-flow model to simulate the fate and transport of a contaminant in the subsurface. The same model domain, active area, cell sizes, and boundary conditions used for groundwater-flow simulation were used for contaminant fate and transport simulations. The model code MT3DMS (Zheng and Wang 1999) was applied to output from the Tarawa Terrace groundwater-flow model to simulate contaminant fate and transport. The following boundary conditions unique to simulated contaminant fate and transport—described in Faye (2008)—were imposed on the active modeled area (Figure I1).

1. A mass loading rate for PCE of 1,200 grams/day (g/d) was assigned to the MT3DMS model cell corresponding to layer 1, row 47, and column 170 and was applied continuously during stress periods 25 (January 1953) to 408 (December 1984). This loading rate was derived through the use of field data and the model calibration process described in the Chapter E (Faye and Green 2007) and Chapter F (Faye 2008) reports. Prior to January 1953 and after December 1984, a mass loading rate of 0.0 g/d was assigned to the cell.
2. A specified dispersive flux of 0.0 (Neuman type II boundary condition) was assumed to exist along the eastern, western, northern, and southern perimeters of the active model domain for all model layers.

Contaminant fate and transport simulations were conducted using monthly stress periods of 28, 29, 30, or 31 days that corresponded to January 1951–December 1994 for a total of 528 stress periods (Appendix I1). Calibrated contaminant fate and transport model parameter values reported by Faye (2008) also are listed in Table I2. Calibration statistics are summarized in the Chapter A report (Maslia et al. 2007) and discussed in detail in the Chapter F report (Faye 2008).

## Water-Distribution System

Since March 1987, the Holcomb Boulevard WTP has provided finished water to the Holcomb Boulevard and Tarawa Terrace water-distribution systems (Figure I3). Consequently, it was necessary to develop calibrated models for both water-distribution systems that were reflective of present-day conditions using field data collected during the period May–October 2004 (Maslia et al. 2004, 2005; Sautner et al. 2005, 2007). For the purpose of the Chapter I report, more emphasis and detail are given to the discussion of the Tarawa Terrace water-distribution system. The Chapter J report (Sautner et al. In press 2009) provides additional details for both the Tarawa Terrace and Holcomb Boulevard water-distribution systems.

The public domain water-distribution system model, EPANET 2 (Rossman 2000), was used to simulate hydraulics and water-quality dynamics of the Tarawa Terrace and Holcomb Boulevard water-distribution systems (Sautner et al. 2005, 2007, In press 2009). Table I3 lists information used to characterize the present-day (2004) Tarawa Terrace and Holcomb Boulevard water-distribution systems for EPANET 2 model simulations. As described above, since 1987, the Holcomb Boulevard WTP has provided finished water to Tarawa Terrace ground-storage tank STT-39 (Figure I3). From a modeling perspective, however, Tarawa Terrace ground-storage tank STT-39 was modeled as the source of finished water for the Tarawa Terrace water-distribution system.

Based on expert peer review of using the water-distribution system modeling approach to simulate spatially distributed PCE concentrations (Maslia 2005) and exhaustive reviews of historical data—including water-supply well and WTP operational data when available—study staff concluded that the Tarawa Terrace WTP and water-distribution system

**Table I2.** Calibrated groundwater-flow and contaminant fate and transport model parameters, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[ft/d, foot per day; d, day; in/yr, inch per year; g/ft$^3$, gram per cubic foot; ft, foot; ft$^2$/g, cubic foot per gram; g/d, gram per day; ft$^2$/d, square foot per day]

| Model parameter[2] | Calibrated value | Method of assigning values |
|---|---|---|
| Groundwater-flow model parameters[3] | | |
| Horizontal hydraulic conductivity, Layer 1, $K_H$ (ft/d) | 12.2–53.4 | Distributed by cell |
| Horizontal hydraulic conductivity, Layer 2, $K_H$ (ft/d) | 1.0 | Distributed by cell |
| Horizontal hydraulic conductivity, Layer 3, $K_H$ (ft/d) | 4.3–20.0 | Distributed by cell |
| Horizontal hydraulic conductivity, Layer 4, $K_H$ (ft/d) | 1.0 | Distributed by cell |
| Horizontal hydraulic conductivity, Layer 5, $K_H$ (ft/d) | 6.4–9.0 | Distributed by cell |
| Horizontal hydraulic conductivity, Layer 6, $K_H$ (ft/d) | 1.0 | Distributed by cell |
| Horizontal hydraulic conductivity, Layer 7, $K_H$ (ft/d) | 5.0 | Distributed by cell |
| Leakance, $K_z / \delta z$ (1/d) | $3.6 \times 10^{-3}$–$4.2 \times 10^{-1}$ | Distributed by cell |
| Infiltration (recharge), $I_R$ (in/yr) | 6.6–19.3 | Constant annual value for layer 1; annual value varied by year (every 12 stress periods) |
| Specific yield, $S_y$ | 0.05 | Constant for layer 1 |
| Storage coefficient, $S$ | $4.0 \times 10^{-4}$ | Constant for layers 2–7 |
| Contaminant fate and transport model parameters[4] | | |
| Bulk density, $\rho_b$ (g/ft$^3$) | 77,112 | Constant for model |
| Longitudinal dispersivity, $\alpha_L$ (ft) | 25 | Constant for model |
| Distribution coefficient, $K_d$ (ft$^3$/g) | $5.0 \times 10^{-6}$ | Constant for model |
| Effective porosity, $n_E$ | 0.2 | Constant for model |
| Mass-loading rate, $q_s C_s$ (g/d) | 1,200 | [5]Single cell, constant for stress periods 25 to 408 |
| Molecular diffusion, $D^*$ (ft$^2$/d) | $8.5 \times 10^{-4}$ | Constant for model |
| Reaction rate, $r$ (1/d) | $5.0 \times 10^{-4}$ | Constant for model |

[1]Refer to the Chapter C report (Faye and Valenzuela 2007) for a discussion of groundwater-flow simulation; refer to the Chapter F report (Faye 2008) for a discussion of contaminant fate and transport simulation

[2]Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

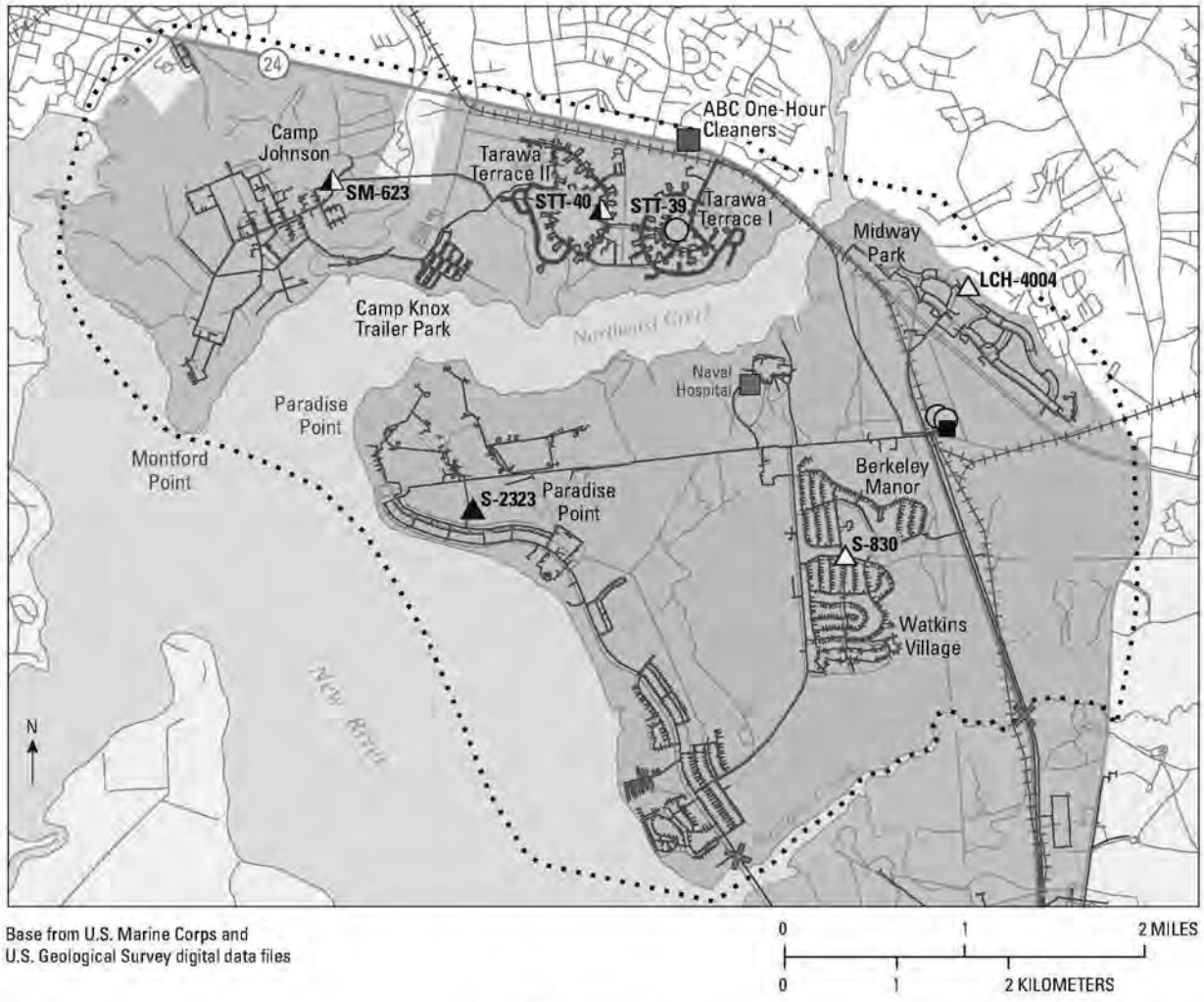
[3]MODFLOW-96 model code (Harbaugh and McDonald 1996) used to conduct groundwater-flow simulations

[4]MT3DMS model code (Zheng and Wang 1999) used to conduct contaminant fate and transport simulations

[5]Refer to Appendix I1 for month and year corresponding to stress period

were not interconnected with other water-distribution systems at Camp Lejeune (for example, Holcomb Boulevard) for any substantial time periods (greater than 2 weeks) during the period of interest to this study (1968–1985).[11] All water arriving at the Tarawa Terrace WTP was assumed to originate solely from Tarawa Terrace water-supply wells (Faye and Valenzuela 2007) and to be completely and uniformly mixed prior to delivery to residences of Tarawa Terrace through the network of water-distribution system pipelines and storage tanks. Accordingly, study staff concluded that a simple mixing model approach, based on the principles of continuity and conservation of mass (Masters 1998, Maslia et al. 2007), would provide a sufficient level of detail and accuracy to estimate monthly PCE concentrations at Tarawa Terrace. To test the appropriateness of this assumption, results of a simulation for December 1984 conditions based on using the mixing model and water-distribution system model approaches are listed in Table I4. These results demonstrate that after 7 days, the mixing model and the spatially derived EPANET 2 concentrations of PCE are equivalent—even at the furthest extent of the water-distribution system (Montford Point area, Figure I3). These results confirmed the decision to use the simple mixing model approach for estimating PCE concentrations in finished water delivered to the Tarawa Terrace housing area.

[11] The term "interconnection" is defined in this study as the continuous flow of water in a pipeline from one water-distribution system to another for periods exceeding two weeks. Pipelines constructed in 1984 and 1986 to the Holcomb Boulevard and Montford Point water-distribution systems, respectively, did connect to the Tarawa Terrace water-distribution system (Maslia et al. 2007). However, information and operational data are not available to document the continuous flow of water to and from these water-distribution systems. Therefore, the Holcomb Boulevard, Tarawa Terrace, and Montford Point water-distribution systems were assumed not to be interconnected for the purposes of the present study.




**EXPLANATION**

**Present-day (2004) water-distribution system on Camp Lejeune Military Reservation**

- Tarawa Terrace
- Holcomb Boulevard
- Hadnot Point

**Other areas of Camp Lejeune Military Reservation**

**Holcomb Boulevard Water Treatment Plant Service Area**—March 1987 to present

**Holcomb Boulevard Water Treatment Plant**

**Water pipeline**—2004

**Shut-off valve**—Approximate location

**Storage tank**

- S-2323 Elevated—Controlling
- S-830 Elevated—Noncontrolling
- SM-623 Elevated—Intermittently controlling and noncontrolling depending on demand conditions
- STT-39 Ground—Finished water

**Figure I3.** Location of present-day (2004) Tarawa Terrace and Holcomb Boulevard water-distribution systems, U.S. Marine Corps Base Camp Lejeune, North Carolina (modified from Maslia et al. 2007).

**Table I3.** Characterization of the Tarawa Terrace and Holcomb Boulevard present-day (2004) water-distribution systems for EPANET 2 model simulations, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1, 2]

[ft, foot; mi, mile; PVC, polyvinyl chloride; %, percent; CI, cast iron; CU, copper; DI, ductile iron; AC, asbestos cement; gal, gallon; —, not applicable; WTP, water treatment plant]

| Component | Water-distribution system | |
|---|---|---|
| | Tarawa Terrace | Holcomb Boulevard |
| Number of junctions or nodes | 6,186 | 4,782 |
| Number of pipelines | 6,327 | 4,909 |
| Total pipeline length | 269,360 ft (51.0 mi) | 386,813 ft (73.3 mi) |
| Pipeline diameter range | 0.75–12 inches | 0.75–24 inches |
| Pipeline material (percent of total length) | PVC (66.7%), CI (29.5%), CU (3.6%), DI (0.2%) | CI (67.3%), CU (20.8%), AC (7.1%), PVC (2.5%), DI (2.3%) |
| Number of storage tanks, type, and capacity[3] | 3 | [4]3 |
| STT-39 | ground; 250,000 gal | — |
| STT-40 | elevated; 250,000 gal | — |
| SM-623 | elevated; 150,000 gal | — |
| LCH-4004 | — | elevated; 200,000 gal |
| S-830 | — | elevated; 300,000 gal |
| S-2323 | — | elevated; 200,000 gal |

[1]See Figure I3 for water-distribution system locations

[2]EPANET 2 water-distribution system model (Rossman 2000)

[3]Storage tank STT-39 is supplied with finished water from the Holcomb Boulevard WTP and is modeled as the source water for the Tarawa Terrace water-distribution system

[4]Holcomb Boulevard finished water ground tanks are not modeled as part of the Holcomb Boulevard water-distribution system

**Table I4.** Simulated concentrations of tetrachloroethylene (PCE), derived from a mixing model and the EPANET 2 water-distribution system model, December 1984 conditions, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[WTP, water treatment plant; TT, Tarawa Terrace]

| Simulated PCE concentration, in micrograms per liter | | | | | |
|---|---|---|---|---|---|
| Mixing model[2] Tarawa Terrace WTP December 1984 | EPANET 2 water-distribution system model[3] | | | | |
| | Simulation time (days after 0:00 hours, December 1, 1984) | STT-40 (TT-II housing area)[4] | SM-623 (Camp Johnson)[4] | Camp Knox (trailer park housing area) | Montford Point area |
| 173.0 | 0.25 | 173.0 | 0.0 | 0.0 | 0.0 |
| | 0.5 | 173.0 | 0.0 | 0.0 | 0.0 |
| | 0.75 | 173.0 | 172.0 | 0.0 | 0.0 |
| | 1 | 173.0 | 173.0 | 0.0 | 0.0 |
| | 2 | 173.0 | 173.0 | 159.8 | 23.7 |
| | 3 | 173.0 | 173.0 | 172.9 | 162.9 |
| | 4 | 173.0 | 173.0 | 173.0 | 167.9 |
| | 5 | 173.0 | 173.0 | 173.0 | 168.6 |
| | 6 | 173.0 | 173.0 | 173.0 | 172.4 |
| | 7 | 173.0 | 173.0 | 173.0 | 173.0 |
| | 14 | 173.0 | 173.0 | 173.0 | 173.0 |
| | 21 | 173.0 | 173.0 | 173.0 | 173.0 |
| | 28 | 173.0 | 173.0 | 173.0 | 173.0 |

[1]See Figure I3 for water-distribution system location

[2]Mixing model based on principles of continuity and conservation of mass (Masters 1998, Maslia et al. 2007); mixing model assumes constant concentration value on a monthly basis

[3]EPANET 2 water-distribution system model (Rossman 2000)

[4]STT-40 and SM-623 are the Tarawa Terrace and Camp Johnson elevated storage tanks, respectively

## Sensitivity Analyses

Sensitivity analysis is a method used to ascertain the dependency of a given model output (for example, water level, hydraulic head, or concentration) upon model input parameters (for example, hydraulic conductivity, pumping rate, or mass loading rate). Thus, sensitivity analysis is the study of how the variations in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation. Numerous methods are described in the literature for conducting a sensitivity analysis. One such method, referred to as the one-at-a-time design or experiment, is conducted by changing the values of input parameters of a calibrated model, one at a time; then, the variation of the output is measured (Saltelli et al. 2000). Results of sensitivity analyses are commonly reported as a metric such as an average measure of an output parameter difference; for example, the change in average PCE concentration at a particular location due to a 10-percent (%) change in the calibrated value of porosity. Another common metric is the root-mean-square, or *RMS*, which can be defined as the mean deviation of an output parameter (for example, PCE concentration) from the calibrated output parameter value by perturbing or modifying an input parameter value (for example, horizontal hydraulic conductivity). Because the calibrated model is assumed to be a reliable predictor of a given condition, quantifying model sensitivity to changes in certain parameters will help to assess the robustness of the model. Although sensitivity analysis has the limitation of weakly assessing the effect of simultaneous changes in input parameters, it is an important tool that can be used to identify essential parameters to be analyzed for a probabilistic analysis (Cullen and Frey 1999).

### Groundwater-Flow and Contaminant Fate and Transport Models

For Tarawa Terrace groundwater-flow and contaminant fate and transport models, the following sensitivity analyses were conducted (Figure I2):

- input parameter sensitivity analysis,
- cell-size sensitivity analysis, and
- time-step size sensitivity analysis.

#### Input Parameter Sensitivity Analysis

For the Tarawa Terrace groundwater-flow and contaminant fate and transport models (Faye and Valenzuela 2007, Faye 2008), 18 input parameters were subjected to input parameter sensitivity analysis. The groundwater-flow model sensitivity analysis included 11 input parameters. These parameters were: horizontal hydraulic conductivity ($K_H$) for model layers 1–7, leakance ($K_Z/\Delta z$), infiltration ($I_R$), specific yield ($S_y$), and storage coefficient ($S$; Table I2).[12] Seven parameters were included in the sensitivity analysis of the contaminant fate and transport model. These were: bulk density ($\rho_b$), longitudinal dispersivity ($\alpha_L$), distribution coefficient ($K_d$), effective porosity ($n_E$), mass-loading rate ($q_s C_s$), molecular diffusion coefficient ($D^*$), and reaction rate ($r$). For definitions of specific parameters relative to the groundwater-flow and contaminant fate and transport models, readers should refer to Harbaugh and McDonald (1996), Zheng and Wang (1999), Chiang and Kinzelbach (2001), Faye and Valenzuela (2007), and Faye (2008).

Five metrics were used to assess the sensitivity of groundwater-flow and contaminant fate and transport model parameters (Table I5): (1) relative change in duration ($R_D$) when finished water at the Tarawa Terrace WTP exceeded the current maximum contaminant level[13] (MCL) for PCE (5 micrograms per liter [µg/L]), (2) relative change in maximum concentration ($R_C$) when finished water at the Tarawa Terrace WTP exceeded the current MCL for PCE, (3) root-mean-square of concentration difference at water-supply wells and the WTP (*RMS*), (4) absolute mean relative change ($\overline{R}$), and (5) standard deviation of absolute mean relative change ($\sigma_{\overline{R}}$).[14] For the input parameter sensitivity analysis, the bases for all computations are the calibrated parameter values and resulting calibrated PCE concentrations in water-supply well TT-26 or the PCE concentration of finished water at the Tarawa Terrace WTP described in the Chapter A (Maslia et al. 2007), Chapter C (Faye and Valenzuela 2007), and Chapter F (Faye 2008) reports. Mathematical formulae and definitions for the aforementioned five metrics used to assess the sensitivity of model input parameters are listed in Table I5.

The perturbed duration ($D_i''$) refers to the duration in months that finished water at the Tarawa Terrace WTP exceeded the current MCL for PCE of 5 µg/L. The perturbed

[12] Symbolic notation used to describe model parameters was obtained from PMWIN by Chiang and Kinzelbach (2001); leakance, identified as *VCONT* in PMWIN, is defined as follows:

$$VCONT = \frac{2}{\frac{\Delta v_k}{(K_Z)_{k,i,j}} + \frac{\Delta v_{k+1}}{(K_Z)_{k+1,i,j}}},$$

where $(K_Z)_{k,i,j}$ and $(K_Z)_{k+1,i,j}$ are the vertical hydraulic conductivity values of layers $K$ and $K$+1, respectively, and $\Delta v_k$ and $\Delta v_{k+1}$ are the thicknesses of layers $K$ and $K$+1, respectively.

[13] The maximum contaminant level (MCL) is a legal threshold limit set by the U.S. Environmental Protection Agency on the amount of a hazardous substance that is allowed in drinking water under the Safe Drinking Water Act; usually expressed as a concentration in milligrams or micrograms per liter. Effective dates for MCLs are as follows: trichloroethylene (TCE) and vinyl chloride (VC), January 9, 1989; tetrachloroethylene (PCE) and *trans*-1,2-dichloroethylene (1,2-tDCE), July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.).

[14] The fourth and fifth metrics listed in Table I5, the absolute mean relative change ($\overline{R}$) and the standard deviation of absolute mean relative change ($\sigma_{\overline{R}}$), will be discussed in the "Probabilistic Analysis of Groundwater Flow and Contaminant Fate and Transport" section of this report.

**Table I5.** Mathematical formulae and definitions of metrics used to assess sensitivity of model parameters, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[WTP, water treatment plant; MCL, maximum contaminant level; PCE, tetracholorethylene; µg/L, microgram per liter]

| Metric name and symbol | Mathematical formula | Definition of variables | Notes |
|---|---|---|---|
| Relative change in duration, in percent, $R_D$ | $R_D = \frac{D_i^p - D_i^{cal}}{D_i^{cal}} \times 100\%$ | $D_i^p$ = perturbed duration in months using varied parameter $i$;<br>$D_i^{cal}$ = calibrated duration in months using calibrated parameter $i$ | Duration refers to the number of months finished water at the WTP exceeded the MCL for PCE of 5 µg/L. |
| Relative change in maximum concentration, in percent, $R_C$ | $R_C = \frac{C_i^p - C_i^{cal}}{C_i^{cal}} \times 100\%$ | $C_i^p$ = perturbed maximum concentration using varied parameter $i$;<br>$C_i^{cal}$ = calibrated maximum concentration using calibrated parameter $i$ | Concentration refers to maximum simulated concentration of PCE in finished water at the WTP. |
| Root-mean-square of concentration difference, in µg/L, *RMS* | $RMS = \left[ \frac{\sum_{i=1}^{N_{SP}} \left( C_{t_i}^p - C_{t_i}^{cal} \right)^2}{N_{SP}} \right]^{1/2}$ | $C_{t_i}^p$ = perturbed concentration for stress period $i$;<br>$C_{t_i}^{cal}$ = calibrated concentration for stress period $i$;<br>$N_{SP}$ = number of stress periods used to calculate *RMS* | Concentration refers to simulated concentration of PCE in finished water at the WTP.<br>Number of stress periods ($N_{SP}$) equals 352 (November 1957–February 1987). |
| Absolute mean relative change, in percent, $\overline{R}$ | $\overline{R} = \frac{\sum_{i=1}^{N_{SP}} \left\lvert \frac{C_{t_i}^p - C_{t_i}^{cal}}{C_{t_i}^{cal}} \right\rvert}{N_{SP}} \times 100\%$ | $C_{t_i}^p$ = perturbed concentration for stress period $i$;<br>$C_{t_i}^{cal}$ = calibrated concentration for stress period $i$;<br>$N_{SP}$ = number of stress periods used to calculate $\overline{R}$ | Concentration refers to simulated concentration of PCE in finished water at the WTP.<br>Number of stress periods ($N_{SP}$) equals 201 (January 1968–January 1985).[1] |
| Standard deviation of absolute mean relative change, in percent, $\sigma_{\overline{R}}$ | $\sigma_{\overline{R}} = \left[ \frac{\sum_{i=1}^{N_{SP}} \left( R_{C_i} - \overline{R} \right)^2}{N_{SP} - 1} \right]^{1/2}$ | $R_{C_i}$ = relative change in concentration for stress period $i$, in percent<br>$\overline{R}$ = absolute mean relative change, in percent;<br>$N_{SP}$ = number of stress periods used to calculate $\sigma_{\overline{R}}$ | Concentration refers to simulated concentration of PCE in finished water at the WTP.<br>Number of stress periods ($N_{SP}$) equals 201 (January 1968–January 1985).[1] |

[1]Number of stress periods excludes times when water-supply well TT-26 was not in service—July–August 1980 (stress periods 355–356) and January–February 1983 (stress periods 385–386)

duration was determined by using a model input parameter that was modified from the calibrated value of that parameter. (Refer to Table 12 for a listing of calibrated model input parameters and their values.) Similarly, the perturbed concentration ($C_i^p$) refers to the simulated maximum concentration in finished water at the Tarawa Terrace WTP that is in excess of the current MCL. Also note that the metric identified as the *RMS*, or root-mean-square, of concentration difference is referred to by some in the literature as the root-mean-square of error (Anderson and Woessner 1992). As used in the current analysis, the *RMS* provides an indication of the mean or average deviation from calibrated finished water concentrations. The smaller the deviation (that is, the closer the *RMS* value is to 0), the closer the value of the perturbed parameter is to the calibrated parameter value.

Table I6 is a list of results of the sensitivity analysis conducted using the relative change in duration and concentration metrics ($R_D$ and $R_C$, respectively, in Table I5) for calibrated Tarawa Terrace groundwater-flow and contaminant fate and transport models. Results were obtained using the one-at-a-time method. Calibrated model parameters—with the exception of pumpage[15]—were multiplied by factors ranging from about 50% to 200% of their calibrated values. For example, horizontal hydraulic conductivity ($K_H$) for model layers 1–7 was varied by 90, 110, 150, and 250% of calibrated values; longitudinal dispersivity ($\alpha_L$) was varied by 50, 90, 110, 200, and 400% of calibrated values. Thus, for example, for a calibrated

[15] Sensitivity to changes in pumpage values (that is, uncertainty and variation in the scheduling and operations of water-supply wells) is discussed in the "Probabilistic Analysis of Groundwater Flow and Contaminant Fate and Transport" section of this report and in the Chapter H report (Wang and Aral 2008).

**Table I6.** Relative change in duration and concentration metrics ($R_D$ and $R_C$) computed as part of the sensitivity analysis of groundwater-flow and contaminant fate and transport model parameters, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[MCL, maximum contaminant level; µg/L, microgram per liter; ft/d, foot per day; —, not applicable; d, day; in/yr, inch per year; ft³/g, cubic foot per gram; ft, foot; g/ft³, gram per cubic foot; g/d, gram per day; ft²/d, square foot per day]

| Model parameter[1] | Calibrated value | Ratio of varied to calibrated parameter value | Simulated tetrachloroethylene (PCE) concentrations in finished water at the water treatment plant[2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Date first exceeding MCL[3] | Duration exceeding MCL, in months | Relative change in duration, in percent[4] | Maximum concentration, in µg/L[5] | Relative change in concentration, in percent[6] |
| Groundwater-flow model parameters | | | | | | | |
| Horizontal hydraulic conductivity, all layers, $K_H$ (ft/d) | 1.0–53.4 | 0.9 | —[7] | —[7] | —[7] | —[7] | —[7] |
| | | 1.1 | Sept. 1957 | 350 | 1.2 | 189 | 3.4 |
| | | 1.5 | Feb. 1957 | 359 | 3.8 | 202 | 10.2 |
| | | 2.5 | Apr. 1956 | 371 | 7.2 | 186 | 1.6 |
| Horizontal hydraulic conductivity, layer 1, $K_H$ (ft/d) | 12.2–53.4 | 0.9 | —[7] | —[7] | —[7] | —[7] | —[7] |
| | | 1.1 | Aug. 1957 | 351 | 1.4 | 196 | 7.0 |
| | | 1.5 | Oct. 1956 | 365 | 5.5 | 223 | 22.0 |
| | | 2.5 | Oct. 1955 | 377 | 9.0 | 209 | 14.1 |
| Horizontal hydraulic conductivity, layer 2, $K_H$ (ft/d) | 1.0 | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | –0.1 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | 0.1 |
| | | 1.5 | Nov. 1957 | 346 | 0.0 | 184 | 0.4 |
| | | 2.5 | Oct. 1957 | 347 | 0.3 | 186 | 1.6 |
| Horizontal hydraulic conductivity, layer 3, $K_H$ (ft/d) | 4.3–20.0 | 0.9 | Oct. 1957 | 348 | 0.6 | 184 | 0.5 |
| | | 1.1 | Nov. 1957 | 345 | –0.3 | 182 | –0.5 |
| | | 1.5 | Feb. 1958 | 341 | –1.4 | 179 | –2.3 |
| | | 2.5 | July 1958 | 339 | –2.0 | 187 | 2.1 |
| Horizontal hydraulic conductivity, layer 4, $K_H$ (ft/d) | 1.0 | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | 0.3 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | –0.3 |
| | | 1.5 | Nov. 1957 | 345 | –0.3 | 181 | –1.2 |
| | | 2.5 | Dec. 1957 | 343 | –0.9 | 176 | –3.6 |
| Horizontal hydraulic conductivity, layer 5, $K_H$ (ft/d) | 6.4–9.0 | 0.9 | Oct. 1957 | 347 | 0.3 | 185 | 1.2 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 181 | –1.0 |
| | | 1.5 | Jan. 1958 | 343 | –0.9 | 176 | –4.0 |
| | | 2.5 | Apr. 1958 | 339 | –2.0 | 169 | –7.9 |
| Horizontal hydraulic conductivity, layer 6, $K_H$ (ft/d) | 1.0 | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 1.5 | Nov. 1957 | 346 | 0.0 | 183 | –0.1 |
| | | 2.5 | Nov. 1957 | 346 | 0.0 | 182 | –0.3 |
| Horizontal hydraulic conductivity, layer 7, $K_H$ (ft/d) | 5.0 | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | –0.1 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | 0.1 |
| | | 1.5 | Nov. 1957 | 345 | –0.3 | 184 | 0.5 |
| | | 2.5 | Nov. 1957 | 345 | –0.3 | 185 | 1.2 |
| Leakance, $K_z/\Delta z$ (1/d) | $3.6 \times 10^{-5}$–$4.2 \times 10^{-1}$ | 0.9 | Nov. 1957 | 346 | 0.0 | 182 | –0.3 |
| | | 1.1 | Oct. 1957 | 347 | 0.3 | 183 | 0.2 |
| Infiltration (recharge), $I_R$ (in/yr) | 6.6–19.3 | 0.75 | —[7] | —[7] | —[7] | —[7] | —[7] |
| | | 0.9 | Nov. 1957 | 347 | 0.3 | 186 | 1.5 |
| | | 1.1 | Nov. 1957 | 345 | –0.3 | 195 | 6.5 |
| | | 1.25 | Dec. 1957 | 343 | –0.9 | 210 | 14.8 |
| Specific yield, $S_y$ | 0.05 | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | 0.1 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 2.5 | Nov. 1957 | 345 | –0.3 | 183 | –0.3 |
| | | 5.0 | Nov. 1957 | 344 | –0.6 | 183 | –0.1 |
| | | 10.0 | Nov. 1957 | 342 | –1.2 | 182 | –0.6 |
| | | 20.0 | Nov. 1957 | 338 | –2.3 | 178 | –2.6 |
| Storage coefficient, $S$ | $4.0 \times 10^{-4}$ | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 2.5 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 5.0 | Nov. 1957 | 346 | 0.0 | 183 | –0.1 |
| | | 10.0 | Nov. 1957 | 346 | 0.0 | 183 | –0.2 |
| | | 20.0 | Nov. 1957 | 346 | 0.0 | 182 | –0.3 |

**Table I6.** Relative change in duration and concentration metrics ($R_D$ and $R_C$) computed as part of the sensitivity analysis of groundwater-flow and contaminant fate and transport model parameters, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[MCL, maximum contaminant level; µg/L, micrograms per liter; ft/d, feet per day; in/yr, inch per year; ft³/g, cubic feet per gram; ft, feet; d, day; g/ft³, grams per cubic foot; g/d, grams per day; ft²/d, feet squared per day; —, not applicable]

| Model parameter[1] | Calibrated value | Ratio of varied to calibrated parameter value | Simulated tetrachloroethylene (PCE) concentrations in finished water at the water treatment plant[2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Date first exceeding MCL[3] | Duration exceeding MCL, in months | Relative change in duration, in percent[4] | Maximum concentration, in µg/L[5] | Relative change in concentration, in percent[6] |
| Contaminant fate and transport model parameters | | | | | | | |
| Distribution coefficient, $K_d$ (ft³/g) | $5.0\times10^{-6}$ | 0.5 | Apr. 1956 | 371 | 7.2 | 214 | 16.7 |
| | | 0.9 | July 1957 | 352 | 1.7 | 191 | 4.2 |
| | | 1.1 | Mar. 1958 | 338 | –2.3 | 180 | –1.8 |
| | | 1.5 | June 1959 | 310 | –10.4 | 165 | –10.0 |
| | | 2.0 | Dec. 1960 | 286 | –17.3 | 143 | –21.8 |
| | | 4.0 | Nov. 1972 | 143 | –58.7 | 61 | –66.5 |
| Bulk density, $\rho_b$ (g/ft³) | 77.112 | 0.9 | July 1957 | 352 | 1.7 | 191 | 4.2 |
| | | 1.1 | Mar. 1958 | 338 | –2.3 | 180 | –1.8 |
| Effective porosity, $n_E$ | 0.2 | 0.5 | Dec. 1956 | 363 | 4.9 | 349 | 90.9 |
| | | 0.9 | Sept. 1957 | 349 | 0.9 | 205 | 11.9 |
| | | 1.1 | Jan. 1958 | 340 | –1.7 | 169 | –7.7 |
| | | 1.5 | Oct. 1958 | 318 | –8.1 | 124 | –32.1 |
| | | 2.0 | Sept. 1959 | 301 | –13.0 | 86 | –53.0 |
| Reaction rate, $r$ (d⁻¹) | $5.0\times10^{-4}$ | 0.5 | Oct. 1957 | 349 | 0.9 | 294 | 60.4 |
| | | 0.9 | Nov. 1957 | 347 | 0.3 | 199 | 8.6 |
| | | 1.1 | Nov. 1957 | 344 | –0.6 | 171 | –6.8 |
| | | 1.5 | Dec. 1957 | 335 | –3.2 | 130 | –29.1 |
| | | 2.0 | Jan. 1958 | 326 | –5.8 | 94 | –48.7 |
| | | 4.0 | July 1958 | 315 | –9.0 | 30 | –83.7 |
| Mass-loading rate, $q_s C_s$ (g/d)[5] | 1.200 | 0.5 | May 1958 | 329 | –4.9 | 92 | –50.0 |
| | | 0.9 | Dec. 1957 | 343 | –0.9 | 165 | –10.0 |
| | | 1.1 | Oct. 1957 | 348 | 0.6 | 201 | 10.0 |
| | | 1.5 | Aug. 1957 | 351 | 1.4 | 275 | 50.0 |
| | | 2.0 | June 1957 | 353 | 2.0 | 366 | 100.0 |
| Longitudinal dispersivity, $\alpha_L$ (ft) | 25 | 0.5 | Apr. 1958 | 337 | –2.6 | 184 | 0.3 |
| | | 0.9 | Dec. 1957 | 344 | –0.6 | 183 | 0.1 |
| | | 1.1 | Oct. 1957 | 348 | 0.6 | 183 | –0.1 |
| | | 2.0 | Mar. 1957 | 356 | 2.9 | 181 | –1.0 |
| | | 4.0 | June 1956 | 367 | 6.1 | 176 | –3.7 |
| Molecular diffusion coefficient, $D^*$ (ft²/d) | $8.5\times10^{-4}$ | 0.9 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 1.1 | Nov. 1957 | 346 | 0.0 | 183 | 0.0 |
| | | 5.0 | Nov. 1957 | 346 | 0.0 | 183 | –0.1 |
| | | 10.0 | Nov. 1957 | 346 | 0.0 | 183 | –0.1 |
| | | 20.0 | Nov. 1957 | 346 | 0.0 | 182 | –0.3 |

[1]Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[2]For calibrated model, date finished water at water treatment plant exceeded MCL for PCE is November 1957, duration of exceeding MCL is 346 months, and maximum PCE concentration is 183 µg/L—see Maslia et al. (2007, Table A12 and Appendix A2)

[3]Maximum contaminant level (MCL) for PCE is 5 µg/L

[4]Refer to Table I5 for mathematical formula and definition of relative change in duration ($R_D$)

[5]Concentration values rounded to three significant digits for reporting purposes; simulations conducted with concentration values containing six significant digits

[6]Refer to Table I5 for mathematical formula and definition of relative change in concentration ($R_C$)

[7]Dry wells simulated for this sensitivity analysis

value of $K_H$ of 20 feet per day (ft/d) for model layer 1, a value used for the sensitivity analysis of 30 ft/d would yield a ratio of varied to calibrated $K_H$ for model layer 1 of 30 ft/d divided by 20 ft/d, or 1.5 (Table I6).[16]

Measures of the effect of varying the groundwater-flow and contaminant fate and transport model parameters were quantified in terms of five computations listed in Table I6: (1) the date (month and year) when finished drinking water at the Tarawa Terrace WTP first exceeded the current MCL for PCE (5 µg/L), (2) the duration (in months) that finished drinking water at the WTP exceeded the current MCL, (3) the relative change in these durations (percent) caused by varying the calibrated parameter values ($R_D$ in Table I5), (4) the maximum PCE concentration in finished water at the Tarawa Terrace WTP, and (5) the relative change (percent) in the maximum concentration ($R_C$ in Table I5). For calibrated model input parameters, the date that the PCE in finished water at the WTP first exceeded the current MCL was simulated as November 1957; the duration that finished water exceeded the MCL for PCE was 346 months; and the maximum concentration of PCE was 183 µg/L (Maslia et al. 2007, Figure A18 and Table A12; Faye 2008). Results of the sensitivity analysis show that some parameters are insensitive to change, even when varied by factors of 10 and 20. For example, large changes in specific yield ($S_y$), storage coefficient ($S$), and molecular diffusion ($D^*$) (ratios of 10:1 and 20:1, Table I6) resulted in very little change in simulated results—less than 3% change in relative duration or concentration. Changes in other parameters, such as horizontal hydraulic conductivity ($K_H$) for model layer 1 and infiltration ($I_R$), that were less than the calibrated value (for example, a ratio of varied to calibrated value of 0.9) resulted in wells going dry during the groundwater-flow simulation process.[17] Generally, increasing or decreasing a calibrated parameter value by 10% (ratio of varied to calibrated parameter value of 0.9–1.1) resulted in changes of 6 months or less to the date that finished water first exceeded the MCL for PCE (5 µg/L).

Results of selected sensitivity analyses listed in Table I6 also are shown graphically in Figure I4. Results are shown in terms of date on the abscissa and simulated PCE concentrations at water-supply well TT-26 or in finished water at the Tarawa Terrace WTP on the ordinate. Review of the graphical sensitivity analysis results indicates that horizontal hydraulic conductivity ($K_H$) for model layer 1 is the most sensitive groundwater-flow model input parameter and that reaction rate ($r$) is the most sensitive contaminant fate and transport model input parameter. Other model input parameters, such as those for the contaminant fate and transport model—effective porosity ($n_E$), mass-loading rate ($q_s C_s$), and distribution coefficient ($K_d$)—also show significant sensitivity (also refer to Table I6). Using the graphs in Figure I4 to make qualitative comparisons between the groundwater-flow and contaminant fate and transport model parameters, the following observations can be made:

- overall, simulated results of the contaminant fate and transport model are significantly more sensitive to changes in parameter values relative to calibrated values than simulated results of the groundwater-flow model, and
- sensitivity of groundwater-flow model parameters appears to be greater during early years of simulation (prior to about 1960) compared to the sensitivity of fate and transport model parameters which appear to indicate greater sensitivity subsequent to 1960.

The diminished sensitivity of groundwater-flow model simulation results compared to corresponding results of the contaminant fate and transport model is possibly related to the number and temporal distribution of field data used for model calibration. Although limited, field data for $K_H$, $I_R$, pumpage, and water levels were available for groundwater-flow model development and calibration. By comparison, parameter values assigned to the contaminant fate and transport model were obtained largely from literature-reported values, and concentration data were sparse and available only between 1985 and 1991 (Faye 2008, Table F13). Thus, part of the contaminant fate and transport model sensitivity may be attributed strictly to numerical properties because input parameter values were not specifically calibrated against measured field-derived or laboratory-derived properties unique to Tarawa Terrace and vicinity.

The *RMS* computations of concentration differences are listed in Table I7. Results of the sensitivity analysis using the *RMS* metric were computed using simulated concentrations during the period November 1957–February 1987 (stress periods 83–434, or 352 stress periods; Appendix I1). November 1957 represents the date when the concentration of finished water at the Tarawa Terrace WTP first exceeded the current MCL for PCE of 5 µg/L, based on calibrated model simulations (Maslia et al. 2007, Faye 2008). February 1987 represents the date when all Tarawa Terrace water-supply wells were removed from continuous operation (Faye and Valenzuela 2007, Maslia et al. 2007). The *RMS* metric provides additional confirmation that horizontal hydraulic conductivity ($K_H$) for model layer 1 and infiltration ($I_R$) are by far the most sensitive groundwater-flow model input parameters. Note that as the sensitivity of a model input parameter increases, its deviation from an *RMS* value of 0.0 also increases. Furthermore, the sensitivity of the groundwater-flow model to changes in $K_H$ for all model layers is primarily driven by the sensitivity to the change in the $K_H$ value for model layer 1. For example, an increase of 10% from the calibrated

[16] The terms factor, ratio, and percent may be used inconsistently in the literature. For the purposes of this report, they are defined according to the following example: a calibrated value of 10 and a perturbed value of 15 are related by a factor of 1.5, a ratio of 1.5:1, 150%, or an increase of 50%.

[17] When a well goes dry during a groundwater-flow simulation, the simulation process is halted and concentrations cannot be computed from that time forward. As a consequence, sensitivity analysis metrics also cannot be computed (Table I6).

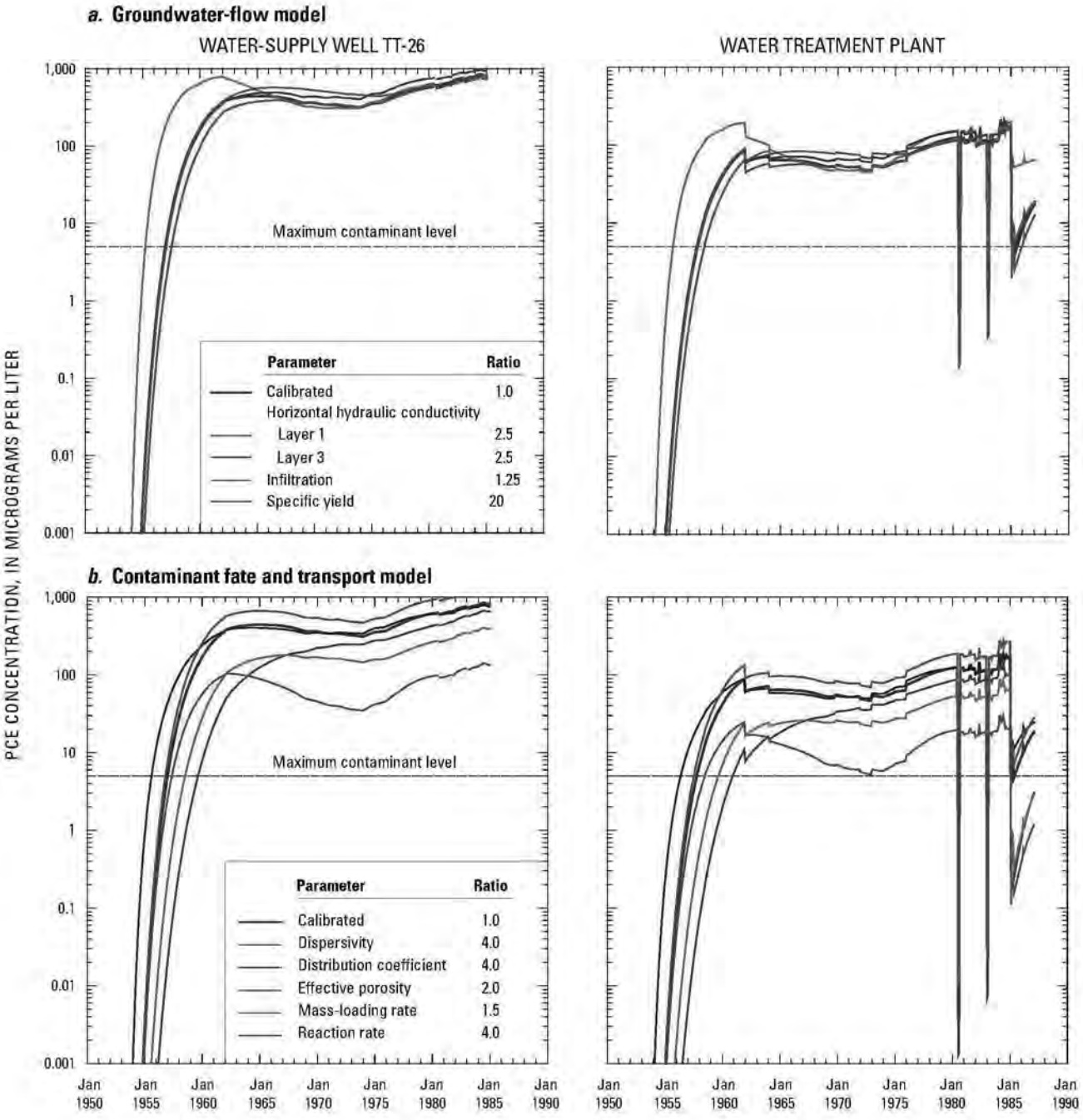



**Figure I4.** Sensitivity of simulated tetrachloroethylene concentration to changes in model parameter values: *(a)* groundwater-flow model and *(b)* contaminant fate and transport model, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene]

**Table I7.** Root-mean-square of concentration difference in finished water at the water treatment plant computed as part of sensitivity analysis of groundwater-flow and contaminant fate and transport model parameters, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[*RMS*, root-mean-square; µg/L$^3$, microgram per cubic liter; ft/d, foot per day; —, not applicable; d, day; in/yr, inch per year; g/ft$^3$, gram per cubic foot; ft, foot; ft$^3$/g, cubic foot per gram; g/d, gram per day; ft$^2$/d, square foot per day]

| Model parameter[2] | Ratio of varied to calibrated parameter value | *RMS* difference, in µg/L$^3$ |
|---|---|---|
| Horizontal hydraulic conductivity, all layers, $K_H$ (ft/d) | 0.9 | —[4] |
| | 1.1 | 3.312 |
| | 1.5 | 13.99 |
| | 2.5 | 26.87 |
| Horizontal hydraulic conductivity, layer 1, $K_H$ (ft/d) | 0.9 | —[4] |
| | 1.1 | 5.184 |
| | 1.5 | 22.34 |
| | 2.5 | 47.72 |
| Horizontal hydraulic conductivity, layer 2, $K_H$ (ft/d) | 0.9 | 0.062 |
| | 1.1 | 0.060 |
| | 1.5 | 0.294 |
| | 2.5 | 1.587 |
| Horizontal hydraulic conductivity, layer 3, $K_H$ (ft/d) | 0.9 | 0.888 |
| | 1.1 | 0.847 |
| | 1.5 | 3.861 |
| | 2.5 | 9.378 |
| Horizontal hydraulic conductivity, layer 4, $K_H$ (ft/d) | 0.9 | 0.227 |
| | 1.1 | 0.225 |
| | 1.5 | 1.108 |
| | 2.5 | 3.203 |
| Horizontal hydraulic conductivity, layer 5, $K_H$ (ft/d) | 0.9 | 1.110 |
| | 1.1 | 0.983 |
| | 1.5 | 4.054 |
| | 2.5 | 8.847 |
| Horizontal hydraulic conductivity, layer 6, $K_H$ (ft/d) | 0.9 | 0.042 |
| | 1.1 | 0.043 |
| | 1.5 | 0.207 |
| | 2.5 | 0.597 |
| Horizontal hydraulic conductivity, layer 7, $K_H$ (ft/d) | 0.9 | 0.240 |
| | 1.1 | 0.232 |
| | 1.5 | 1.087 |
| | 2.5 | 2.719 |
| Leakance, $K_z/\Delta z$ (1/d) | 0.9 | 0.814 |
| | 1.1 | 0.689 |
| Infiltration (recharge), $I_R$ (in/yr) | 0.75 | —[4] |
| | 0.9 | 6.466 |
| | 1.1 | 6.306 |
| | 1.25 | 15.17 |
| Specific yield, $S_y$ | 0.9 | 0.089 |
| | 1.1 | 0.088 |
| | 2.5 | 1.261 |
| | 5.0 | 3.251 |
| | 10.0 | 7.1025 |
| | 20.0 | 14.53 |
| Storage coefficient, $S$ | 0.9 | 0.003 |
| | 1.1 | 0.004 |
| | 2.5 | 0.049 |
| | 5.0 | 0.130 |
| | 10.0 | 0.289 |
| | 20.0 | 0.602 |
| Bulk density, $\rho_b$ (g/ft$^3$) | 0.9 | 5.358 |
| | 1.1 | 4.953 |
| Longitudinal dispersivity, $\alpha_L$ (ft) | 0.5 | 2.589 |
| | 0.9 | 0.463 |
| | 1.1 | 0.440 |
| | 1.5 | 2.000 |
| | 2.0 | 3.596 |
| | 4.0 | 7.754 |
| Distribution coefficient, $K_d$ (ft$^3$/g) | 0.5 | 30.16 |
| | 0.9 | 5.358 |
| | 1.1 | 4.953 |
| | 1.5 | 21.00 |
| | 2.0 | 34.77 |
| | 4.0 | 64.70 |
| Effective porosity, $n_E$ | 0.5 | 52.15 |
| | 0.9 | 8.017 |
| | 1.1 | 7.151 |
| | 1.5 | 29.11 |
| | 2.0 | 46.54 |
| Mass-loading rate, $q_s C_s$ (g/d) | 0.5 | 39.38 |
| | 0.9 | 7.877 |
| | 1.1 | 7.877 |
| | 1.5 | 39.38 |
| Molecular diffusion, $D^*$ (ft$^2$/d) | 0.9 | $1.7 \times 10^{-3}$ |
| | 1.1 | $1.8 \times 10^{-4}$ |
| | 1.5 | $8.7 \times 10^{-3}$ |
| | 5 | $6.9 \times 10^{-2}$ |
| | 10 | $1.6 \times 10^{-1}$ |
| | 20 | $3.3 \times 10^{-1}$ |
| Reaction rate, $r$ (d$^{-1}$) | 0.5 | 35.54 |
| | 0.9 | 5.905 |
| | 1.1 | 5.419 |
| | 1.5 | 23.09 |
| | 2.0 | 38.59 |
| | 4.0 | 66.13 |

[1] *RMS* metric computed for simulation period of November 1957–February 1987 (stress periods 83–434; total of 352 stress periods)

[2] Symbolic notations used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[3] Refer to Table I5 for mathematical formula and definition of root-mean-square of concentration difference

[4] Dry wells simulated for this sensitivity analysis

value of $K_H$ (that is, a ratio of 1.1) results in an *RMS* value of about 5.2 µg/L for model layer 1 and 3.3 µg/L for all model layers combined. This result is compared to an *RMS* value of less than 1 for all other individual model layers. With the exception of the aforementioned model parameters of $K_H$ and $I_R$, groundwater-flow model input parameters are relatively insensitive to changes from their calibrated values.

The *RMS* metric computed for contaminant fate and transport model parameters indicates that the reaction rate ($r$), distribution coefficient ($K_d$), effective porosity ($n_E$), and mass-loading rate ($q_s C_s$) are most sensitive to changes in calibrated parameter values with calculated *RMS* values exceeding 20 µg/L for a varied to calibrated input parameter ratio of 1.5. The *RMS* values for other contaminant fate and transport model parameters (for example, $\alpha_L$ and $D^*$) are much lower, and some are near a value of 0.0.

Selected sensitivity analysis results computed using the *RMS* of concentration differences metric (Table I7) are shown graphically in Figures I5 and I6. The value of 100% on the abscissa and a value of 0 on the ordinate of these figures indicate the calibrated model parameter value (Table I6). Figure I5 shows the sensitivity for changes in horizontal hydraulic conductivity ($K_H$) for all model layers combined and for each model layer modified independently. Results indicate a high degree of sensitivity to changes in $K_H$ for model layer 1. In addition, the sensitivity to change in $K_H$ for model layer 1 apparently accounts for the overall sensitivity to $K_H$ for all layers combined. Furthermore, results shown in Figure I5 indicate that the groundwater-flow model is insensitive to input parameter value changes in $K_H$ for model layers 2, 4, 6, and 7. Note, for $K_H$ values of less than 100% of calibrated values, water-supply wells were simulated as dry (also see Tables I6 and I7). Simulations were halted once a water-supply well was simulated as dry, and subsequent concentrations were not simulated.

Figure I6 shows *RMS* concentration differences plotted for selected groundwater-flow (other than $K_H$) and contaminant fate and transport model parameters as they were varied from calibrated values (*RMS* = 0 and percentage of calibrated value = 100%). Groundwater-flow and contaminant fate and transport model input parameters indicating less sensitivity to

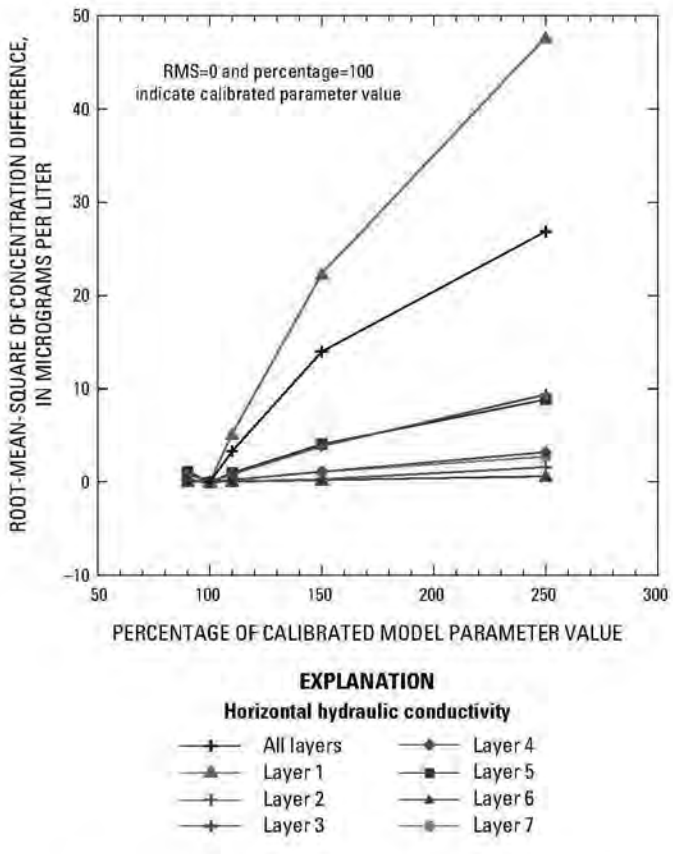



**Figure I5.** Sensitivity analysis results for horizontal hydraulic conductivity for all model layers in terms of root-mean-square (*RMS*) of concentration difference in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

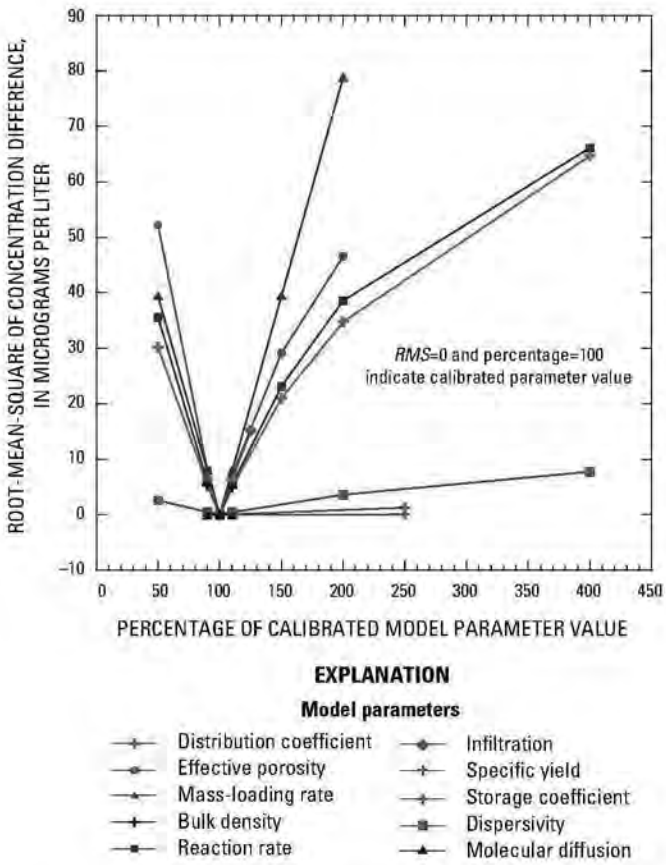



**Figure I6.** Sensitivity analysis results for groundwater-flow and contaminant fate and transport model parameters in terms of root-mean-square (*RMS*) of concentration difference in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

change from calibrated values are storage coefficient ($S$), specific yield ($S_y$), longitudinal dispersivity ($\alpha_L$), and molecular diffusion ($D^*$). Parameters indicating a relatively high degree of sensitivity to change from calibrated values are distribution coefficient ($K_d$), reaction rate ($r$), effective porosity ($n_E$), and mass-loading rate ($q_s C_s$).

In summary, the aforementioned one-at-a-time sensitivity analyses are limited with respect to assessing the effect of simultaneous changes in multiple model input parameters. However, the sensitivity analysis did identify essential parameters that should be included in enhanced analyses ($K_H$, $I_R$, $K_d$, $n_E$, $r$, and $q_s C_s$). The variability and uncertainty of these and other model input parameters (pumpage, $\rho_b$, and $\alpha_L$) are described in detail in the "Probabilistic Analysis of Groundwater Flow and Contaminant Fate and Transport" section of this report.

## Cell-Size Sensitivity Analysis

A sensitivity analysis was conducted to determine if the finite difference cell size of 50 ft per side, which was used for the calibrated groundwater-flow and contaminant fate and transport models (Faye and Valenzuela 2007, Faye 2008), was appropriate in terms of simulating the water level in a pumping well when compared to a smaller cell size. For this analysis, a refined model grid consisting of a smaller cell size was used in the areas surrounding water-supply wells and the contaminant source (Figure I7). The cell dimensions of the refined grid were 25 ft along each cell side. Figure I7 shows the location of the calibrated model grid (50-ft cells) and the refined model grid (25-ft cells). The refined model grid is located within the rectangular area bounded by cells at row and column coordinates 36 and 151, respectively, and 112 and 191, respectively.[18] Water levels simulated using the refined model grid (25-ft cells) were compared to simulated water levels in well TT-26 using the grid of the calibrated model (50-ft cells). Comparisons were made for January 1952, November 1957, January 1968, and March 1987 (Figure I8). The graphs in Figure I8 show that water levels simulated using the refined and calibrated model grids (50-ft and 25-ft cells, respectively) are nearly identical. For example, during January 1952, the simulated water level in well TT-26 using the calibrated model grid was –18.3 ft (Faye and Valenzuela 2007); for the refined model grid, the simulated water level was –14.6 ft (Figure I8*a*). Thus, sensitivity to a 50% reduction in cell dimension (75% reduction in cell area) throughout much of the active model domain is apparent only at cells where pumpage is assigned. The difference in simulated water levels at these cells is small compared to total simulated drawdown. Simulated differences (maximum of 3.7 ft [Figure I8]) are well within the transient model calibration target range of ±12 ft (Faye and Valenzuela 2007).

[18] Cell coordinates are defined by a row, column designation for each model layer. In this case, coordinates for two cells that bound a rectangular area of 25-ft cells have been defined as follows (Figure I7): upper left or northwestern corner, row 36, column 151; lower right or southeastern corner, row 112, column 191.

## Time-Step Size Sensitivity Analysis

When conducting fate and transport simulations, numerical instability related to inappropriate temporal discretization (that is, time-step size) is minimized when the Courant number ($C$) equals 1.0 or less. The Courant number is defined as:

$$C = \frac{V\Delta t}{\Delta l}, \tag{1}$$

where

$C$ = Courant number, [$L^0$];
$V$ = simulated groundwater-flow velocity, [$LT^{-1}$];
$\Delta t$ = stress-period length or time-step size, [T]; and
$\Delta l$ = a characteristic length, [L].[19]

The characteristic length of finite-difference numerical models is typically related to grid cell dimensions. The MODFLOW-96 and MT3DMS models applied to Tarawa Terrace and vicinity are uniform at 50 ft per side (Faye and Valenzuela 2007, Faye 2008). Therefore, the characteristic length, $\Delta l$, becomes the length of the cell side or the distance between two adjacent cell centroids (50 ft). To minimize and control oscillations of the numerical solution resulting from the temporal discretization, Daus and Frind (1985) indicate that the Courant number ($C$) should be less than or equal to 1. For the Tarawa Terrace models, the stress periods were equal to the number of days in a month (that is, 28, 29, 30, or 31). Except in the immediate vicinity of water-supply wells, groundwater-flow velocities ranged between 0.01 and 1.0 ft/d (Faye and Valenzuela 2007, Faye 2008). Thus, applying Equation 1 to the Tarawa Terrace models yields the following values for Courant numbers:

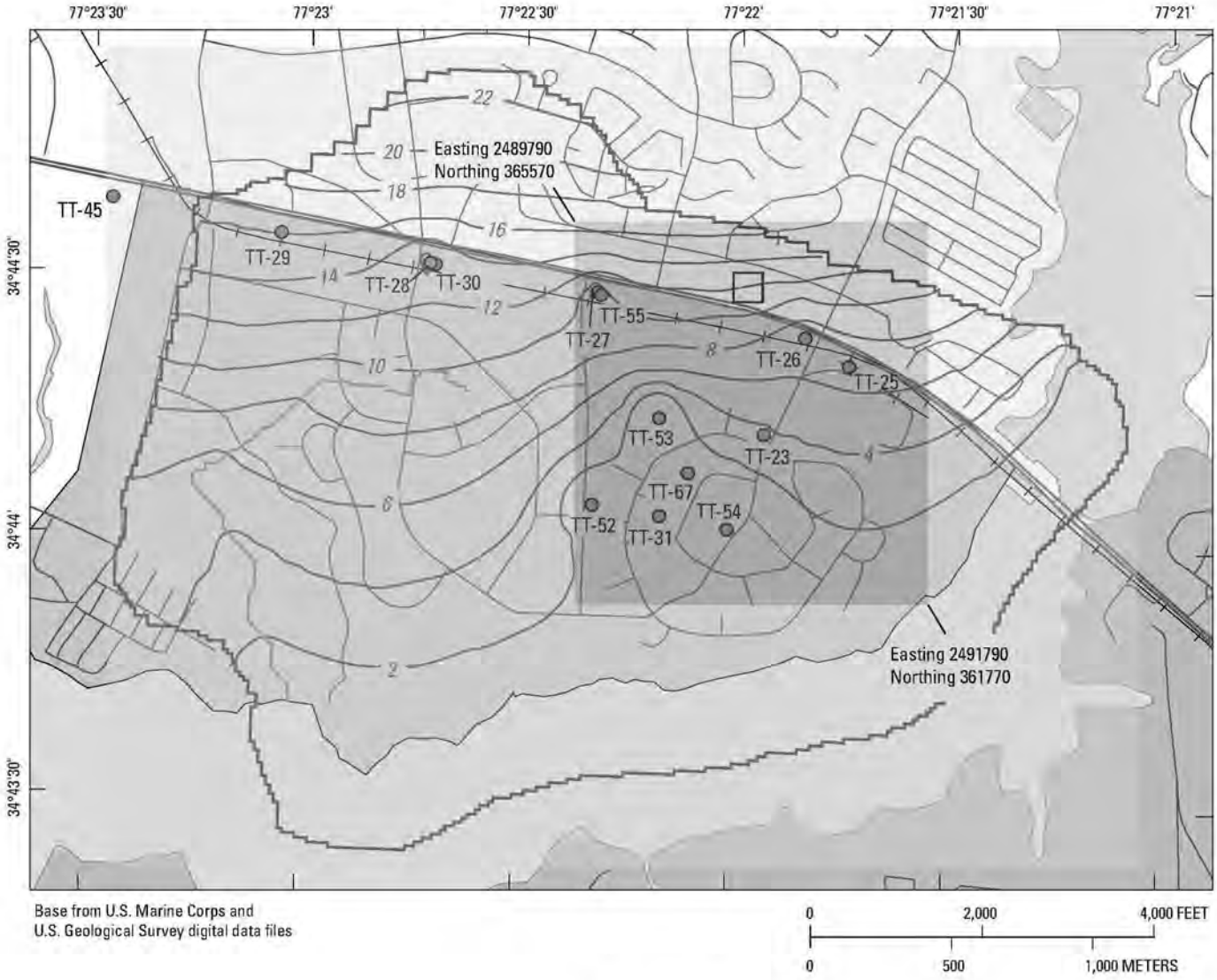
$$\frac{0.01\times 28}{50} \le C \le \frac{1.0\times 31}{50}$$

$$0.006 \le C \le 0.6 \tag{2}$$

This demonstrates that for the Tarawa Terrace models, the Courant number was less than 1 throughout the entire active model domain except in the immediate vicinity of operating water-supply wells.

In the immediate vicinity of operating water-supply wells, velocities were simulated as great as 8 ft/d (Faye and Valenzuela 2007, Faye 2008). Substituting this value of velocity into Equations 1 and 2 results in a maximum-value Courant number of about 5; this number could cause numerical oscillations leading to inaccurate simulated concentrations. To assess the effect of numerical oscillations caused by an inappropriate time discretization (that is, too large of a time step), contaminant fate and transport simulations were conducted by assigning 1-day stress periods ($\Delta t = 1$) to the calibrated Tarawa Terrace contaminant fate and transport

[19] L represents length units; T represents time units; $L^0$ indicates a dimensionless variable.




**EXPLANATION**

**Historical water-supply area**
- Tarawa Terrace
- Holcomb Boulevard

**Model boundary**

**Frenchmans Creek**

**ABC One-Hour Cleaners**

— 4 — **Simulated potentiometric contour**— Shows simulated potentiometric surface during January 1968. Contour interval 2 feet. Datum is National Geodetic Vertical Datum of 1929

TT-52 **Water-supply well and identification**

**Cell size, in feet per side**

50 25

**Figure I7.** Location of model grids containing cell dimensions of 50 feet per side and 25 feet per side used to conduct cell-size sensitivity analysis, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

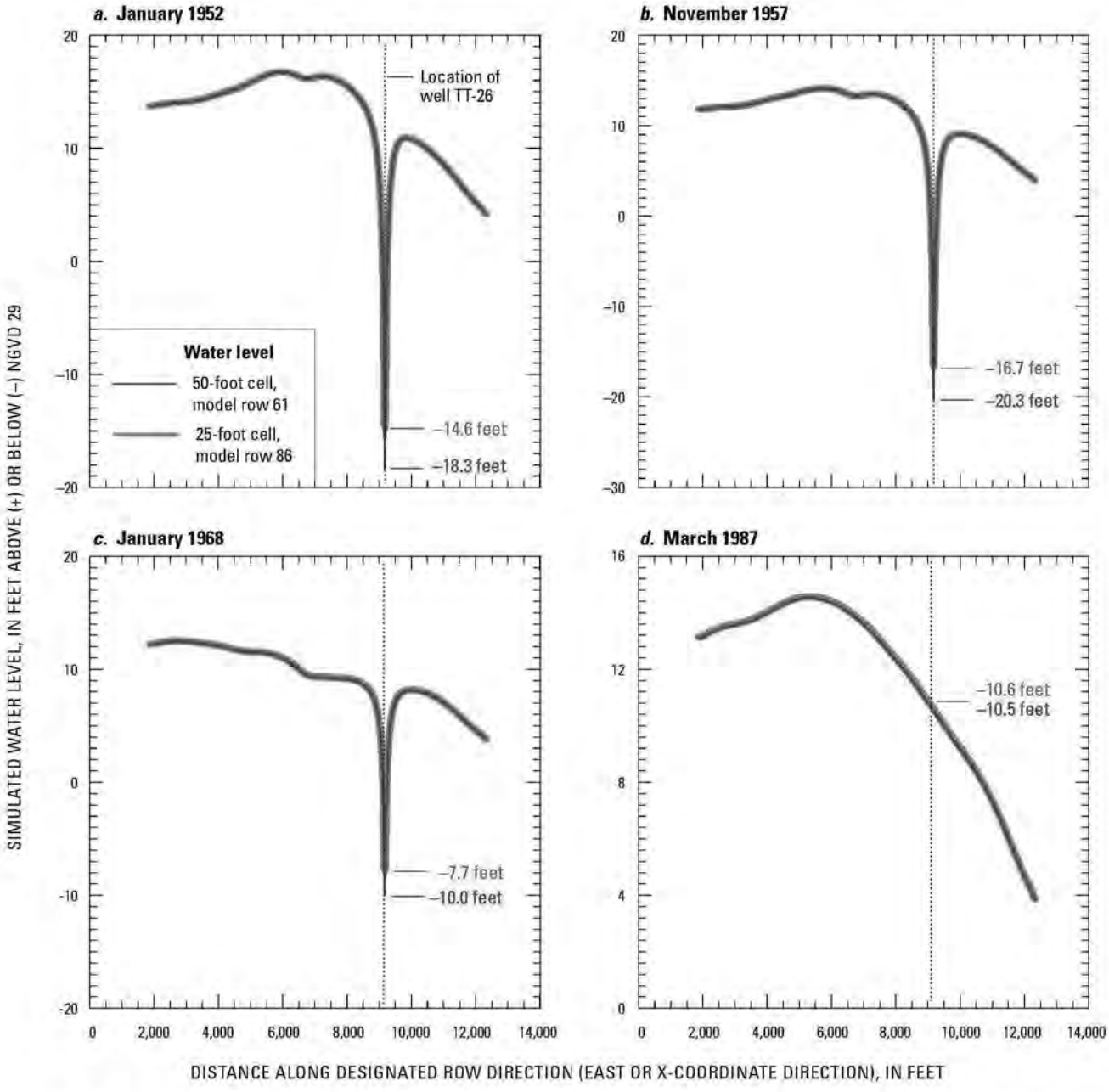



**Figure I8.** Simulated water levels along designated model row containing water-supply well TT-26 using finite-difference cell dimensions of 50 feet per side and 25 feet per side during: *(a)* January 1952, *(b)* November 1957, *(c)* January 1968, and *(d)* March 1987, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [NGVD 29, National Geodetic Vertical Datum of 1929]

model from November 1, 1984 to January 31, 1985. Pumpage assigned to these months in the calibrated model (Faye and Valenzuela 2007) was assigned to every day of each respective month for the time-step sensitivity analysis. Comparisons of calibrated (30- and 31-day time steps) and simulated (1-day time step) concentrations of PCE for the days of November 30, 1984, December 31, 1984, and January 31, 1985 for water-supply wells TT-23 and TT-26 are listed in Table I8. These results show that the relative absolute difference in simulated PCE concentrations at water-supply wells TT-23 and TT-26 between the 1-day time step and the 30- and 31-day time steps is typically less than a tenth of 1 percent and that simulated concentrations at these wells are similar to three or four significant digits. Thus, PCE concentrations simulated by the Tarawa Terrace contaminant fate and transport model were clearly unaffected by numerical oscillations caused by inappropriate temporal discretization.

## Water-Distribution System Model

Calibration of the Tarawa Terrace and Holcomb Boulevard water-distribution system models was accomplished in two stages: (1) a trial-and-error stage wherein model parameters were changed within reasonable limits and simulation results were compared to field data (hydraulic heads and tracer concentrations) and (2) a parameter estimation stage using the advanced parameter estimation tool PEST (Doherty 2005). Final calibration was achieved using parameter estimation to test the sensitivity of simulated hydraulic heads to several model input model parameters. Details of the modeling effort and the collection of field data used to support model calibration are described in Sautner et al. (2005, 2007), Grayman et al. (2006), and in Chapter J of the Tarawa Terrace report series (Sautner et al. In press 2009). The locations of pipelines, storage tanks, and field-test monitoring equipment for the Tarawa Terrace and Holcomb Boulevard water-distribution systems are shown in Figure I9.

During the trial-and-error stage, simulated results varied depending on: (1) which storage-tank model was used to account for mixing within storage tanks (see section on "Storage-Tank Mixing"), (2) the friction factor assigned to pipes with the distribution network (C-factor value), and (3) the pattern of demand imposed on the water-distribution system by water users. These model inputs, individually and in combination, significantly affected the heads simulated in several storage tanks located within the Tarawa Terrace and Holcomb Boulevard water-distribution systems (see Figure I9 for location of storage tanks STT-40, S-2323, S-830, and LCH-4004). Heads simulated in the storage tanks determine, to a large degree, the distribution of hydraulic head within the network and thus, the quality of calibration of the water-distribution system models. Sensitivity tests using parameter estimation methods were used to determine the optimum combination of tank mixing model, C-factors, and demand patterns that minimized the difference between simulated and observed hydraulic head.

**Table I8.** Comparisons of calibrated groundwater concentrations of tetrachloroethylene (PCE) using 30- and 31-day time steps with simulated groundwater concentrations using a 1-day time step, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

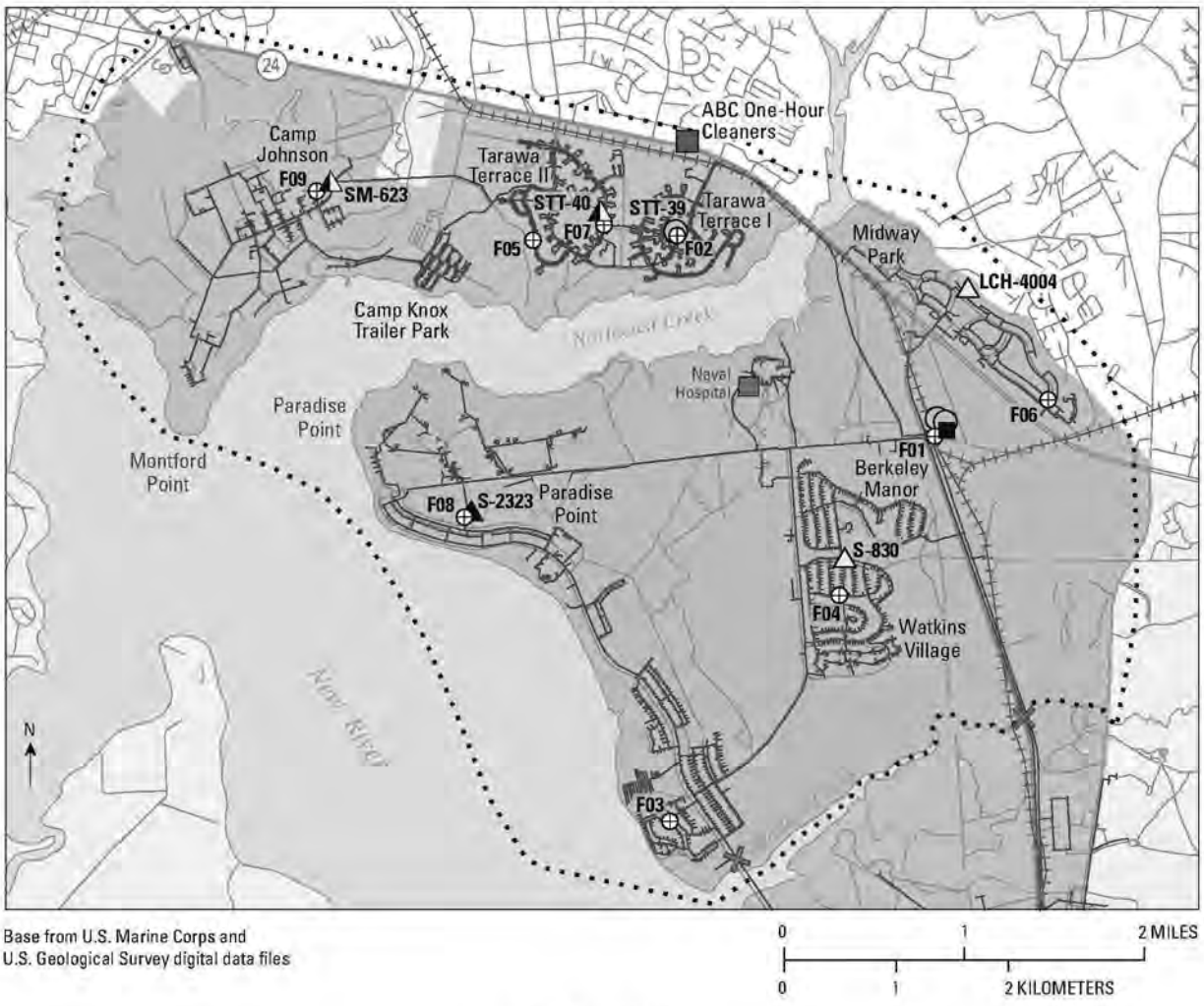
| Site name | Stress period | Date | Simulated elapsed time, in days | Simulated PCE, in grams per cubic foot[1] | | Simulated PCE, in micrograms per liter[1] | | Absolute relative difference, in percent[2] |
|---|---|---|---|---|---|---|---|---|
| | | | | Δt = 30 or 31 days | Δt = 1 day | Δt = 30 or 31 days | Δt = 1 day | |
| TT-23 | 407 | Nov. 30, 1984 | 12,388 | 0.0071823 | 0.0071840 | 253.3 | 253.4 | 0.02 |
| | 408 | Dec. 31, 1984 | 12,419 | 0.0072117 | 0.0072149 | 254.4 | 254.5 | 0.04 |
| | 409 | Jan. 31, 1985 | 12,450 | 0.0072000 | 0.0071987 | 254.0 | 253.9 | 0.02 |
| TT-26 | 407 | Nov. 30, 1984 | 12,388 | 0.0229735 | 0.0229851 | 810.4 | 810.8 | 0.05 |
| | 408 | Dec. 31, 1984 | 12,419 | 0.0227652 | 0.0227989 | 803.0 | 804.2 | 0.15 |
| | 409 | Jan. 31, 1985 | 12,450 | 0.0227541 | 0.0227619 | 802.6 | 802.9 | 0.03 |

[1]Simulated PCE concentrations for Δt = 30 or Δt = 31 days are from calibrated fate and transport model described in Faye (2008)

[2]Absolute relative difference ( $|R_C|$ ) of simulated PCE concentration at water-supply wells defined as:

$$|R_C| = \frac{C_{cal} - C_{\Delta t=1}}{C_{\Delta t=1}} \times 100\%,$$

where $C_{cal}$ is the calibrated PCE concentration simulated using a time-step size of 30 or 31 days and $C_{\Delta t=1}$ is the PCE concentration simulated using a time-step size of 1 day




**EXPLANATION**

**Present-day (2004) water-distribution system on Camp Lejeune Military Reservation**

- Tarawa Terrace
- Holcomb Boulevard
- Hadnot Point

**Other areas of Camp Lejeune Military Reservation**

**Holcomb Boulevard water treatment plant service area**—March 1987 to present

**Holcomb Boulevard water treatment plant**

**Water pipeline**—2004

**Shut-off valve**—Approximate location

F03 **Fluoride logger and number**—CRWQME

**Storage tank**

S-2323 Elevated—Controlling

S-830 Elevated—Noncontrolling

SM-623 Elevated—Intermittently controlling and noncontrolling depending on demand conditions

STT-39 Ground—Finished water

**Figure I9.** Locations of continuous recording water-quality monitoring equipment (CRWQME; F01–F09) and present-day (2004) Tarawa Terrace and Holcomb Boulevard water-distribution systems used for conducting a fluoride tracer test, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2007).

## Storage-Tank Mixing[20]

Storage tanks and reservoirs commonly are used in water-distribution systems to provide emergency water supply for fire fighting and pumping outages in addition to equalizing pumping requirements and operating pressures. Poor mixing in finished water tanks can worsen water-quality conditions in a distribution system. Studies of storage tanks can generally be grouped into three areas: (1) monitoring and sampling, (2) physical-scale modeling, and (3) mathematical modeling. For the purpose of the current study, a subset of mathematical models—simplified input/output representations, referred to as "system models"—were used. Detailed discussions of the different classifications of storage tanks, field-test methods, experimental methods, and analyses can be found in the following references: Grayman and Clark (1993), Kennedy et al. (1993), Boulos et al. (1996), Grayman et al. (1996), Rossman and Grayman (1999), Roberts and Tian (2002), Grayman et al. (2004), Roberts et al. (2005), and Sautner et al. (2007).

When applied to water-distribution systems, system models use highly conceptual empirical relationships to represent mixing in tanks and reservoirs. These system models have been used to represent tanks that operate in the fill-and-drain mode or with continuous inflow and outflow and include complete mixing (CSTR), multi-compartment models, such as two-compartment mixing (2-COMP), first-in, first-out (FIFO) plug flow, and last-in, first-out (LIFO) plug flow. System models are typically used to simulate substances that are conservative or decay according to first-order functions. Water age also can be simulated with system models. System models are easily integrated into hydraulic and water-quality models of distribution systems such as EPANET 2. The four storage-tank mixing models are described in detail by Clark and Grayman (1998) and in the EPANET 2 Users Manual (Rossman 2000). Conceptual diagrams of the four EPANET 2 storage-tank mixing models are shown in Figure I10.

To characterize and understand water-supply areas and the water-distribution systems serving base housing at Camp Lejeune, ATSDR conducted a series of field tests during 2004. These tests were hydraulic (pressure and flow) and water-quality (tracer) tests. Tracer tests consisted of injecting calcium chloride and sodium fluoride into the distribution system and turning WTP fluoride feeds off and on. Test details are described in Maslia et al. (2004, 2005) and Sautner et al. (2005, In press 2009). During initial tracer injection activities (May 2004), water in some storage tanks apparently did not mix completely or uniformly. It was not logistically possible to monitor the internal mixing patterns of the Camp Lejeune storage tanks. Therefore, in subsequent field tests, controlling storage tanks (Figure I9) were equipped with continuous recording water-quality monitoring equipment (CRWQME). The CRWQME was connected to the inlet and outlet of the storage tanks, so that fill and drain patterns of the storage tanks could be continuously recorded and monitored. Storage-tank monitoring occurred at 15-minute (min) intervals. A schematic diagram and photographs showing a typical CRWQME installation at a controlling storage tank is shown in Figure I11. Based on this storage-tank field monitoring design, the CRWQME was expected to capture continuous fill and drain sequences of the storage tank during the tracer test.

[20] Assessment of storage-tank mixing models was originally published by Sautner et al. (2007).

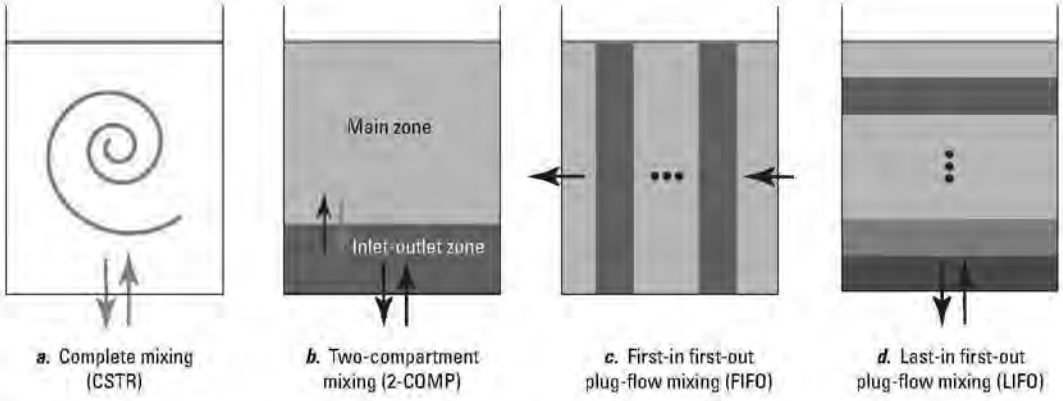



**Figure I10.** Storage-tank mixing models analyzed using test data gathered during a tracer test of the Tarawa Terrace and Holcomb Boulevard water-distribution systems, September 22–October 12, 2004, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Storage-tank mixing models from Rossman 2000]

Hydraulic and water-quality extended period simulations (EPS) of tracer tests were accomplished using the EPANET 2 water-distribution system model software. Detailed descriptions of tracer-test methodology and the tracer tests conducted on the Tarawa Terrace and Holcomb Boulevard water-distribution systems are provided in Maslia et al. (2004, 2005) and Sautner et al. (2005, 2007, In press 2009). Four types of storage-tank mixing models were analyzed using the tracer-test data and the EPANET 2 software. These were: CSTR, 2-COMP, FIFO, and LIFO. A sensitivity analysis approach was used to assess which of the conceptual system storage-tank models was most appropriate for conceptualizing mixing in the Tarawa Terrace and Holcomb Boulevard storage tanks based on data gathered during the tracer test of September 22–October 12, 2004.

Water-quality simulations were conducted by using the collected tracer-test data for source locations (F01 and F02, Figure I9) and the four mixing model options contained in EPANET 2 (Figure I10). The simulations were used to assess characteristics of mixing models and their effect on water-quality dynamics during the simulation. For the Tarawa Terrace water-distribution system, simulation results compared with measured data for controlling storage tank SM-623 (Camp Johnson tank, monitoring location F09; Figure I9) are shown in Figure I12. The four graphs show EPANET 2 simulations using the four storage-tank mixing model types—CSTR, 2-COMP, FIFO, and LIFO—and measured fluoride tracer data. For all simulations, hydraulic and water-quality simulation time steps were 5 and 2 minutes, respectively. For the two-compartment mixing model (2-COMP), it was assumed that the ratio of the first compartment to total tank volume was 1:10 (0.1).

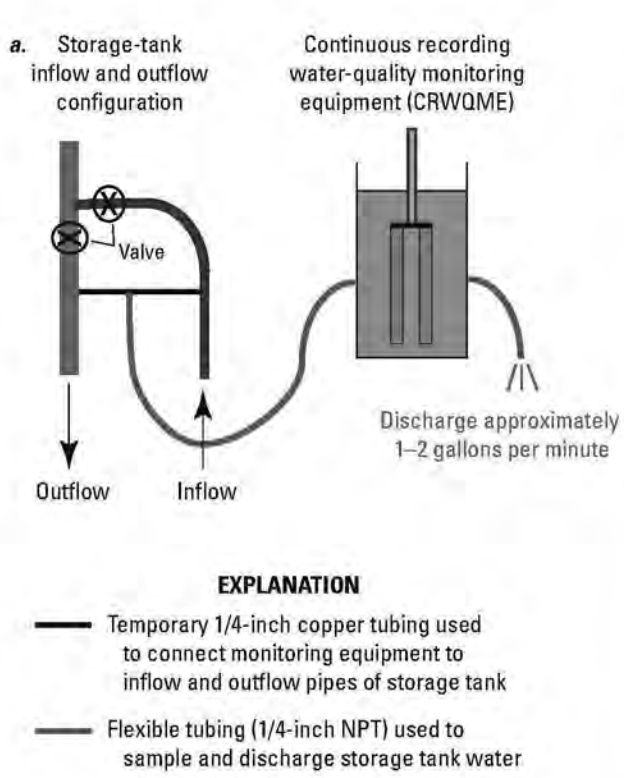





**Figure I11.** Method of connecting CRWQME to controlling storage tank: *(a)* schematic diagram, *(b)* photograph of connection to elevated storage tank SM-623, and *(c)* photograph of housing containing CRWQME and discharge tube, and staff person from U.S. Marine Corps Environmental Management Division. [See Figure I9 for location of storage tank SM-623; from Sautner et al. 2007; NPT, National Pipe Thread]

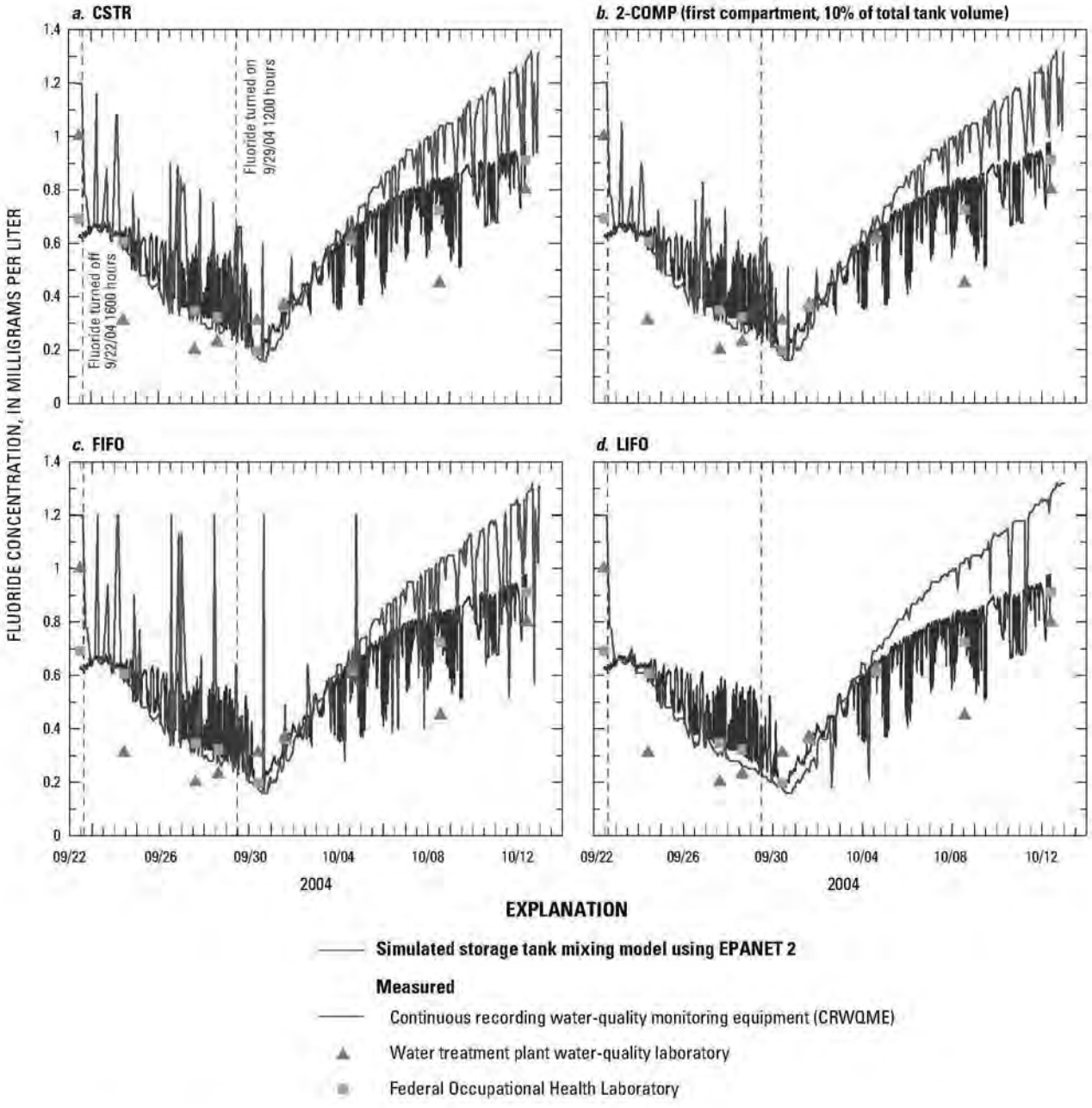



**Figure I12.** Storage-tank mixing model simulated fluoride concentrations and measured data for storage tank SM-623 (Camp Johnson elevated): *(a)* complete mixing (CSTR), *(b)* two-compartment (2-COMP), *(c)* first-in, first-out plug flow (FIFO), and *(d)* last-in, first-out plug flow (LIFO), September 22–October 12, 2004, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Refer to Figure I9 for location of storage tank SM-623]

For the Holcomb Boulevard water-distribution system, simulation results compared with measured data for controlling tank S-2323 (Paradise Point tank, monitoring location F08; Figure I9) are shown in Figure I13. The four graphs also show EPANET 2 simulations using the four mixing model types and measured fluoride tracer data. The same hydraulic and water-quality time and storage-tank parameters used for the Tarawa Terrace simulation were used for the Holcomb Boulevard simulation.

The sensitivity analysis results shown in Figures I12 and I13, using the EPANET 2 results comparing the four storage-tank models—CSTR, 2-COMP, FIFO, and LIFO—with measured data indicate that the choice of mixing model does make a difference. For example, at both elevated storage tanks (SM-623 and S-2323), the FIFO model results show very sharp "spikes" indicating—unrealistically—that mixing is not occurring during the simulation. Alternatively, the LIFO models seem to "dampen out" the fluctuations in

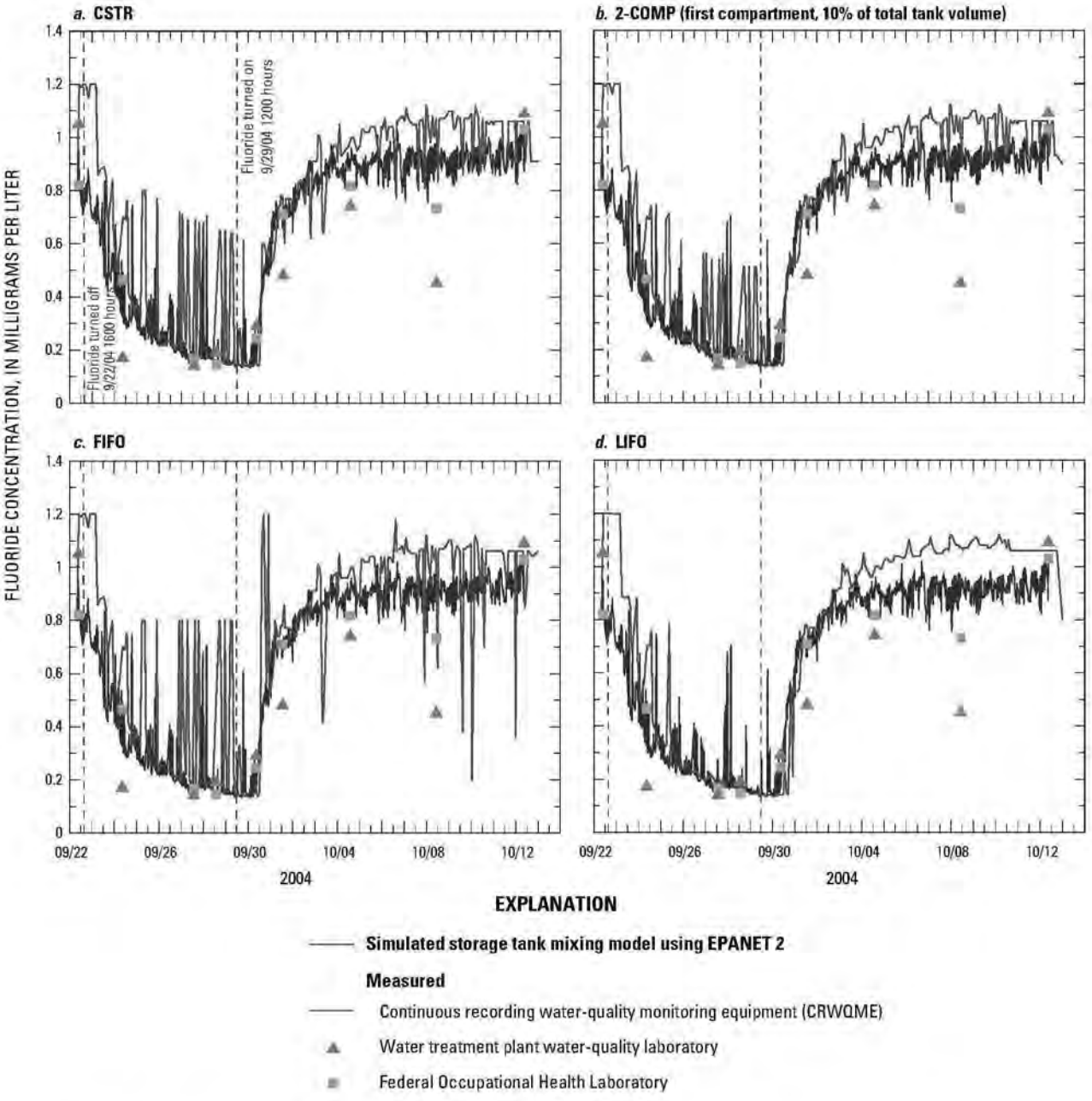



**Figure I13.** Storage-tank mixing model simulated fluoride concentrations and measured data for storage tank S-2323 (Paradise Point elevated): *(a)* complete mixing (CSTR), *(b)* two-compartment (2-COMP), *(c)* first-in first-out plug flow (FIFO), and *(d)* last-in first-out plug flow (LIFO), September 22–October 12, 2004, Holcomb Boulevard water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Refer to Figure I9 for location of storage tank S-2323]

fluoride concentration. Based on these analyses and recorded and measured data, the LIFO storage-tank mixing model was used to represent storage-tank mixing in the calibrated Tarawa Terrace and Holcomb Boulevard water-distribution systems.

Finally, comparison of simulation results and CRWQME data at both of the aforementioned elevated storage tanks indicate that better overall matches are achieved for the Paradise Point storage tank (S-2323, location F08 in Figure I9) than for the Camp Johnson storage tank (SM-623, location F09 in Figure I9). One reason may be the water-quality dynamics associated with the monitoring location identified as the source condition for each water-distribution system. Monitoring data for the Holcomb Boulevard source (location F01 in Figure I9) indicate a significantly sharper front than do data for the Tarawa Terrace source (location F02 in Figure I9), which are characterized by a more subdued and attenuated concentration (fluoride tracer) front.

## Parameter Estimation and Sensitivity Analysis Using PEST

Numerous methods have been developed to assess the sensitivity of a model to a set of input parameters. Examples of such approaches are the one-at-a-time approach, which is used for testing sensitivity of groundwater-flow and contaminant fate and transport model input parameters, and the alternative conceptual model approach, which is used to assess the effect of selecting different storage-tank model conceptualizations for water-distribution systems. Another method for estimating and assessing the sensitivity of model parameters is referred to as linear and nonlinear parameter estimation. This approach allows for more complex parameterizations than would be possible using trial-and-error calibration and the one-at-a-time sensitivity analysis. Additional information describing linear and nonlinear parameter estimation is provided in Cooley (1977, 1979, 1985) and Hill and Tiedman (2007). One of the most advanced parameter estimation packages (models) available for environmental simulation is called PEST—an acronym for Parameter ESTimation (Doherty 2005). The advantage of using this modeling package is that PEST, a nonlinear parameter estimator, exists independently of any specific model (for example, EPANET 2, MODFLOW-96, or MT3DMS), yet can be used to estimate parameters of interest for any model whether it is a simple analytical model or a complex numerical code. PEST accomplishes this by taking control of an existing model code (for example, EPANET 2) and running it many times until an optimal set of parameters is obtained that minimizes the differences between model-generated numbers and corresponding measured data (for example, simulated and measured hydraulic head). Thus, PEST was chosen to assist with the calibration and sensitivity analysis of parameters contained in the EPANET 2 model that was applied to the Tarawa Terrace and Holcomb Boulevard water-distribution systems. Details relative to parameter values and the calibration procedure for the EPANET 2 model applied to the Tarawa Terrace and Holcomb Boulevard water-distribution system are provided in Chapter J of the Tarawa Terrace report series (Sautner et al. In press 2009).

Two groups of model input parameters were analyzed using the PEST code: (1) pipe material roughness coefficients (C-factors) and (2) demand-pattern factors. PEST, in combination with EPANET 2, was used to assess which parameters required adjustment during the calibration process and to automate the calibration of the water-distribution models for Tarawa Terrace and Holcomb Boulevard (instead of using a manual trial-and-error method for model calibration). The objective function minimized by PEST is the sum of the squared differences between measured and simulated storage-tank hydraulic head. Definitions of the aforementioned model input parameters and of hydraulic head are provided below.

- Pipe material roughness coefficient (C-factor)—also known as the Hazen-Williams C-factor; represents a pipe carrying capacity. Higher C-factors represent smoother pipes (for example, polyvinyl chloride [PVC]), and lower C-factors represent rougher pipes (for example, cast iron [CI]) (Walski et al. 2001).
- Demand-pattern factor—a set of multipliers that scale base demand (consumption) distributed at locations throughout the water-distribution system network (Boulos et al. 2006). For a 24-hour diurnal pattern, a demand-pattern factor is generally assigned to each hour of the 24-hour pattern.
- Storage-tank hydraulic head—the sum of the water level in a storage tank and the elevation of the bottom of the storage tank. Water levels in storage tanks are recorded at certain time intervals (for example, 15 min), most often using a supervisory control and data acquisition (SCADA) system. Thus, as part of the calibration process for the water-distribution system model, an attempt is made to minimize the difference between measured and simulated storage-tank hydraulic head.

The PEST model requires three types of input files: (1) template files, identified with the suffix *ptf*, (2) instruction files, identified with the suffix *pinsf*, and (3) a control file, identified with the suffix *pst*. Using these three file types, PEST generates additional files during the course of a simulation. All of these files are provided on the compact disc read-only memory (CD–ROM) containing the PEST files for the Tarawa Terrace and Holcomb Boulevard simulations included with this report. For details pertaining to the construction of the PEST file types and running the PEST model, readers should refer to the PEST users manual (Doherty 2005).

Pipe material roughness coefficient, or Hazen-Williams C-factor value, varies depending on parameters and conditions such as pipe material, age, roughness, and diameter. Typical values for C-factors are provided in numerous water-distribution system modeling texts such as Walski (1992) and Cesario (1995). For the Tarawa Terrace and Holcomb Boulevard water-distribution systems, initial C-factor values for CI and PVC pipes were estimated as 94 and 145, respectively (Table I9). These values were obtained from typical C-factor values provided in Walski (1992) and Cesario (1995) for CI and PVC pipe. The result of the PEST simulation produced similar C-factor values for CI and PVC pipe of 83 and 149, respectively (Table I9). The PEST analysis for C-factor also indicates that the water-distribution system model is relatively insensitive to C-factor, with PEST-computed sensitivities in the range of $10^{-4}$ to $10^{-5}$. The *RMS* of hydraulic head difference also was computed by PEST using measured water levels from storage tank STT-40. In this situation, the *RMS* was computed to be 0.06 ft using initial C-factor values and also using values derived from the PEST analysis. Based on the small PEST-computed sensitivities and no change in *RMS* of hydraulic head difference, the initial estimates for values of C-factor—94 for CI pipe and 145 for PVC pipe—were used in all EPANET 2 model simulations.

The PEST results summarized in Table I9 also indicate that the model is about an order of magnitude more sensitive

**Table I9.** Initial estimates and PEST-derived C-factor values, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[C-factor, pipe material roughness coefficient]

| Pipe material | C-factor (initial estimate)[1] | PEST-derived values[2] | | | |
|---|---|---|---|---|---|
| | | C-factor | 95-percent confidence interval | Sensitivity | Relative sensitivity |
| Cast iron (CI) | 94 | 83 | 78–88 | $5.365 \times 10^{-5}$ | $4.442 \times 10^{-3}$ |
| Polyvinyl chloride (PVC) | 145 | 149 | 147–151 | $1.564 \times 10^{-4}$ | $2.335 \times 10^{-2}$ |

[1]Inital C-factor values derived from water-balance analysis and values described in Walski (1992) and Cesario (1995) for CI and PVC pipes

[2]See PEST Users Manual (Doherty 2005) for details pertaining to use and implementation of the PEST model

to C-factor value for pipes constructed of PVC than for pipes constructed of CI—computed relative sensitivities of about $2.3 \times 10^{-2}$ for PVC pipe C-factor and about $4.4 \times 10^{-3}$ for CI pipe C-factor. To further emphasize this finding, a series of simulations were conducted for the Tarawa Terrace water-distribution system using C-factors for PVC pipe that varied from 120 to 180, while keeping the C-factor for CI pipe constant at a value of 94. Another series of simulations were conducted using C-factors for CI pipe that varied from 70 to 120, while keeping the C-factor for PVC pipe constant at a value of 145.[21] Results of these simulations are shown in Figure I14 by plotting C-factor value versus the sum of hydraulic head difference squared for storage tank STT-40. These results clearly demonstrate that the water-distribution system model is significantly more sensitive to changes in PVC pipe C-factor value than to changes in CI pipe C-factor value. For the Tarawa Terrace water-distribution system, total length of PVC pipe is 179,747 ft compared with a total length of CI pipe of 79,405 ft.

The Tarawa Terrace and Holcomb Boulevard water-distribution system models were initially constructed using a single (or global) demand pattern that was determined from a water-balance analysis derived from information and data contained in a water-conservation analysis conducted by ECG, Inc. (1999). Examples of the initial estimated demand factors for a 4-day period—September 23–26, 2004—from a tracer test conducted September 22–October 12, 2004, are shown in Figure I15.[22] A complete hourly listing of the numerical values of the initial demand-pattern factors for the duration of the tracer test (September 22–October 12, 2004) is provided in Appendix I2. PEST was used to derive optimized demand-pattern factors using information and data from the aforementioned tracer test of the Tarawa Terrace and Holcomb Boulevard water-distribution systems. To derive the optimized demand-pattern factors, measured water levels in storage tanks STT-40, S-830, S-2323, and LCH-4004 (Figure I9) were obtained from the Camp Lejeune SCADA system. These water levels were used to compute hydraulic heads from which comparisons were made against simulated hydraulic heads (Figure I16). Simulated hydraulic heads were derived by using the EPANET 2 water-distribution system modeling software.

In PEST, the objective function to be minimized is the sum of the squared differences between measured and simulated hydraulic head. Table I10 lists the *RMS* and correlation coefficient for simulated hydraulic heads derived from the water-balance analysis and from PEST for the four aforementioned storage tanks. Overall, the PEST-derived

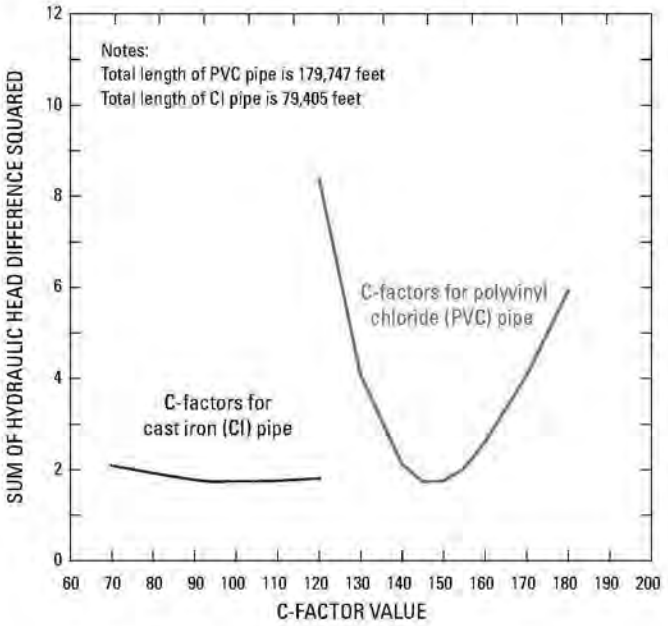



**Figure I14.** Sensitivity of hydraulic head to C-factor value at storage tank STT-40, Tarawa Terrace water-distribution system, U.S. Marine Corps Base Camp Lejeune, North Carolina. [See Figure I9 for storage tank location]

[21] This is another example of the application of the one-at-a-time design sensitivity analysis (Saltelli 2000), previously presented. In this application, however, the one-at-a-time sensitivity analysis was automated by using the PEST model.

[22] The examples provided in this discussion are derived from a fluoride tracer test of the Holcomb Boulevard and Tarawa Terrace water-distribution systems that was conducted September 22–October 12, 2004. Refer to the Chapter J report (Sautner et al. In press 2009) for details relative to the tracer test.

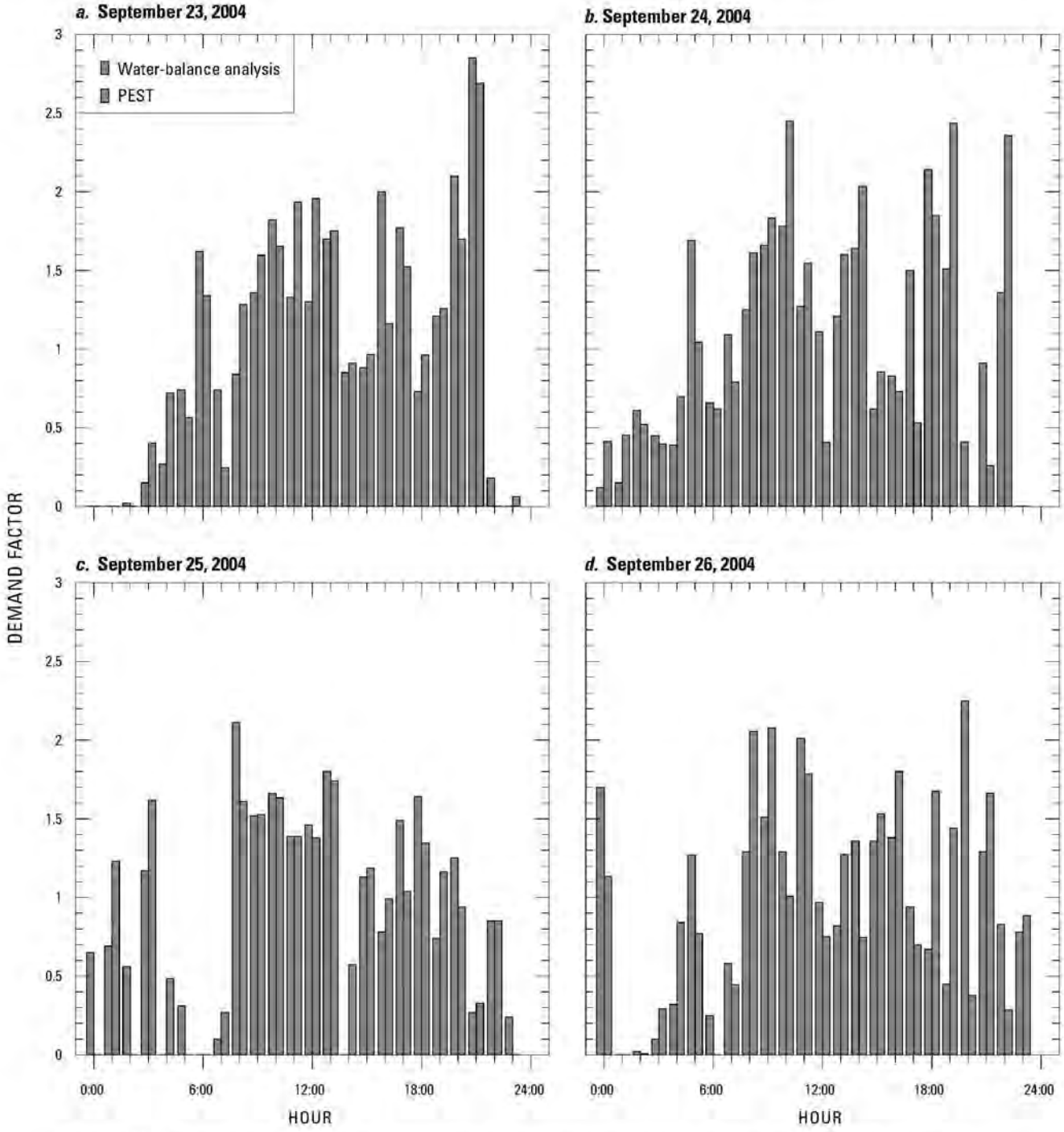



**Figure I15.** Demand-pattern factors estimated from water-balance analysis and derived from PEST simulation, September 23–26, 2004, Tarawa Terrace and Holcomb Boulevard water-distribution systems, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PEST, parameter estimation model developed by Doherty (2005); missing bar indicates demand factor value of 0.0]

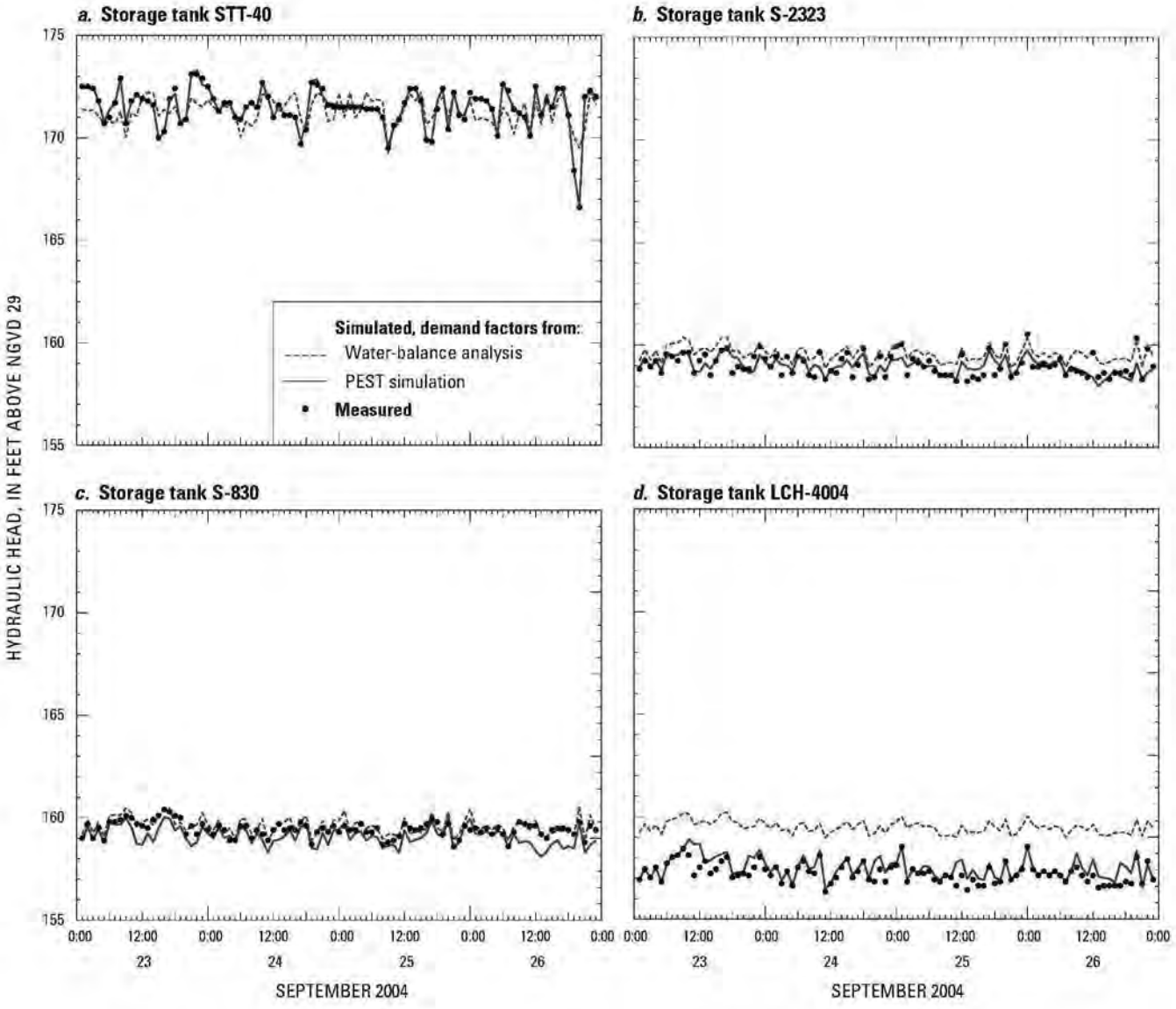



**Figure I16.** Measured and simulated hydraulic head for storage tanks: *(a)* STT-40, *(b)* S-2323, *(c)* S-830, and *(d)* LCH-4004, September 23–26, 2004, Tarawa Terrace and Holcomb Boulevard water-distribution systems, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PEST, parameter estimation model developed by Doherty (2005); NGVD 29, National Geodetic Vertical Datum of 1929; see Figure I9 for storage tank locations]

demand-pattern factors resulted in lower *RMS* values, greater correlation coefficients (Table I10), and closer matches between measured and simulated hydraulic heads in the storage tanks (Figure I16). For storage tanks STT-40, S-2323, and LCH-4004, the PEST-derived demand-pattern factors (Figure I15) result in much closer agreement between measured and simulated hydraulic head than do the initial demand-pattern factors. At storage tank S-830, little improvement is seen between measured and simulated hydraulic head, regardless of the choice of demand-pattern factor—initial or PEST-derived (Figure I16).

In summary, therefore, the PEST-derived demand-pattern factors were used as input for EPANET 2 in constructing the calibrated Tarawa Terrace and Holcomb Boulevard water-distribution system models (Sautner et al. In press 2009). The EPANET 2 input files and typical PEST input and simulation files are also provided on the CD–ROM included with this report.

**Table I10.** Root-mean-square and correlation coefficient for varying demand factors, Tarawa Terrace and Holcomb Boulevard water-distribution systems, U.S. Marine Corps Base Camp Lejeune, North Carolina.

| [2]Storage-tank identification | [1]Source of demand factors | | | |
|---|---|---|---|---|
| | Water-balance analysis | | PEST simulation | |
| | [3]Root-mean-square of hydraulic head difference, in feet | Correlation coefficient | [3]Root-mean-square of hydraulic head difference, in feet | Correlation coefficient |
| Tarawa Terrace water-distribution system | | | | |
| STT-40 | 0.70 | 0.63 | 0.06 | 0.99 |
| Holcomb Boulevard water-distribution system | | | | |
| S-2323 | 0.57 | 0.82 | 0.41 | 0.63 |
| S-830 | 0.34 | 0.80 | 0.43 | 0.70 |
| LCH-4004 | 2.22 | 0.79 | 0.35 | 0.83 |

[1] Water-balance analysis derived from information and data contained in the water-conservation analysis conducted by ECG, Inc. (1999); PEST, parameter estimation model developed by Doherty (2005)

[2] See Figure I9 for storage-tank locations

[3] Root-mean-square of difference between measured hydraulic head in storage tank derived from SCADA (supervisory control and data acquisition) system data and EPANET 2 simulated hydraulic head in storage tank

## Probabilistic Analysis of Groundwater Flow and Contaminant Fate and Transport

A probabilistic analysis can be defined as an analysis in which frequency or probability distributions are assigned to represent uncertainty or variability in model parameters; the output of a probabilistic analysis is a probability distribution (Cullen and Frey 1999). A probabilistic analysis is used to generate uncertainties in model inputs (for example, hydraulic conductivity or contaminant-source mass-loading rate) in order to estimate uncertainties of model outputs (for example, water level or PCE concentration in groundwater). Although the sensitivity analyses provide some insight into the relative importance of selected model parameters, a probabilistic analysis provides a quantitative range and likelihood (probability) of model outputs. Probabilistic analysis is frequently used to understand and quantify variability and uncertainty of model output (Cullen and Frey 1999). Several methods are available for conducting a probabilistic analysis (that is, for propagating distributions or the moments of distributions through models) and those most commonly used are listed in Table I11. These methods are grouped as follows: (1) analytical solutions for moments, (2) analytical solutions for distributions, (3) approximation methods for moments, and (4) numerical methods. The probabilistic analysis used to characterize uncertainty and variability of Tarawa Terrace model output is a numerical method—Monte Carlo (MC) simulation. General and theoretical discussions of probabilistic analysis methods, and in particular MC simulation, are found in U.S. Environmental Protection Agency (USEPA; 1997), Deutsch and Journel (1998), Cullen and Frey (1999), Zhang (2002), Doherty (2005), and Tung and Yen (2005).

It is important to understand the conceptual difference between the deterministic modeling analysis approach used to calibrate model parameter values, described in Faye and Valenzuela (2007) and Faye (2008), and a probabilistic analysis. As described in Maslia and Aral (2004), with respect to the approach referred to as a deterministic modeling analysis, single-point values are specified for model input parameters and results are obtained in terms of single-valued output, for example, the concentration of PCE. This approach is shown conceptually in Figure I17*a*. In a probabilistic analysis, input parameters (all or a selected subset) of a particular model (for example, contaminant fate and transport) are characterized in terms of statistical distributions that can be generated using the MC simulation method (USEPA 1997, Tung and Yen 2005) or a sequential Gaussian (SG) simulation method (Deutsch and Journel 1998, Doherty 2005). Results are obtained in terms of distributed-value output that can be used to assess model uncertainty and parameter variability as part of the probabilistic analysis (Figure I17*b*).

MC simulation is a computer-based (numerical) method of analysis that uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model (USEPA 1997). The MC simulation method is used to simulate probability density functions (PDFs). PDFs are mathematical functions that express the probability of a random variable (variant or model input) falling within some

**Table I11.** Classification of common probabilistic methods for propagating moments of distributions through models.[1]

| |
|---|
| **Analytical Solutions for Moments** |
| Central limit theorems |
| Properties of the mean and variance |
| **Analytical Solutions for Distributions** |
| Transformation of variables |
| **Approximation Methods for Moments** |
| First-order methods |
| Taylor series expansions |
| **Numerical Methods** |
| Monte Carlo simulation |
| Latin hypercube sampling |
| Importance sampling |
| Fourier amplitude sensitivity test |
| Others |

[1]From Cullen and Frey (1999)

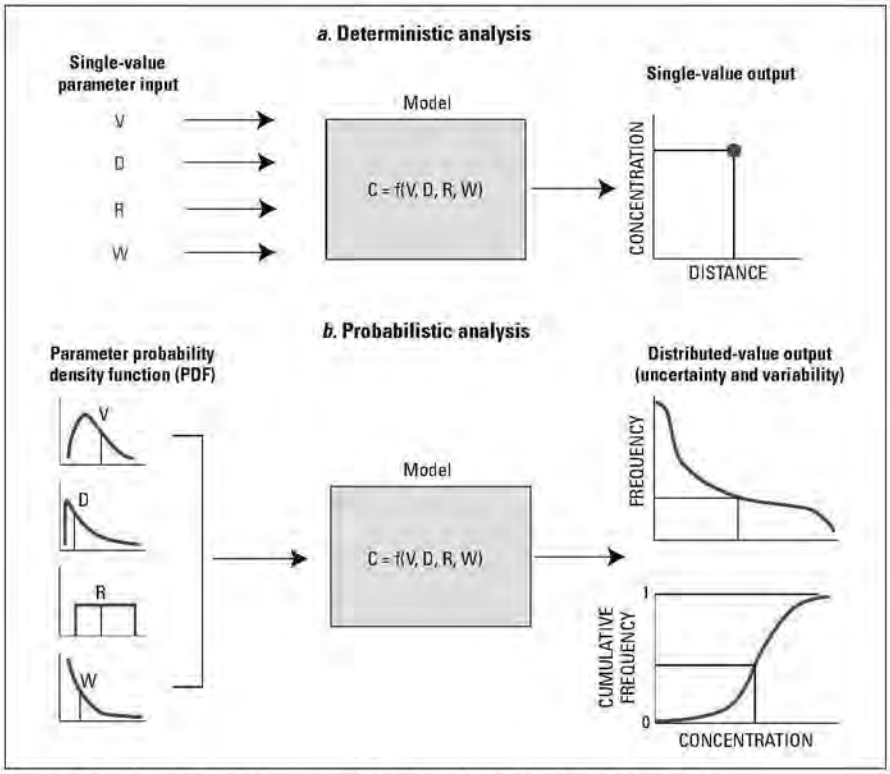



**Figure I17.** Conceptual framework for *(a)* a deterministic analysis and *(b)* a probabilistic analysis (from Maslia and Aral 2004).

interval. SG simulation is a process in which a field of values (such as horizontal hydraulic conductivity) is obtained multiple times, assuming the spatially interpolated values follow a Gaussian (normal) distribution. Additional details pertaining to the SG simulation methodology are provided in Deutsch and Journel (1998) and Doherty (2005).

The process used to incorporate MC and SG simulation into the Tarawa Terrace groundwater-flow and contaminant fate and transport models is shown in Figure I18. Monte Carlo analysis was used in a two-stage approach. In stage 1, random values were generated to approximate the PDF of a model's input parameter (for example, infiltration). In stage 2, the model was run (for example, MT3DMS) using input values generated during stage 1. The MC simulation procedure shown in Figure I18 can be explained as follows.

1. Select the most sensitive and uncertain parameters to be included in the probabilistic analysis (Monte Carlo analysis) using results from the sensitivity analyses.
2. Generate statistically defined random values for uncertain input parameters (variants) of the groundwater-flow and contaminant fate and transport models using pseudo-random number generators (PRNGs). Examples are PDFs for infiltration and longitudinal dispersivity and random fields of horizontal hydraulic conductivity generated using SG simulation. Each set of uncertain parameter values is referred to as a realization.
3. Run the groundwater-flow model (MODFLOW-2000) code[23] for each realization using a filter to discard physically implausible realizations. The filter compares the potentiometric head values for 13 Tarawa Terrace water-supply wells and 16 other locations of interest against specific model criteria—dry wells and potentiometric heads. Simulations that do not meet these criteria are discarded. Table I12 lists the criteria used by the filter to identify physically implausible solutions.
4. If the MODFLOW-2000 simulation is physically plausible (that is, a simulation that is not discarded by the filter), then run the contaminant fate and transport model (MT3DMS).

[23] MODFLOW-96 was the code used in Faye and Valenzuela (2007) to calibrate the Tarawa Terrace groundwater-flow model. Because of programming requirements associated with conducting the MC simulation, it was programmatically more efficient to use the MODFLOW-2000 model code (Harbaugh et al. 2000). MODFLOW-2000, developed by the U.S. Geological Survey, is an updated version of the MODFLOW-96 model code. Model parameter values for MODFLOW-2000 were identical and equivalent to the calibrated model parameter values derived using MODFLOW-96 (Table I2; Faye and Valenzuela 2007). Groundwater-flow simulation results were identical for both MODFLOW-96 and MODFLOW-2000.

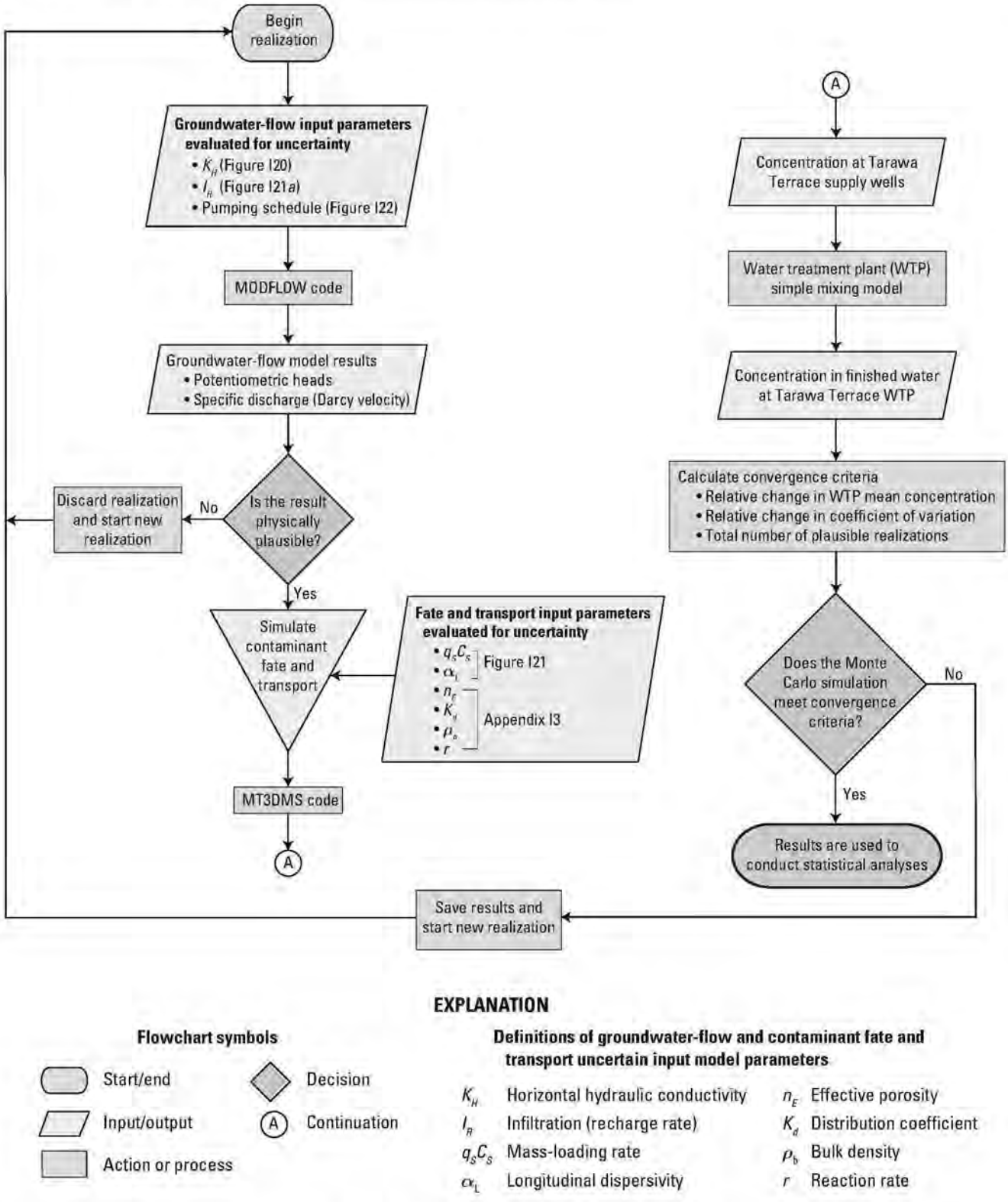



**Figure I18.** Flowchart for incorporating Monte Carlo simulation into groundwater-flow and contaminant fate and transport models, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

**Table I12.** Identification of water-supply wells, control points, and criteria used to determine physically implausible realizations for Monte Carlo simulations of groundwater-flow and contaminant fate and transport, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929]

| Site name | Groundwater-flow model location[1] | | | Criteria for a physically implausible solution |
|---|---|---|---|---|
| | Layer | Row | Column | |
| Water-supply wells | | | | |
| TT-23 | 3 | 84 | 175 | |
| TT-25 | 3 | 67 | 194 | |
| TT-26 | 3 | 61 | 184 | |
| TT-27 | 3 | 52 | 135 | |
| TT-28 | 3 | 47 | 96 | |
| TT-29 | 3 | 41 | 61 | Water-supply well goes dry for any stress period; simulation is halted. |
| TT-30 | 3 | 47 | 97 | |
| TT-31 | 1 | 104 | 152 | |
| TT-52 | 1 | 101 | 136 | |
| TT-53 | 1 | 81 | 151 | |
| TT-54 | 1 | 106 | 167 | |
| TT-55 | 1 | 53 | 136 | |
| TT-67 | 3 | 93 | 158 | |
| Control points | | | | |
| CP-1 | 1 | 12 | 108 | |
| CP-2 | 1 | 78 | 61 | |
| CP-3 | 1 | 83 | 96 | |
| CP-4 | 1 | 74 | 119 | |
| CP-5 | 1 | 111 | 61 | |
| CP-6 | 1 | 120 | 38 | |
| CP-7 | 1 | 111 | 91 | Potentiometric head is less than 24 ft below (–24 ft) or greater than 28 ft above (+28 ft) NGVD 29; simulation is halted. |
| CP 8 | 1 | 134 | 69 | |
| CP-9 | 1 | 166 | 81 | |
| CP-10 | 1 | 141 | 122 | |
| CP-11 | 1 | 137 | 154 | |
| CP-12 | 1 | 132 | 190 | |
| CP-13 | 1 | 112 | 213 | |
| CP-14 | 1 | 97 | 198 | |
| CP-15 | 1 | 75 | 237 | |
| CP-16 | 1 | 46 | 159 | |

[1]Refer to Faye and Valenzuela (2007) for details describing groundwater-flow model grid

5. Extract model-simulated concentrations at Tarawa Terrace water-supply wells and use these concentrations with a simple mixing model (Maslia et al. 2007, Faye 2008) to obtain the concentration in finished water at the Tarawa Terrace WTP.
6. Compute statistics of arithmetic mean ($\overline{C}$), standard deviation ($\sigma_C$), and coefficient of variation of change ($C_v$) in the finished water concentration at Tarawa Terrace WTP for every new realization.
7. If computed statistics in Step 6 indicate less than a 0.25% change (between two successive realizations) and the total number of physically plausible realizations exceeds 500 realizations, the MC simulation has converged and the process is stopped; otherwise, begin a new realization.

Step 6 lists three statistical quantities—the arithmetic mean ($\overline{C}$), standard deviation ($\sigma_C$), and coefficient of variation ($C_v$)—that are used in step 7 to compute stopping criteria for the MC simulation process. These statistics all use and reference the simulated PCE concentration in finished water at the Tarawa Terrace WTP. The mathematical formulae defining these statistical metrics and the formulae used to compute changes in the three statistical quantities for comparison with the MC simulation stopping criteria are listed in Table I13.

In Step 7, convergence is defined as the point where it is reasonable to assume that samples are truly representative of the underlying stationary distribution (Cowles and Carlin 1996). At the converging point, the output distributions do not change markedly by including additional samples. Some metrics usually used as a measure of convergence are sample mean versus true mean, skewness, percentile probabilities, or other statistics (Palisade 2008). For the Tarawa Terrace MC simulations, convergence criteria were needed to determine when the number of samples (realizations) sufficiently represented the underlying distribution. It is important to note, however, that results of an MC simulation do not directly provide a distribution, but rather, a sample of the distribution (Cowles and Carlin 1996).

The MC simulation procedure shown in Figure I18 and described above was incorporated into the Tarawa Terrace groundwater-flow and contaminant fate and transport models using a series of customized computer codes. A description of these codes and how they were implemented in the MC simulation process follows.

1. Subroutines from the IMSL™ FORTRAN numerical libraries (IMSL 2003) were used to generate the PRNG for model input parameter PDFs (for example, PDFs for infiltration, mass-loading rate, etc.).
2. FIELDGEN (Doherty 2005), a computer code developed for conducting SG simulation, was used to generate multiple realizations of the horizontal hydraulic conductivity fields for model layers 1, 3, and 5.
3. A customized FORTRAN 77 code, compiled using the Absoft® (2005) FORTRAN compiler, was developed to generate values from input parameter PDFs and the random horizontal hydraulic conductivity field in the required model input format for the groundwater-flow (MODFLOW-2000) and contaminant fate and transport (MT3DMS) models.

Simulations were conducted using six Dell Precision 690 workstations configured with Windows® XP Professional x64 edition operating system and 8 gigabytes of random access memory. For the Tarawa Terrace models, two sets of probabilistic analyses were conducted: (1) MC simulations excluding pumping schedule uncertainty and (2) MC simulations including pumping schedule uncertainty (Figure I2).

**Table I13.** Mathematical formulae and definitions of metrics used to compute stopping criteria for Monte Carlo simulations, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; WTP, water treatment plant; PCE, tetrachloroethylene]

| Metric name and symbol | Mathematical formula | Definition of variables |
|---|---|---|
| Arithmetic mean of concentration, $\overline{C}$, in µg/L | $\overline{C} = \frac{\sum_{i=1}^{N_{SP}} C_i^{WTP}}{N_{SP}}$ | $C_i^{WTP}$ = finished water concentration of PCE at the WTP for stress period $i$;<br>$N_{SP}$ = number of stress periods[1] |
| Relative change in arithmetic mean of concentration, $\Delta\overline{C}$, in percent | $\Delta\overline{C} = \frac{\frac{\sum_{j=2}^{N_R} \overline{C_j}}{j} - \frac{\sum_{j=2}^{N_R} \overline{C_{j-1}}}{j-1}}{\frac{\sum_{j=2}^{N_R} \overline{C_{j-1}}}{j-1}} \times 100\%$ | $\overline{C_j}$ = arithmetic mean of concentration for realization $j$;<br>$N_R$ = number of Monte Carlo realizations |
| Standard deviation of concentration, $\sigma_C$, in µg/L | $\sigma_C = \left[\frac{\sum_{i=1}^{N_{SP}} \left(C_i^{WTP} - \overline{C}\right)^2}{N_{SP} - 1}\right]^{1/2}$ | $C_i^{WTP}$ = finished water concentration at the WTP for stress period $i$;<br>$\overline{C}$ = arithmetic mean of concentration<br>$N_{SP}$ = number of stress periods[1] |
| Relative change in standard deviation of concentration, $\Delta\sigma_C$, in percent | $\Delta\sigma_C = \frac{\frac{\sum_{j=2}^{N_R} \sigma_{C,j}}{j} - \frac{\sum_{j=2}^{N_R} \sigma_{C,j-1}}{j-1}}{\frac{\sum_{j=2}^{N_R} \sigma_{C,j-1}}{j-1}} \times 100\%$ | $\sigma_{C,j}$ = standard deviation of concentration for realization $j$;<br>$N_R$ = number of Monte Carlo realizations |
| Coefficient of variation of concentration, $C_v$ | $C_v = \sigma_C / \overline{C}$ | $\overline{C}$ = arithmetic mean of concentration<br>$\sigma_C$ = standard deviation of concentration |
| Relative change in coefficient of variation, $\Delta C_v$, in percent | $\Delta C_v = \frac{\frac{\sum_{j=2}^{N_R} C_{v,j}}{j} - \frac{\sum_{j=2}^{N_R} C_{v,j-1}}{j-1}}{\frac{\sum_{j=2}^{N_R} C_{v,j-1}}{j-1}} \times 100\%$ | $C_{v,j}$ = coefficient of variation of concentration for realization $j$;<br>$N_R$ = number of Monte Carlo realizations |

[1] The number of stress periods, $N_{SP}$, is 528 (Faye and Valenzuela 2007, Faye 2008)

## Selection of Uncertain Input Parameters

The uncertain model input parameters that were included in MC simulations were selected based on results of the sensitivity analyses described previously (refer to the "Sensitivity Analyses" section of this report). Table I14 lists results for sensitivity analyses expressed in terms of the absolute mean relative change, $\overline{R}$, and the standard deviation of the absolute mean relative change, $\sigma_{\overline{R}}$, computed for model parameters increased and decreased by 10% from calibrated values (refer to Table I5 for mathematical formulae defining $\overline{R}$ and $\sigma_{\overline{R}}$). According to these results, during the period January 1968–January 1985, the two most sensitive groundwater-flow parameters were horizontal hydraulic conductivity ($K_H$) for model layer 1 and infiltration ($I_R$). $K_H$ for model layer 1 was considered sensitive to change because a 10% decrease from its calibrated value resulted in water-supply wells drying out (Table I14). Infiltration ($I_R$) was considered sensitive to change because varying its calibrated value by ±10% resulted in an $\overline{R}$ value of about 9.5% and a $\sigma_{\overline{R}}$ value of about 2%—the maximum values for $\overline{R}$ and $\sigma_{\overline{R}}$ of any of the parameters listed in Table I14. The least sensitive groundwater-flow parameters ($\overline{R} \leq 0.02\%$) were horizontal hydraulic conductivity ($K_H$) for model layer 6, specific yield ($S_y$), and storage coefficient ($S$). For the contaminant fate and transport model input parameters, five of seven fate and transport parameters—bulk density ($\rho_b$), distribution coefficient ($K_d$), effective porosity ($n_E$), mass-loading rate ($q_s C_s$), and reaction rate ($r$)—had $\overline{R}$ values exceeding 2% for changes in calibrated values of ±10%. Based on the aforementioned sensitivity analysis, all model input parameters with computed $\overline{R}$ values exceeding 1% were included as uncertain parameters in the probabilistic analysis. In addition to these model input parameters, $K_H$ for model layers 3 and 5 also was included because $K_H$ is used to derive groundwater velocity which is critical to the simulation of contaminant transport. Longitudinal dispersivity ($\alpha_L$), although showing less sensitivity to change than other fate and transport parameters (Table I14), also was included as an uncertain parameter in the probabilistic analysis because it is a characteristic aquifer property and represents the effect of aquifer heterogeneity on the spreading of a dissolved contaminant mass (Schwartz and Zhang 2003).

As summarized in Chapter A (Maslia et al. 2007) and described in detail in Chapter H (Wang and Aral 2008), pumping schedule variation and uncertainty can cause changes in the arrival times of PCE at water-supply wells and the Tarawa Terrace WTP and, in turn, possibly affect the ensuing epidemiological study. For completeness, therefore, pumpage uncertainty and variation were included in the probabilistic analysis. For the Tarawa Terrace models, two scenarios of MC simulations were conducted. In scenario 1, pumpage was not considered uncertain, and in scenario 2, pumpage was considered uncertain (Figure I2). For the scenario where pumpage was considered an uncertain model parameter (scenario 2), the generation of uncertain and variable pumpage values is described in this report in the section on "Generation of Uncertain Input Parameters."

To summarize, the following 10 model input parameters were considered uncertain and were included in all probabilistic analyses using MC simulation: horizontal hydraulic conductivity ($K_H$) for model layers 1, 3, and 5, infiltration ($I_R$), bulk density ($\rho_b$), longitudinal dispersivity ($\alpha_L$), distribution coefficient ($K_d$), effective porosity ($n_E$), mass-loading rate ($q_s C_s$), and reaction rate ($r$). Calibrated values of pumpage ($Q$) were not varied in one set of MC simulations (scenario 1) and were considered uncertain in a second set of MC simulations (scenario 2).[24]

## Generation of Uncertain Input Parameters

Three procedures were used to generate uncertain model input parameters: (1) SG simulation, used to generate random fields of horizontal hydraulic conductivity, (2) PRNGs, used to generate parameter PDFs (for example, infiltration), and (3) statistical analysis of historical pumping variation, used to generate pumping realizations through the application of MC simulation. The process and procedures used to generate the uncertain input parameters are described below.

### Sequential Gaussian Simulation

SG simulation is a process in which a field of values (such as $K_H$) is obtained multiple times assuming the spatially interpolated values follow a Gaussian (normal) distribution (Deutsch and Journel 1998, Doherty 2005).[25] Because of the availability of field values of $K_H$, spatial distributions of $K_H$ were generated using the SG simulation method. Point values for $K_H$ were derived from aquifer-test analyses described in Faye (2007) and Faye and Valenzuela (2007). A total of 36 $K_H$ values were available for the Tarawa Terrace groundwater-flow model: 13 values for model layer 1; 14 values for model layer 3; and 9 values for model layer 5. Ranges for calibrated $K_H$ values were 12.2–53.4 ft/d for model layer 1, 4.3–20.0 ft/d for model layer 3, and 6.4–9.0 ft/d for model layer 5 (Table I14). The SG simulation method was implemented through the application of the computer code FIELDGEN (Doherty 2005)—a two-dimensional stochastic field generator. The SG simulation method is similar to other interpolating techniques such as kriging (Davis 1973); the distinction is that multiple fields (spatial distributions) of a parameter can be obtained with SG simulation. The SG simulation method can be explained in three steps.

[24] Leakance, defined in PMWIN (Chiang and Kinzelbach 2001) as VCONT, is a function of vertical hydraulic conductivity ($K_z$), which is a scaled factor of $K_H$. Although leakance was not varied or considered uncertain independently, when $K_H$ is uncertain and varied in MC simulations, leakance also varies because it is a function of a scaled value of $K_H$.

[25] The Tarawa Terrace analyses assume the spatially interpolated $K_H$ values follow a Gaussian distribution. Additional research and field data would be required to determine if other statistical distributions could or should be used to describe spatially interpolated field values of $K_H$ and other model parameters.

**Table I14.** Sensitivity analysis metrics used for selecting uncertain parameters for conducting probabilistic analysis, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft/d, foot per day; —, not applicable; d, day; in/yr, inch per year; g/ft³, gram per cubic foot; ft, foot; ft³/g, cubic foot per gram]

| Model parameter[1] | Calibrated value | Ratio of varied to calibrated parameter value | Absolute value of mean relative change ($\overline{R}$), in percent[2, 3] | Standard deviation of mean relative change ($\sigma_{\overline{R}}$), in percent[3] |
|---|---|---|---|---|
| Groundwater-flow model parameters | | | | |
| Horizontal hydraulic conductivity, all layers, $K_H$ (ft/d) | 1.0–53.4 | 0.9 | —[4] | —[4] |
| | | 1.1 | 0.51 | 0.75 |
| Horizontal hydraulic conductivity, layer 1, $K_H$ (ft/d) | 12.2–53.4 | 0.9 | —[4] | — |
| | | 1.1 | 1.13 | 1.32 |
| Horizontal hydraulic conductivity, layer 2, $K_H$ (ft/d) | 1.0 | 0.9 | 0.09 | 0.02 |
| | | 1.1 | 0.08 | 0.01 |
| Horizontal hydraulic conductivity, layer 3, $K_H$ (ft/d) | 4.3–20.0 | 0.9 | 0.40 | 0.29 |
| | | 1.1 | 0.37 | 0.26 |
| Horizontal hydraulic conductivity, layer 4, $K_H$ (ft/d) | 1.0 | 0.9 | 0.27 | 0.04 |
| | | 1.1 | 0.26 | 0.04 |
| Horizontal hydraulic conductivity, layer 5, $K_H$ (ft/d) | 6.4–9.0 | 0.9 | 0.75 | 0.41 |
| | | 1.1 | 0.60 | 0.39 |
| Horizontal hydraulic conductivity, layer 6, $K_H$ (ft/d) | 1.0 | 0.9 | 0.02 | 0.02 |
| | | 1.1 | 0.02 | 0.02 |
| Horizontal hydraulic conductivity, layer 7, $K_H$ (ft/d) | 5.0 | 0.9 | 0.33 | 0.15 |
| | | 1.1 | 0.32 | 0.15 |
| Leakance, $K_Z/d_Z$ (1/d) | $3.6 \times 10^{-3}$–$4.2 \times 10^{-1}$ | 0.9 | 0.87 | 0.39 |
| | | 1.1 | 0.74 | 0.34 |
| Infiltration (recharge), $I_R$ (in/yr) | 6.6–19.3 | 0.9 | 9.59 | 2.06 |
| | | 1.1 | 9.53 | 2.32 |
| Specific yield, $S_y$ | 0.05 | 0.9 | 0.12 | 0.09 |
| | | 1.1 | 0.11 | 0.09 |
| Storage coefficient, $S$ | 4.00E–04 | 0.9 | 0.00 | 0.00 |
| | | 1.1 | 0.01 | 0.00 |
| Contaminant fate and transport model parameters | | | | |
| Bulk density, $\rho_b$ (g/ft³) | 77,112 | 0.9 | 2.05 | 1.47 |
| | | 1.1 | 2.20 | 1.24 |
| Longitudinal dispersivity, $\alpha_L$ (ft) | 25 | 0.9 | 0.32 | 0.26 |
| | | 1.1 | 0.30 | 0.24 |
| Distribution coefficient, $K_d$ (ft³/g) | $5.0 \times 10^{-6}$ | 0.9 | 2.05 | 1.47 |
| | | 1.1 | 2.20 | 1.24 |
| Effective porosity, $n_E$ | 0.2 | 0.9 | 9.11 | 0.95 |
| | | 1.1 | 8.20 | 0.74 |
| Mass-loading rate, $q_s C_s$ (g/d) | 1,200 | 0.9 | 10.00 | 0.00 |
| | | 1.1 | 10.00 | 0.00 |
| Molecular diffusion, $D^*$ (ft²/d) | $8.5 \times 10^{-4}$ | 0.9 | 0.00 | 0.00 |
| | | 1.1 | 0.00 | 0.00 |
| Reaction rate, $r$ (d⁻¹) | $5.0 \times 10^{-4}$ | 0.9 | 7.86 | 0.51 |
| | | 1.1 | 7.22 | 0.42 |

[1]Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[2]Refer to Table I5 for mathematical formula and definition of absolute value of mean relative change, $\overline{R}$, and standard deviation of mean relative change, $\sigma_{\overline{R}}$

[3]Calculated for January 1968–January 1985 (stress periods 205–409), not including periods when water-supply well TT-26 was out of service: July–August 1980 [stress periods 355–356] and January–February 1983 [stress periods 385–386]; TT-26 was permanently taken out of service after January 1985

[4]Water-supply wells simulated as dry for this sensitivity analysis

1. Using conditioning data and kriging, an expected field value and a field standard deviation are determined for a generic point.
2. Using the expected value and standard deviation, a random field value is generated based on the assumption of a Gaussian (normal) probability distribution.
3. Using this new value the same process is repeated for a new location.

To use the SG simulation method that is integrated into FIELDGEN, the structure of the kriging method has to be defined by way of variograms. A variogram, also known as a semivariogram, is a statistically-based (geostatistical), quantitative description of the spatial continuity or roughness of a dataset (Barnes 2003). Variograms for model layers 1, 3, and 5 were obtained and used in FIELDGEN. Initially during model calibration, $K_H$ arrays were developed for the active model domain using the modified Sheperd's method (inverse distance method [Golden Software, Inc. 1999]). The 36 field measurements for $K_H$ (Faye 2007, Faye and Valenzuela 2007) initially were used to generate variograms to apply to FIELDGEN. However, 36 field measurements of $K_H$ alone were insufficient to accomplish the generation of multiple $K_H$ fields representative of the calibrated $K_H$ array; therefore, 100 random $K_H$ values from each model layer were selected as conditioning points. Figure I19 shows the experimental and model variograms used within FIELDGEN. The variograms were constructed using the Surfer® software (Golden Software, Inc. 1999). Using the variograms shown in Figure I19, multiple $K_H$ fields were generated by running FIELDGEN. Figure I20 shows examples of four generations of $K_H$ fields from FIELDGEN for model layer 1. Also shown in Figure I20 are the measured $K_H$ values reported by Faye (2007) and Faye and Valenzuela (2007) for model layer 1. Thus, for each MC realization, when a random field of $K_H$ was required as input to MODFLOW-2000, a spatial distribution, exemplified by the $K_H$ fields shown in Figure I20, was input to the model.

## Pseudo-Random Number Generator

A PRNG is an algorithm for generating a sequence of numbers that approximates the properties of random numbers (Wikipedia 2008). Although not truly random, PRNGs have many significant statistical characteristics in common with true random numbers (Uner 2004); therefore, PRNGs can be used to approximate PDFs. Gaussian (normal) and lognormal PRNGs were used to approximate the PDFs of uncertain groundwater-flow and contaminant fate and transport model input parameters (also referred to as variants). Statistics associated with normal and lognormal PDFs for the uncertain model input parameters, such as the mean, minimum, maximum, and standard deviation, are listed in Table I15. The calibrated value associated with each variant—derived from model calibrations described in the Chapter C (Faye and Valenzuela 2007) and Chapter F reports (Faye 2008)—was assigned as the mean value of the distribution associated with each variant. Examples of PDFs generated for infiltration (recharge rate), mass-loading rate (source concentration), and longitudinal dispersivity compared with the appropriate theoretical distribution are shown in Figure I21. PDFs for all uncertain model input parameters derived from application of the PRNGs ($I_R$, $K_d$, $\rho_b$, $n_E$, $r$, $q_s C_s$, and $\alpha_L$) are shown in Appendix I3. Details describing the generation of uncertain model input parameters using the PRNG method are described below:

**Infiltration** (recharge rate, $I_R$): The PRNG was defined based on the calibrated model approach for assigning infiltration (Faye and Valenzuela 2007). A single value for infiltration was assigned to the uppermost model layer—layer 1—for each simulation year (1951–1994). The arithmetic mean—hereafter referred to as mean—for the Gaussian PRNG was defined as the calibrated recharge rate for each respective year. The range of mean values for infiltration was 6.6–19.3 inches per year (in/yr) (Table I15). The minimum, maximum, and standard deviation values input to the PRNG were 4.4 in/yr, 21.9 in/yr, and 2.2 in/yr, respectively. An example of the infiltration PDF for 1984, derived using the PRNG, is shown in Figure I21*a*. Additional PDFs for infiltration characterizing a dry year (lower recharge) and a wet year (higher recharge) are shown in Appendix I3.

**Distribution coefficient** ($K_d$): For this variant, a Gaussian PRNG was used to assign cell-by-cell values of $K_d$ using a mean value of $5.0\times10^{-6}$ cubic feet per gram ($ft^3/g$). The minimum, maximum, and standard deviation values input to the PRNG were $3.53\times10^{-6}$, $2.68\times10^{-5}$, and $1.77\times10^{-6}$ $ft^3/g$, respectively (Table I15). As a comparison, for PCE in a silt and sand environment, Hoffman (1995) reports a range of values for distribution coefficient of $7.4\times10^{-6}$–$2.7\times10^{-5}$ $ft^3/g$.

**Bulk density** ($\rho_b$): This variant was defined with a Gaussian PRNG and assigned on a cell-by-cell basis using a mean value of 77,112 grams per cubic foot ($g/ft^3$) and a standard deviation of 1,100 $g/ft^3$ (Table I15). The Castle Hayne aquifer system is composed of fine, fossiliferous sand, limestone, and shell limestone (Faye 2007). Densities of silty soils reported by Morris and Johnson (1967) ranged from 69,943 to 79,004 $g/ft^3$. The published range of density values was used to truncate the values obtained from the PRNG to account for silty limestones; that is, these values were used to represent the minimum and maximum values assigned to $\rho_b$.

**Effective porosity** ($n_E$): For this variant, a Gaussian PRNG was used to assign cell-by-cell values of $n_E$ using a mean of 0.2 and a standard deviation of 0.05 (Table I15). For the fine, fossiliferous sand, limestone, and shell limestone of the Castle Hayne aquifer system (Faye 2007), the viable range for $n_E$ was defined with a minimum value of 0.1 and a maximum value of 0.3. Field measurements were not available to determine $n_E$ values in different areas of the model domain. Using the cell-by-cell approach for $n_E$, however, makes the modeling approach consistent because $K_H$ was varied using a cell-by-cell approach, and both $K_H$ and $n_E$ are parameters that are used in the computation of groundwater velocity.

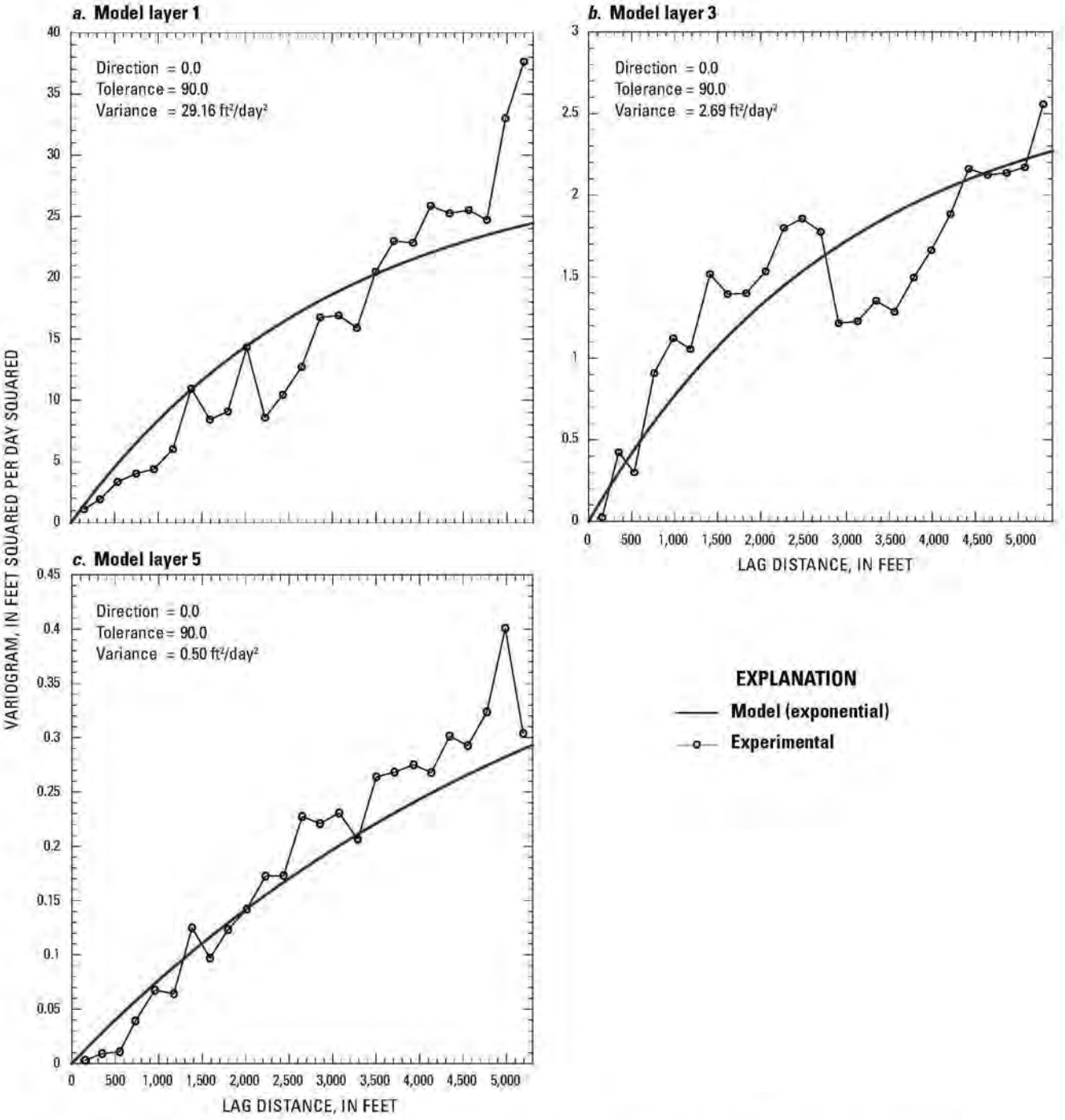



**Figure I19.** Variograms for horizontal hydraulic conductivity ($K_h$) for: *(a)* model layer 1, *(b)* model layer 3, and *(c)* model layer 5, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [ft²/d², feet squared per day squared]

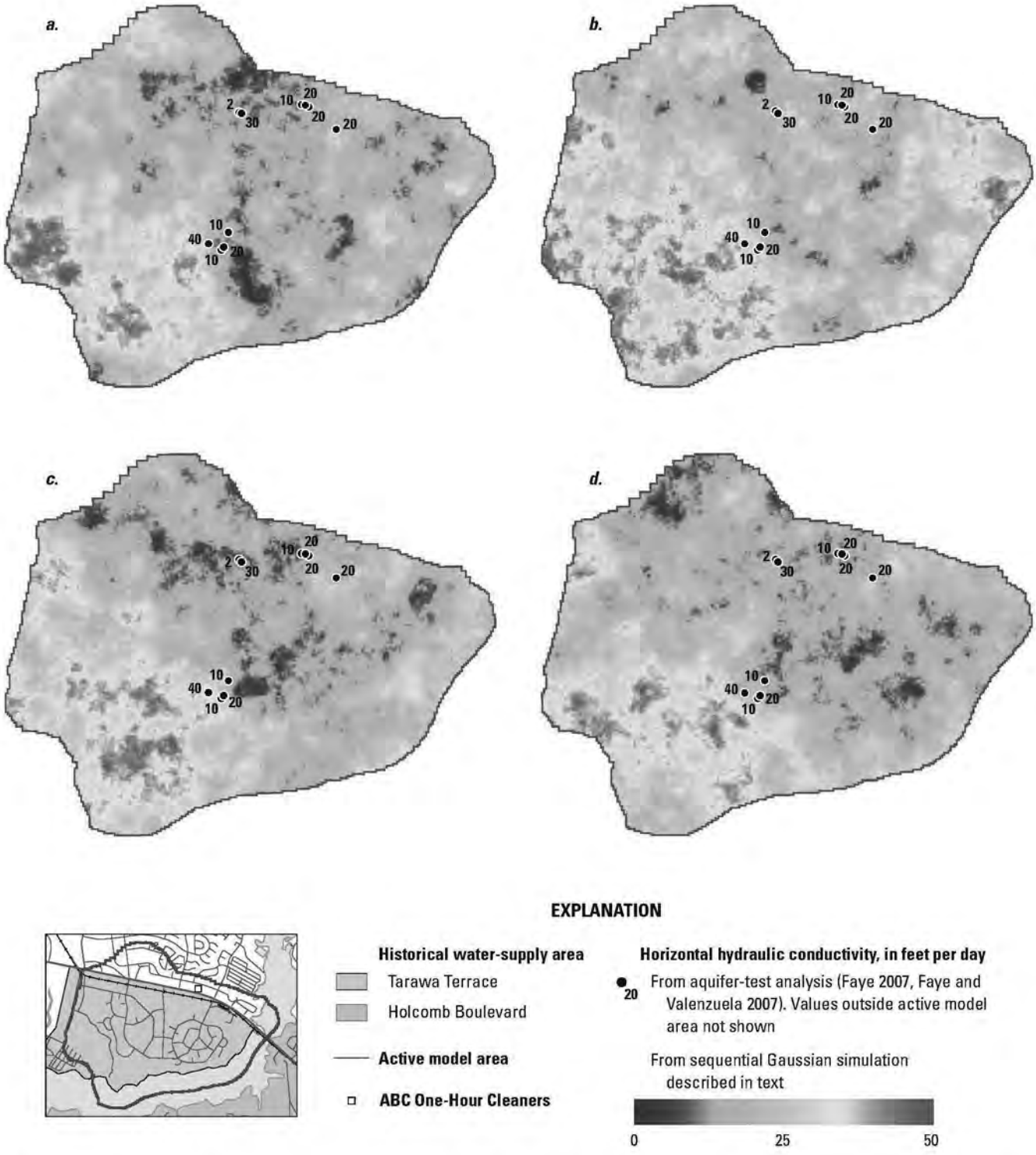



**Figure I20.** Horizontal hydraulic conductivity ($K_H$) fields for model layer 1 obtained from the FIELDGEN program: *(a)* generation 1, *(b)* generation 2, *(c)* generation 3, and *(d)* generation 4, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [FIELDGEN from Doherty (2005); note: all hydraulic conductivity values are greater than 0 and less than 50 feet per day]

**Table I15.** Uncertain input parameters (variants) used in probabilistic analyses, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ft/d, foot per day; —, not applicable; in/yr, inch per year; ft³/g, cubic foot per gram; g/ft³, gram per cubic foot; d, day; g/d, gram per day; ft, foot; SGS, sequential Gaussian simulation; MCS, Monte Carlo simulation; PDF, probability density function; ft³/d, cubic foot per day]

| Model parameter or variant[1,2] | Calibrated value | Statistical descriptions of probabilistic distributions | | | | Method of generating uncertain input parameter | Method of assigning uncertain parameter in models |
|---|---|---|---|---|---|---|---|
| | | Mean | Minimum | Maximum | Standard deviation | | |
| **Groundwater-flow model parameters** | | | | | | | |
| Horizontal hydraulic conductivity, layer 1, $K_H$ (ft/d) | 12.2–53.4 | [3]12.2–53.4 | — | — | — | SGS used to generate random hydraulic conductivity field under a normal distribution[4] | Cell-by-cell distribution |
| Horizontal hydraulic conductivity, layer 3, $K_H$ (ft/d) | 4.3–20.0 | [3]4.3–20.0 | — | — | — | SGS used to generate random hydraulic conductivity field under a normal distribution[4] | Cell-by-cell distribution |
| Horizontal hydraulic conductivity, layer 5, $K_H$ (ft/d) | 6.4–9.0 | [3]6.4–9.0 | — | — | — | SGS used to generate random hydraulic conductivity field under a normal distribution[4] | Cell-by-cell distribution |
| Infiltration (recharge), $I_R$ (in/yr), (ft/d) | 6.6–19.3, $1.5 \times 10^{-3}$–$4.4 \times 10^{-3}$ | 6.6–19.3, $1.5 \times 10^{-3}$–$4.4 \times 10^{-3}$ | 4.4, $1.0 \times 10^{-3}$ | 21.9, $5.0 \times 10^{-3}$ | 2.2, $5.0 \times 10^{-4}$ | MCS used to generate the PDF using a normal distribution; PDF generated for each stress period | Constant value assigned uppermost active cell (model layer 1), varied yearly |
| Pumpage, $Q_K$ (ft³/d) | See footnote 5 | | | | | | |
| **Fate and transport model parameters** | | | | | | | |
| Distribution coefficient, $K_d$ (ft³/g) | $5.0 \times 10^{-6}$ | $5.0 \times 10^{-6}$ | $3.53 \times 10^{-6}$ | $2.68 \times 10^{-5}$ | $1.77 \times 10^{-6}$ | MCS used to generate the PDF using a normal distribution | Cell-by-cell distribution |
| Bulk density, $\rho_b$ (g/ft³) | 77.112 | 77.112 | 69.943 | 79.004 | 1.100 | MCS used to generate the PDF using a normal distribution | Cell-by-cell distribution |
| Effective porosity, $n_E$ | 0.2 | 0.2 | 0.1 | 0.3 | 0.05 | MCS used to generate the PDF using a normal distribution | Cell-by-cell distribution |
| Reaction rate, $r$ ($d^{-1}$) | $5.0 \times 10^{-4}$ | $5.0 \times 10^{-4}$ | $2.30 \times 10^{-4}$ | $7.70 \times 10^{-4}$ | $1.35 \times 10^{-4}$ | MCS used to generate the PDF using a normal distribution | Constant value assigned to entire model |
| Mass-loading rate, $q_S C_S$ (g/d)[5] | 1,200 | 1,200 | 200 | 2,200 | 100 | MCS used to generate the PDF using a normal distribution | Single value assigned to contaminant source cell[6] |
| Longitudinal dispersivity, $\alpha_L$ (ft) | 25 | 3.2189 | 5 | 125 | 0.8047 | MCS used to generate the PDF using a normal distribution[7] | Cell-by-cell spatial distribution |

[1]Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)

[2]Statistical description of pumpage variation is described in the report section "Statistical Analysis of Historical Pumping Variation"

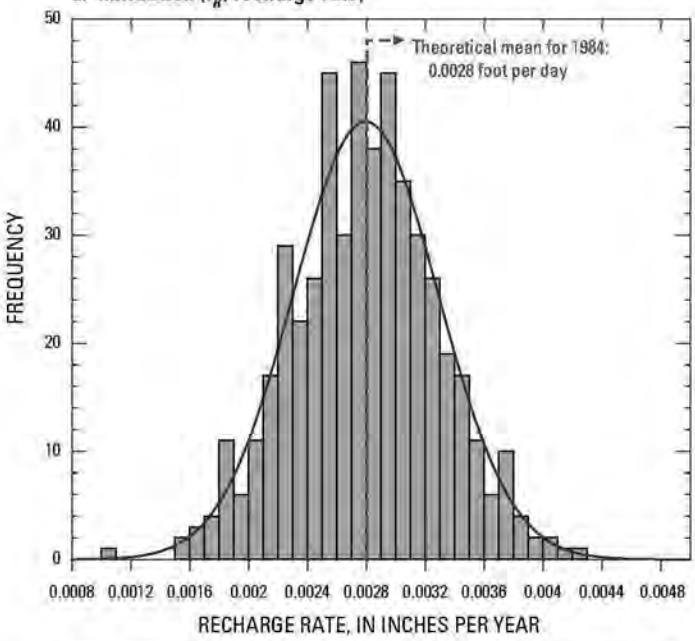
[3]For statistical descriptions of the mean, values were calculated using conditioning data obtained from the calibrated mean values

[4]The FIELDGEN model code described in Doherty (2005) was used to generate the random, spatially varying fields of hydraulic conductivity

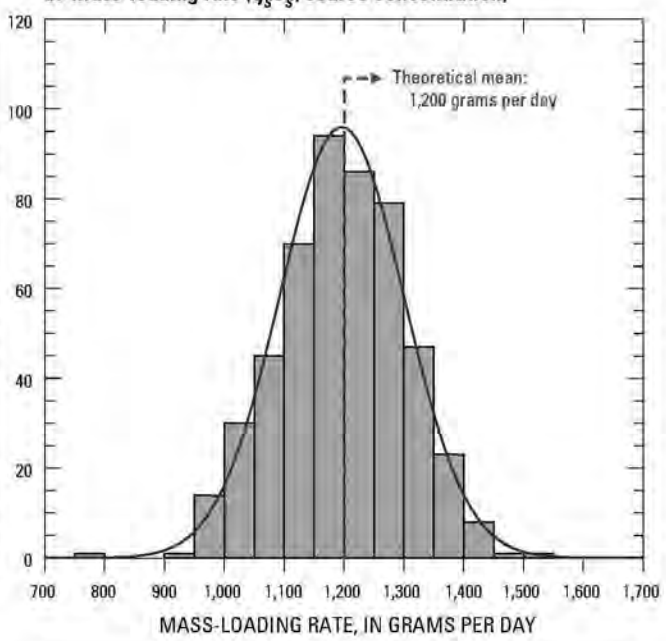
[5]Pumpage varies by month, year, and model layer. Monte Carlo simulation was used to generate monthly pumpage variations based on statistical analyses of historical pumping. This approach is described in detail in the report section "Statistical Analyses of Historical Pumping Variation"

[6]Contaminant source cell is located in model layer 1, row 47, column 170 (Faye 2008)

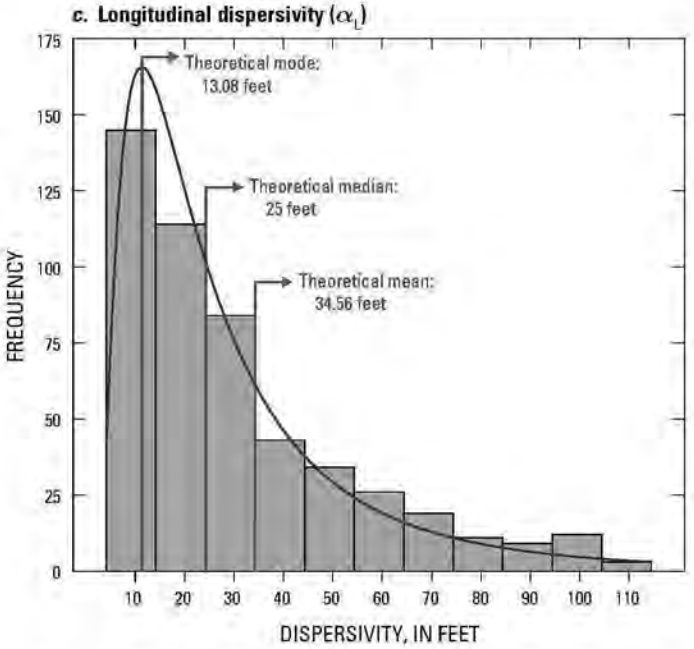
[7]The mean value derived from Ln (25); standard deviation derived from Ln (5)/2, where Ln ( ) is the Naperian logarithm




| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | – Infinity | 0.001 |
| Maximum | + Infinity | 0.005 |
| Mean | 0.00280 | 0.00280 |
| Mode | 0.00280 | 0.00260 |
| Median | 0.00280 | 0.00279 |
| Standard deviation | 0.00050 | 0.00049 |




| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | – Infinity | 200 |
| Maximum | + Infinity | 2,200 |
| Mean | 1,200 | 1,196 |
| Mode | 1,200 | 1,257 |
| Median | 1,200 | 1,198 |
| Standard deviation | 100 | 104.0659 |




| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Lognormal | Lognormal |
| Number of realizations | Not applicable | 500 |
| Minimum | 0 | 5 |
| Maximum | Infinity | 125 |
| Mean | 34.56 | 31.32 |
| Mode | 13.08 | N/A |
| Median | 25 | 23.85 |
| Standard deviation | 32.98 | 23.59 |

**Figure I21.** Probability density functions for *(a)* infiltration ($I_R$, recharge rate), *(b)* mass-loading rate ($q_sC_s$, source concentration), and *(c)* longitudinal dispersivity ($\alpha_L$) used to conduct probabilistic analyses, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [–, minus; +, plus; N/A, not applicable]

**Reaction rate** ($r$): This variant was assigned uniformly—a single value for the entire model—because site information about reaction-driven or reaction-limited zones was not available. Reaction rate values were obtained using a Gaussian PRNG with a mean of $5.0\times10^{-4}$ $d^{-1}$ and a standard deviation of $1.35\times10^{-4}$ $d^{-1}$ (Table I15). The reaction rate range was defined with a minimum value of $2.30\times10^{-4}$ $d^{-1}$ (half-life of 8.3 years) and a maximum value of $7.70\times10^{-4}$ $d^{-1}$ (half-life of 2.5 years). This range corresponds to ±2 times the standard deviation and was selected based on literature values and results from the sensitivity analyses. Howard et al. (1991) reported several values for aerobic and anaerobic biodegradation (that is, reaction rate) ranging from 6 months to 1 year for aerobic half-life and 98 days to 4.5 years for anaerobic half-life. They also report a half-life range for solutes in groundwater of 1–2 years. The reaction rate for the Tarawa Terrace site probably approximates anaerobic conditions; therefore, anaerobic half-life values are more appropriate than aerobic half-life values.

**Mass-loading rate** ($q_sC_s$): This variant was defined with a Gaussian PRNG assuming a month-to-month variation. The $q_sC_s$ value for PCE (the contaminant source) was assigned in the model to the grid cell that corresponded to the location of ABC One-Hour Cleaners' septic tank soil-adsorption system—layer 1, row 47, and column 170 (Faye 2008). The calibrated model used a constant value for $q_sC_s$ of 1,200 g/d that was applied as a continuous contaminant source during stress periods 25–408 (January 1953–December 1984). For the PRNG, the mean and standard deviation were assigned as 1,200 and 100 g/d, respectively (Table I15). Based on mass calculations using a shell methodology described by Pankow and Cherry (1996), a minimum mass-loading rate of about 230 g/d of PCE was calculated (Faye and Green 2007). Thus, a minimum to maximum range of 200–2,200 g/d was used for the PRNG. The PDF for mass-loading rate derived using the PRNG method and a comparison with the theoretical normal distribution are shown in Figure I21*b*.

**Longitudinal dispersivity** ($\alpha_L$): This variant was defined with a log-normal PRNG and assigned in the model on a cell-by-cell basis. Site data for Tarawa Terrace were not available to estimate the range of plausible dispersivity values; however, field studies indicate that dispersivity can vary by orders of magnitude as the length of the plume increases (Gelhar et al. 1992). The calibrated value assigned to $\alpha_L$ is 25 ft as explained in Faye (2008), who also provides a detailed description as to how this value was derived for the Tarawa Terrace area. Because $\alpha_L$ was defined with a log-normal distribution, the mean value for the purposes of the probabilistic analysis is computed as the Naperian logarithm of 25 ft, which is 3.22 ft (Table I15). The minimum, maximum, and standard deviation values assigned to $\alpha_L$ are 5, 125, and 0.8047 ft, respectively, and these values were used to define the PRNG. The PDF for longitudinal dispersivity derived using the PRNG method and a comparison with the theoretical log-normal distribution are shown in Figure I21*c*.

Descriptive statistics for theoretical variants are shown in Figure I21 and in Appendix I3. For each variant, these statistics are compared to PDFs generated using PRNGs and MC simulation. The descriptive statistics for the PRNG-generated values show that 500 realizations (or MC simulations) produce similar statistics when compared with the theoretical statistics for each variant's PDF. For example, the descriptive statistics for mass-loading rate (Figure I21*b*) show a theoretical mean and standard deviation of 1,200 and 100 g/d, respectively. Comparing these values with the mean and standard deviation obtained from the MC simulation of 1,196 and 104 g/d, respectively, indicates that 500 realizations result in a PDF for this variant that is representative of the theoretical PDF for mass-loading rate.

## Statistical Analysis of Historical Pumping Variation

The Chapter H report (Wang and Aral 2008) describes pumping schedule variations that result in different PCE arrival times at Tarawa Terrace water-supply wells and corresponding changes in concentration of PCE in finished water at the Tarawa Terrace WTP. Such variations could affect the results of the epidemiological study. Because historical pumping records are incomplete—pumping dates are recorded for 55 of 528 stress periods (Table I16)—the calibrated Tarawa Terrace models are based on uncertain and variable pumpage quantities. The effect of this uncertainty on modeling results was assessed using probabilistic techniques.

A statistical analysis procedure for analyzing historical pumping schedule variation was developed using available Tarawa Terrace pumpage data (Table I16). Results of the statistical analysis were then incorporated into a probabilistic analysis to account for historical pumping uncertainty (Figure I18). The method for incorporating the statistical analysis results into the MC simulation procedure is shown in a flowchart diagram in Figure I22.

Historical records for total groundwater withdrawals that supplied raw water to the Tarawa Terrace WTP are incomplete for the period covering model simulation (1951–1994). However, nearly complete monthly pumping records are available for 1978, 1980–1981, and 1983–1984 and were obtained from Henry Von Oesen and Associates, Inc. (1979) and various Camp Lejeune water documents (CLW 4436–4483) (Table I16). Using historical monthly pumpage data, ratios of monthly groundwater pumping rates ($Q_{monthly}$) to annual monthly mean pumping rates ($Q_{mean}$) were computed, and these ratios ($Q_{monthly} / Q_{mean}$) are listed in Table I17. The $Q_{monthly} / Q_{mean}$ ratios were computed by dividing monthly total raw water delivered to the Tarawa Terrace WTP ($Q_{monthly}$; monthly entries listed in Table I16) by the annual monthly mean pumping rates ($Q_{mean}$; entries from last row in Table I16). Statistical analyses are summarized in Table I18 using the $Q_{monthly} / Q_{mean}$ ratios listed in Table I17 and also are shown graphically in Figure I23. The results of the statistical analysis indicate that pumping demand is higher in summer and early fall, and these results are representative of a realistic pumping demand pattern for North Carolina (North Carolina Rural Economic Development Center 2006). Note that during the

**Table I16.** Historical record of total monthly raw water (groundwater) delivered to the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[—, data not available]

| Month | Monthly groundwater pumping demand ($Q_{monthly}$), in cubic feet per day[1] | | | | |
|---|---|---|---|---|---|
| | 1978 | 1980 | 1981 | 1983 | 1984 |
| January | 119,674 | 125,086 | 106,089 | 111,644 | 103,463 |
| February | 135,982 | 98,563 | 95,123 | 110,156 | 112,682 |
| March | 108,621 | 112,088 | 109,729 | — | 108,281 |
| April | 119,572 | 91,796 | 114,599 | 118,113 | 111,943 |
| May | 112,722 | 96,054 | 116,780 | 126,212 | 121,114 |
| June | 131,734 | 105,847 | 133,186 | 141,676 | 116,413 |
| July | 128,454 | 121,037 | 128,808 | 137,481 | 111,394 |
| August | 120,174 | 108,078 | 123,805 | 143,216 | 124,077 |
| September | 119,942 | 104,973 | 122,291 | 126,377 | 113,008 |
| October | 135,070 | 99,043 | — | — | 115,538 |
| November | 103,271 | 94,300 | — | 115,952 | 113,775 |
| December | 103,847 | 97,400 | — | 147,365 | 108,211 |
| **Annual total** | **1,439,063** | **1,254,265** | **1,050,410** | **1,278,192** | **1,359,899** |
| **Annual monthly mean ($Q_{mean}$)** | **119,921.9** | **104,522.1** | **116,712.2** | **127,819.2** | **113,324.9** |

[1]1978 data from Henry Von Oesen and Associates, Inc. (1979); 1980–1981 and 1983–1984 data from CLW 4436–4483

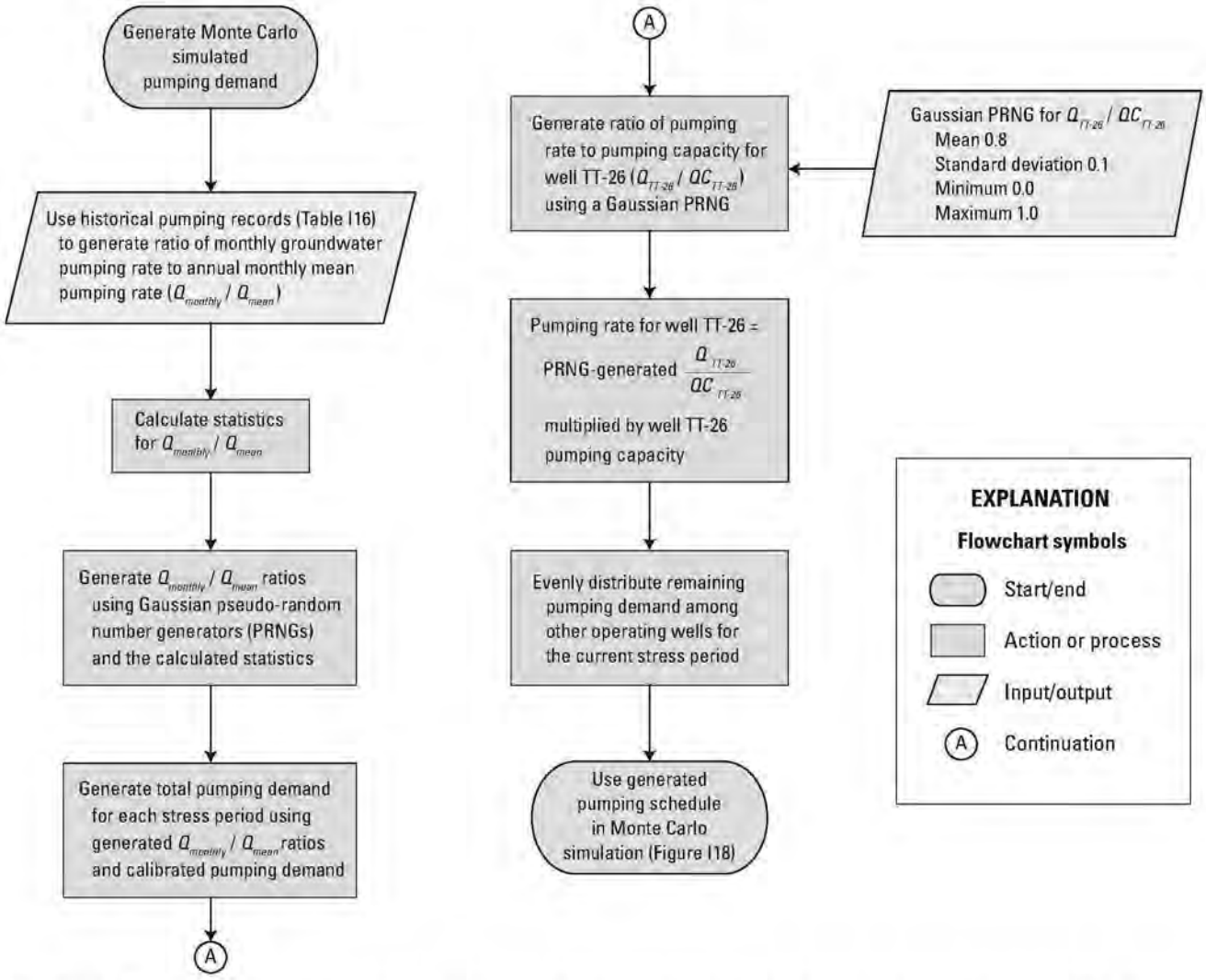



**Figure I22.** Flowchart for incorporating statistical analysis procedure used to assess historical pumping variation into Monte Carlo simulation, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

12-month period shown in Figure I23, the mean value of the delivery of raw water to the Tarawa Terrace WTP (mean value of groundwater pumping demand) is indicated by a value for the ratio $Q_{monthly} / Q_{mean}$ of 1.0. During the months of June–October the yearly mean is exceeded; during the remaining months of the year, the $Q_{monthly} / Q_{mean}$ ratios are equal to or less than the yearly mean.

Results of the statistical analysis summarized in Tables I16–I18 and shown in Figure I23 were used to generate total pumping demand for each stress period (Figure I22) in which pumping occurred (stress periods 13–434 [January 1952–February 1987, respectively]). For each MC simulation, when pumping input data are required (Figure I18), the total pumping demand for 1978, 1980–1981, and 1983–1984 reflects the historical pumping demand data listed in Table I16 (annual total). For all other monthly stress periods, the yearly average pumping demand used for the calibrated model (Faye and Valenzuela 2007) was multiplied by the $Q_{monthly} / Q_{mean}$ ratios for each month of the year. The Gaussian PRNG procedure using the ratio-adjusted monthly pumping rates was then used to generate a pumping-demand schedule. This schedule was characterized with statistical properties of a mean and standard deviation based on the analyses of ratios listed in Table I18 and shown in Figure I23. An example of the statistically generated pumping demand used as input to MODFLOW-2000 for one MC simulation (realization) is shown in Figure I24.

After total pumping demand for each stress period was generated, it was assigned to all operating water-supply wells to create the well-package input data required by MODFLOW-2000.[26] Pumping rates for all operating Tarawa Terrace water-supply wells were calculated in accordance with the following procedure (Figure I22, middle column).

[26] A listing by stress period as to which water-supply wells were operating, for modeling purposes, is provided in the Chapter K report as supplemental information (Maslia et al. In press 2009).

**Table I17.** Ratios of historical monthly groundwater pumping rates to annual monthly mean pumping rates, ($Q_{monthly} / Q_{mean}$), Tarawa Terrace, U.S. Marine Corps Base, Camp Lejeune, North Carolina.

[—, data not available]

| Month | [1]Ratio of monthly groundwater pumping rate to annual monthly mean pumping rate ($Q_{monthly} / Q_{mean}$) | | | | |
|---|---|---|---|---|---|
| | 1978 | 1980 | 1981 | 1983 | 1984 |
| January | 0.997933 | 1.196742 | 0.908979 | 0.873453 | 0.912977 |
| February | 1.133921 | 0.942987 | 0.815022 | 0.861811 | 0.994327 |
| March | 0.905764 | 1.072386 | 0.940167 | — | 0.955492 |
| April | 0.997082 | 0.878245 | 0.981894 | 0.924063 | 0.987806 |
| May | 0.939962 | 0.918983 | 1.000581 | 0.987426 | 1.068732 |
| June | 1.098498 | 1.012676 | 1.141149 | 1.108409 | 1.027250 |
| July | 1.071147 | 1.158004 | 1.103638 | 1.075590 | 0.982961 |
| August | 1.002102 | 1.034021 | 1.060772 | 1.120458 | 1.094878 |
| September | 1.000167 | 1.004314 | 1.047799 | 0.988717 | 0.997203 |
| October | 1.126316 | 0.947580 | — | — | 1.019529 |
| November | 0.861152 | 0.902202 | — | 0.907156 | 1.003972 |
| December | 0.865955 | 0.931860 | — | 1.152918 | 0.954874 |

[1]Ratios of $Q_{monthly} / Q_{mean}$ computed by dividing monthly total raw water delivered to water treatment plant ($Q_{monthly}$) by annual monthly mean ($Q_{mean}$), listed in Table I16

**Table I18.** Statistical analyses of ratios of historical monthly groundwater pumping rates to annual monthly mean pumping rates, ($Q_{monthly} / Q_{mean}$), Tarawa Terrace, U.S. Marine Corps Base, Camp Lejeune, North Carolina.[1]

| Month | [2,3]Ratio of monthly groundwater pumping rate to mean annual monthly pumping rate ($Q_{T\text{-}monthly} / Q_{T\text{-}mean}$) | | | |
|---|---|---|---|---|
| | Mean | Standard deviation | Minimum | Maximum |
| January | 0.978017 | 0.130545 | 0.873453 | 1.196742 |
| February | 0.949614 | 0.124335 | 0.815022 | 1.133921 |
| March | 0.968452 | 0.072342 | 0.905764 | 1.072386 |
| April | 0.953818 | 0.051019 | 0.878245 | 0.997082 |
| May | 0.983137 | 0.058372 | 0.918983 | 1.068732 |
| June | 1.077596 | 0.055169 | 1.012676 | 1.141149 |
| July | 1.078268 | 0.063527 | 0.982961 | 1.158004 |
| August | 1.062446 | 0.047089 | 1.002102 | 1.120458 |
| September | 1.007640 | 0.023166 | 0.988717 | 1.047799 |
| October | 1.031142 | 0.089932 | 0.947580 | 1.126316 |
| November | 0.918620 | 0.060521 | 0.861152 | 1.003972 |
| December | 0.976402 | 0.123563 | 0.865955 | 1.152918 |

[1]Statistical analyses based on pumpage data for years 1978, 1980, 1981, 1983, and 1984—see Table I16.

[2]Ratios of $Q_{monthly} / Q_{mean}$ computed by dividing monthly total raw water delivered to water treatment plant ($Q_{monthly}$) by annual monthly mean ($Q_{mean}$)—see Table I16.

[3]Mean, standard deviation, minimum, and maximum values derived from monthly $Q_{monthly} / Q_{mean}$ ratios—see Table I17.

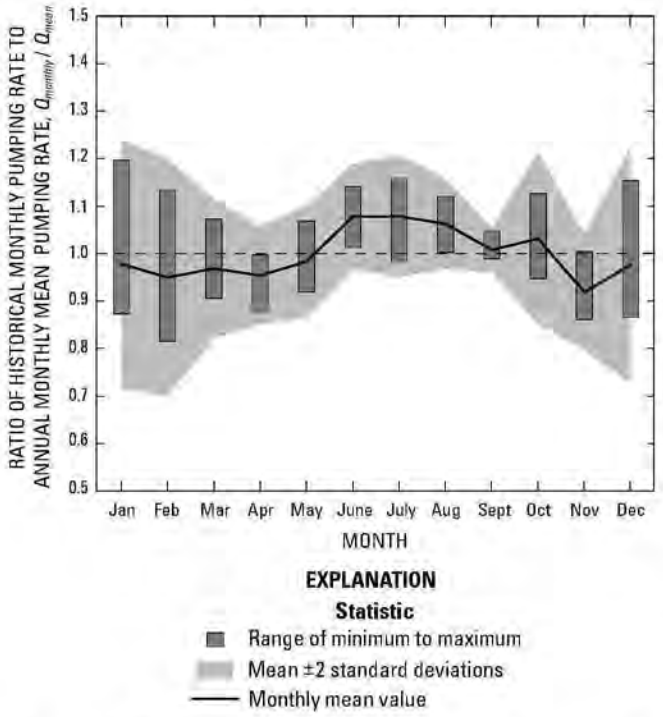



**Figure I23.** Results of statistical analysis of ratios of historical monthly pumping ($Q_{monthly}$) to annual monthly mean pumping ($Q_{mean}$), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [Historical pumpage data sources: Henry Von Oesen and Associates, Inc. 1979; CLW 4436–4483]

1. A pumping rate to pumping capacity ratio for Tarawa Terrace water-supply well TT-26 ($Q_{TT\text{-}26} / QC_{TT\text{-}26}$) was generated using a Gaussian PRNG with a mean of 0.8 and a standard deviation of 0.1. For this ratio, the pumping rate is defined by the variable $Q_{TT\text{-}26}$, and the pumping capacity is defined by the variable $QC_{TT\text{-}26}$. The minimum and maximum values of the ratio are 0.0 and 1.0, respectively. By this definition, water-supply well TT-26 is pumping at approximately 80 percent of its capacity in a statistical sense.

2. The pumping rate assigned to water-supply well TT-26 is calculated using the statistically generated ratio $Q_{TT\text{-}26} / QC_{TT\text{-}26}$ and the known pumping capacity for water-supply well TT-26, which is 150 gallons per minute (Faye and Valenzuela 2007, Table C9).

3. The remaining pumping demand for all other Tarawa Terrace water-supply wells (total pumping demand minus pumping rate in well TT-26) is evenly distributed to all other operating water-supply wells for the stress period in question, based on each respective water-supply well's pumping capacity.

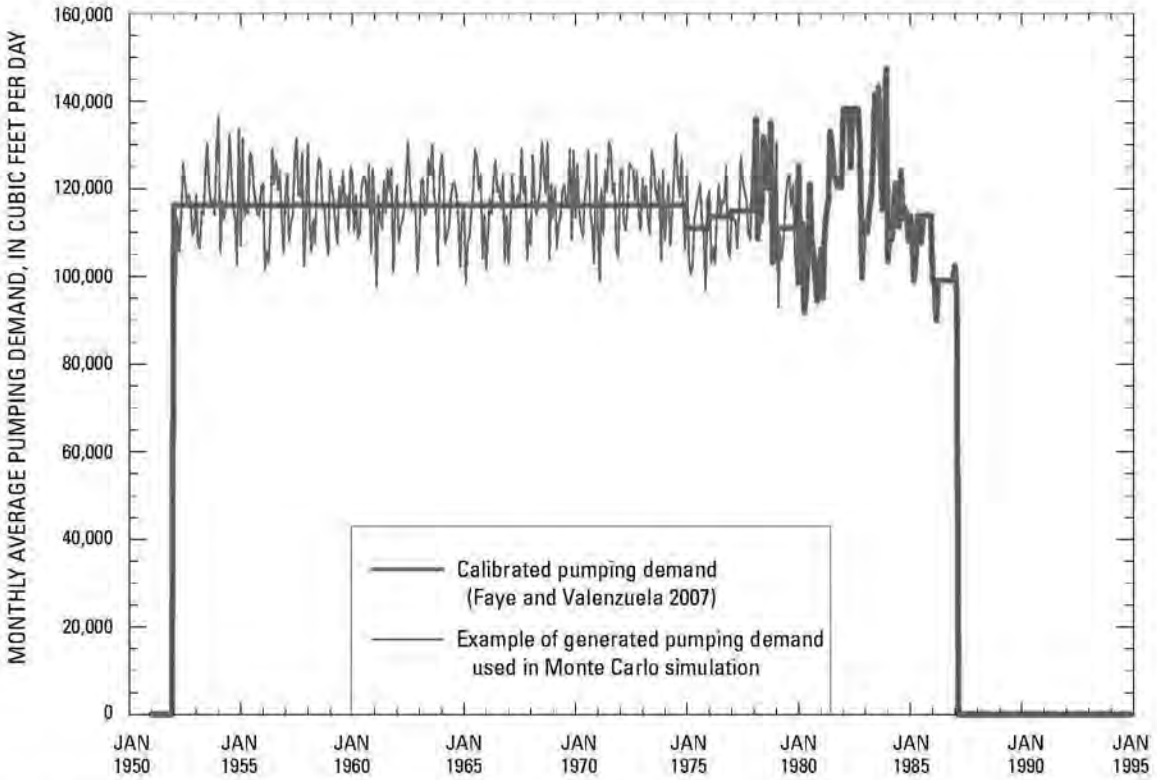
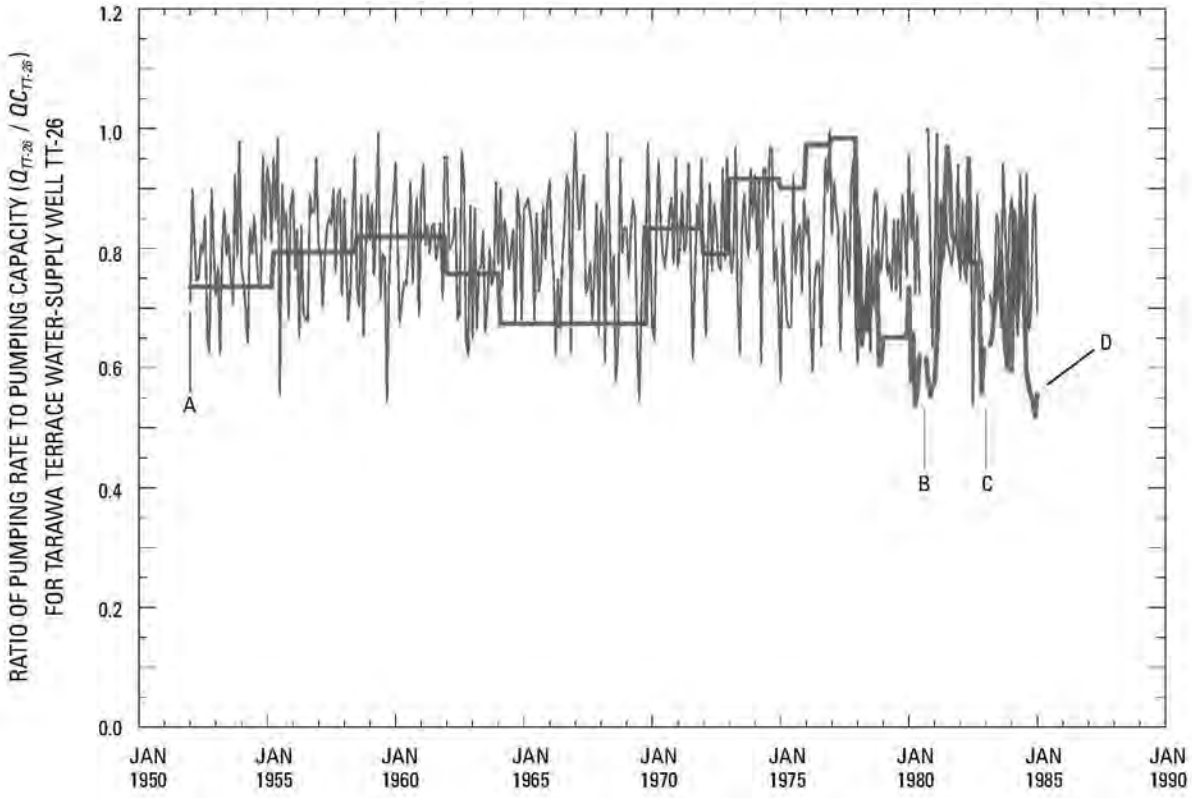



**Figure I24.** Comparison between calibrated pumping demand and Monte Carlo simulation generated pumping demand, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

For the example of water-supply well TT-26, a plot of the ratio $Q_{TT\text{-}26} / QC_{TT\text{-}26}$ versus time is shown in Figure I25. Because the $Q_{TT\text{-}26} / QC_{TT\text{-}26}$ ratio was generated using a PRNG with a mean of 0.8 and a standard deviation of 0.1, the pumping rate in water-supply well TT-26 is close to 80% of its rated capacity in a statistical sense (that is, the mean value), and the rate varies from stress period to stress period. By comparison, for the calibrated model (Faye and Valenzuela 2007), the $Q_{TT\text{-}26} / QC_{TT\text{-}26}$ ratio for water-supply well TT-26 shows a mean of about 77% (Figure I25) and periods of no monthly variation.

In summary, information, data, methods, and analyses have been presented relative to three procedures that were used to generate uncertain input parameters: (1) SG simulation, used to generate random fields of horizontal hydraulic conductivity ($K_H$) (Figure I20); (2) PRNGs, used to generate parameter PDFs for infiltration ($I_R$), distribution coefficient ($K_d$), bulk density ($\rho_b$), effective porosity ($n_E$), reaction rate ($r$), mass-loading rate ($q_s C_s$), and longitudinal dispersivity ($\alpha_L$) (Figure I21 and Appendix I3); and (3) statistical analysis of historical pumping variation used to generate pumping realizations through the application of a Gaussian PRNG and MC simulation (Figures I22 and I25).




**EXPLANATION**

**Simulation**

Calibrated model (Faye and Valenzuela 2007)

Monte Carlo simulation

**Well TT-26 operations**

| | |
|---|---|
| A | January 1952, begin operations |
| B | July–August 1980, not in service |
| C | January–February 1983, not in service |
| D | February 1985, shut down permanently |

**STATISTICS**

| | Calibrated model | Theoretical distribution | Monte Carlo simulation |
|---|---|---|---|
| Number of stress periods | 393 | 393 | 393 |
| Distribution | — | Normal | Normal |
| Mean | 0.7722 | 0.8000 | 0.8008 |
| Standard deviation | 0.1001 | 0.1000 | 0.0963 |

**Figure I25.** Ratio of pumping rate to pumping capacity ($Q_{TT\text{-}26} / QC_{TT\text{-}26}$) for water-supply well TT-26, calibrated model and Monte Carlo simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

## Monte Carlo Simulation

Once the uncertain input parameters (Table I15) were generated as previously described, they were applied sequentially to MODFLOW-2000 and MT3DMS groundwater-flow and contaminant fate and transport models, respectively. This probabilistic analysis process is shown conceptually in Figure I17*b*, and is shown algorithmically in a flow diagram format in Figure I18. Each MC simulation (realization) did not necessarily result in a physically plausible groundwater-flow solution based on constraints assigned to water-supply wells and selected potentiometric heads (Table I12). Realizations not resulting in physically plausible groundwater-flow solutions were discarded, in accordance with the procedure shown in the flowchart diagram (Figure I18).

Two probabilistic MC simulation scenarios were conducted (Figure I2). For scenario 1 (pumping uncertainty excluded), 840 MC simulations were initiated, and 510 realizations were successfully completed, which is a 61% success rate. For scenario 2 (pumping uncertainty included), 700 MC simulations were initiated, and 684 realizations were successfully completed, which is a 98% success rate. Determination of the total number of successful realizations was accomplished through the use of convergence or stopping criteria (Figures I18 and I26).

Three stopping criteria were used to halt the MC simulation: (1) relative change in the arithmetic mean of PCE concentration in finished water at the Tarawa Terrace WTP, $\Delta\overline{C}$; (2) relative change in the standard deviation of PCE concentration in finished water at the Tarawa Terrace WTP, $\Delta\sigma_C$; and (3) relative change in the coefficient of variation of PCE concentration in finished water at the Tarawa Terrace WTP, $\Delta C_V$. Mathematical formulae and definitions of the aforementioned stopping criteria metrics are listed in Table I13. In applying the stopping criteria to the MC simulations, an upper and lower bound of ±0.25% was used for each metric (Figure I26). When the computed relative change ($\Delta\overline{C}$, $\Delta\sigma_C$, and $\Delta C_V$) was within the aforementioned bounds and the total number of realizations was 500 or more, the MC simulation process was halted. As examples, the stopping criteria for each metric for scenario 1 simulations are shown graphically in Figure I26. Thus, for scenario 1—pumping uncertainty excluded—the MC simulations were halted after 510 realizations, and for scenario 2—pumping uncertainty included—the MC simulations were halted after 684 realizations. Results of the MC simulations and interpretation of the probabilistic analysis for each of the two simulation scenarios are discussed in subsequent sections of this report.

## Probability of Occurrence

Probabilistic analysis results derived using MC simulation can be used to compare probabilities of occurrence. These probabilities, in turn, can be used to provide information on the probability of the occurrence of contaminated drinking water at specified concentrations (for example, the MCL). Several methods are available to derive the probabilities—mathematical, tabular, and graphical. The mathematical method refers to the analytical integration of the integral of the probability density function (Appendix I4). Analytical integration can be accomplished by the explicit solution of the integral of the probability density function or through the application of numerical integration techniques (for example, the trapezoidal Riemann sum rule—Appendix I4).

The tabular method was derived prior to the ubiquitous availability and use of computers for mathematical problem solving (for example, integration). This method uses a table of common values, referred to as the standard normal distribution table (Appendix I4). The values in this table were derived from the analytical solution of the integral of the normal probability density function. Details of the application of the tabular method for hydrologic-based problems are provided in Hann (1977). Example calculations of the probability of occurrence using Tarawa Terrace results for the mathematical and tabular methods are presented in Appendix I4.

In the graphical method, a histogram is used to estimate the probability density function. The limiting value of relative frequency or probability is defined as the ordinate value of the histogram for a selected interval or bin (Appendix I4, Figure I4.2*c*). In the ensuing discussion of Tarawa Terrace results, the application of the graphical method is described in detail, and this method is used to estimate probabilities for specific PCE concentrations of finished water at the Tarawa Terrace WTP.

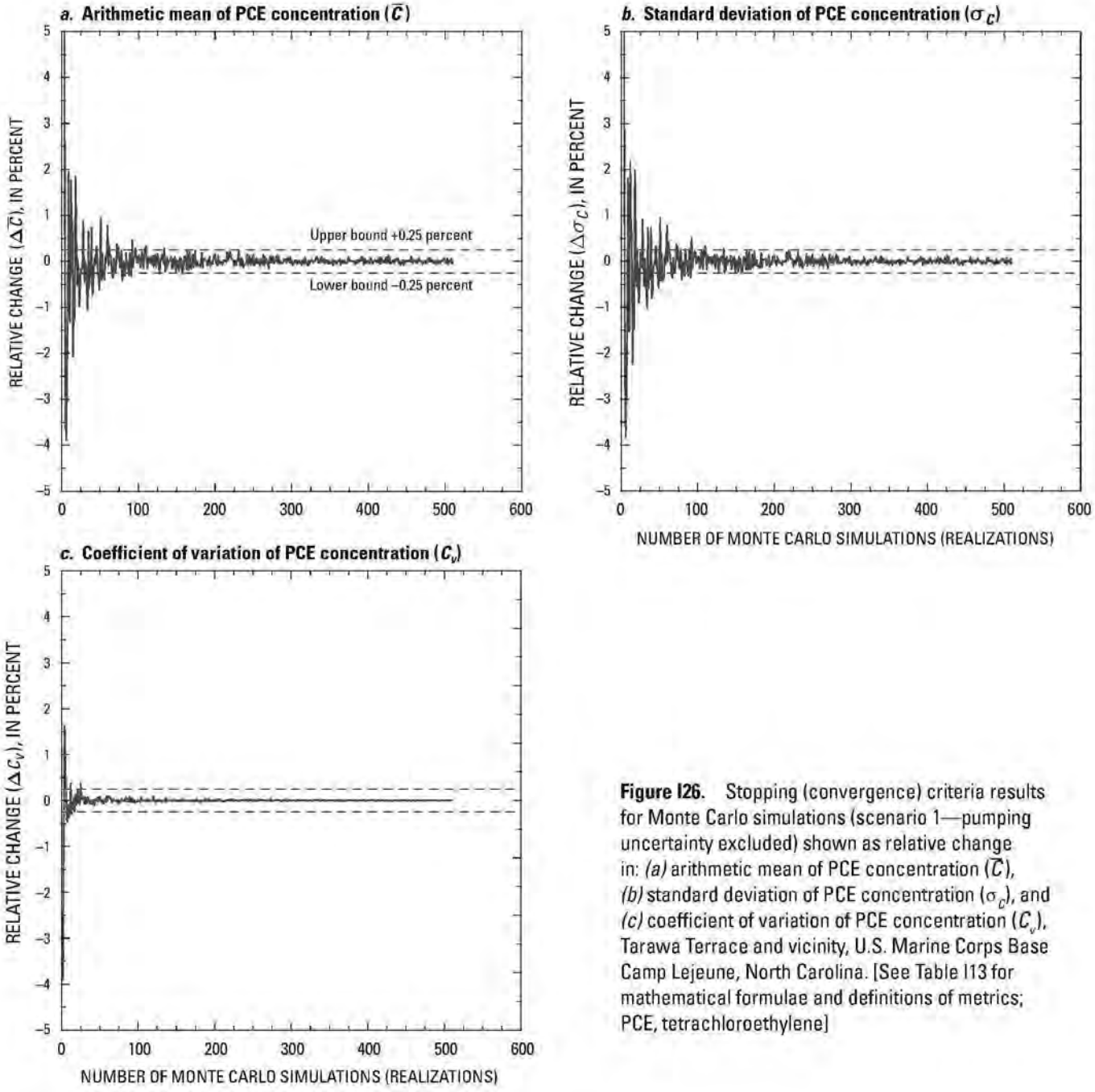



**Figure I26.** Stopping (convergence) criteria results for Monte Carlo simulations (scenario 1—pumping uncertainty excluded) shown as relative change in: *(a)* arithmetic mean of PCE concentration ($\overline{C}$), *(b)* standard deviation of PCE concentration ($\sigma_C$), and *(c)* coefficient of variation of PCE concentration ($C_v$), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina. [See Table I13 for mathematical formulae and definitions of metrics; PCE, tetrachloroethylene]

## Scenario 1: Pumping Uncertainty Excluded

Probabilistic analysis results of PCE concentrations in finished water for the Tarawa Terrace WTP are shown as a series of histograms for selected times: January 1958, January 1968, January 1979, and January 1985 (Figure I27). These histograms show the probability of a range of PCE-concentrations occurring during a specific month and year. For example, the probability of a PCE concentration of about 100 µg/L, occurring in finished water at the Tarawa Terrace WTP during January 1979 can be identified according to the following procedure:

1. Locate the nearest concentration range or bin that includes the 100-µg/L PCE-concentration value along the x-axis of the graph in Figure I27*c* (in this example, the histogram bar between 96 and 105 µg/L).
2. Move vertically upward until intersecting the top of the histogram bar derived from the MC simulation results.
3. Move horizontally to the left until intersecting the y-axis. For this example, the probability is between 14% and 15%.

In this example, the value on the y-axis of Figure I27*c* at the point of intersection—between 14% and 15%—is the probability that finished water at the Tarawa Terrace WTP was contaminated with a PCE concentration of about 100 µg/L during January 1979. This result, obtained using the graphical (histogram) method, is approximately the same as the result obtained using the more exact mathematical or tabular method described in Appendix I4 (13.45% and 13.66%, respectively).

As a comparison, the same procedure described above is used to determine the probability that finished water was contaminated with the same concentration of PCE (100 µg/L) during January 1985 (Figure I27*d*). For this situation, the probability that finished water at the Tarawa Terrace WTP was contaminated with a PCE concentration of about 100 µg/L during January 1985 is determined to be less than 2%. In other words, for conditions occurring during January 1985, a PCE concentration in the range of 100 µg/L is on the lower end (or "tail") of the normal distribution curve (Figure I27*d*).

MC simulation results for scenario 1 for PCE concentrations in finished water at the Tarawa Terrace WTP for all stress periods are listed in Appendix I5. In this appendix, comparisons can be made between the calibrated values reported by Faye (2008)—derived from the deterministic, single-value output—and the distributed-value output considering uncertainty and variability using the probabilistic analysis. In Appendix I5, the $P_{2.5}$, $P_{50}$, and $P_{97.5}$ values represent PCE concentrations in finished water at the Tarawa Terrace WTP for MC simulations at the 2.5 percentile, 50 percentile, and 97.5 percentile, respectively. Three points are noteworthy:

1. Because the calibrated parameter values were used as the mean values for input parameter PDFs and all input parameters were characterized by a normal (Gaussian) distribution except for $\alpha_L$ (Table I15), the 50 percentile or $P_{50}$ values of simulated PCE concentration are close in value to the calibrated PCE concentration values.
2. The range of PCE concentrations for 95% of the MC simulations can be determined by subtracting the simulated concentration for $P_{2.5}$ from the simulated concentration for $P_{97.5}$. For example, during January 1968, the PCE concentrations corresponding to $P_{2.5}$ and $P_{97.5}$ for scenario 1 are 38.91 µg/L and 76.43 µg/L, respectively, resulting in a range of 37.52 µg/L. This range is interpreted as representing 95% of all realizations that were simulated during January 1968. Thus, based on a probabilistic analysis, the simulated PCE concentration in finished water at the Tarawa Terrace WTP during January 1968 was about 8 to 15 times greater than the current MCL for PCE of 5 µg/L.
3. Using values reported in Appendix I5, for scenario 1 (pumping uncertainty excluded), 95% of the MC simulations show that the current MCL for PCE of 5 µg/L was first exceeded in finished water at the Tarawa Terrace WTP during the period October 1957–August 1958. These results include November 1957, the date of first exceedance determined from the calibrated contaminant fate and transport model (Faye 2008) that was based on a deterministic approach (single-value parameter input and output).

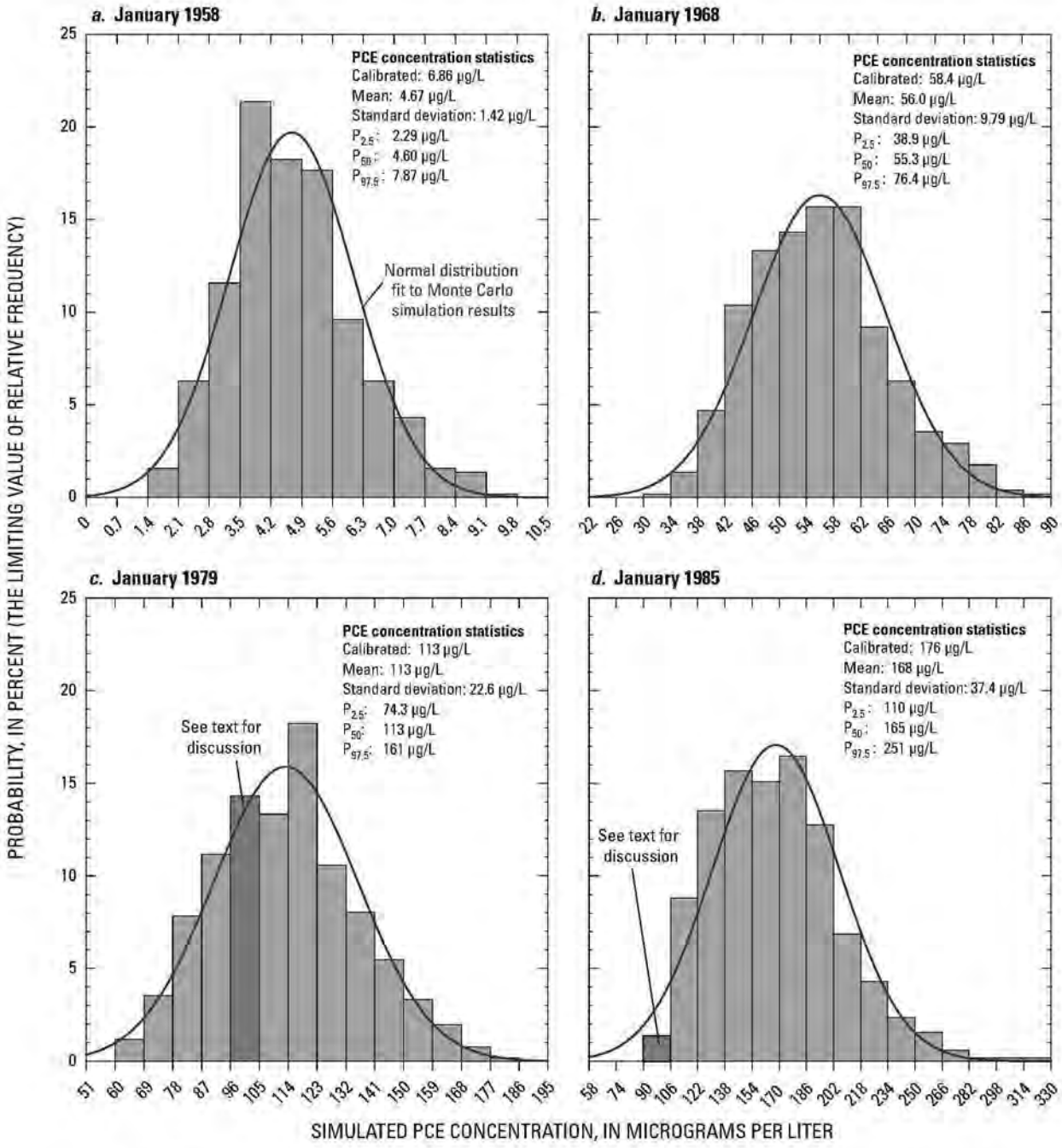



**Figure I27.** Probability of occurrence of tetrachloroethylene contamination in finished water at the water treatment plant derived from scenario 1 (pumping uncertainty excluded) probabilistic analysis using Monte Carlo simulation for *(a)* January 1958, *(b)* January 1968, *(c)* January 1979, and *(d)* January 1985, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L, micrograms per liter; $P_{2.5}$, $P_{50}$, and $P_{97.5}$ concentrations at 2.5, 50, and 97.5 percent, respectively; calibrated concentration from Maslia et al. 2007, Appendix A2]

For purposes of a health study or exposure assessment, epidemiologists and health scientists are interested in the probability that a person or population was exposed to a contaminant exceeding a given health guideline or criteria. An example of this is the probability that residents of Tarawa Terrace were exposed to drinking water contaminated with PCE exceeding the current MCL of 5 µg/L. To address this issue, the MC simulation results previously described can be presented in the form of the complementary cumulative probability function and plotted as a series of probability "type curves" (Figure I28). The complementary cumulative probability function describes the probability of exceeding a certain value, or shows how often a random variable (for example, the concentration of PCE in finished water) is above a certain value. Using results shown in Figure I28, the probability that the PCE concentration in finished water at the Tarawa Terrace WTP exceeded a value of 5 µg/L during January 1958 is determined in the following manner.

1. Locate the probabilistic type curve for January 1958 in Figure I28*a*.
2. Locate the 5-µg/L PCE concentration along the x-axis of the graph in Figure I28*a*.
3. Follow the vertical line until it intersects with the January 1958 complementary cumulative probability function type curve (point A, Figure I28*a*).
4. Follow the horizontal line until it intersects the y-axis—for this example, the probability is 39%.

In this case, the probability is 39% that the PCE concentration in finished water at the Tarawa Terrace WTP exceeded the current MCL of 5 µg/L during January 1958. Because the vertical MCL line does not intersect any other type curves on the graph (Figure I28*a*), the probability of exceeding the MCL for PCE is at least 99.8%, or a near certainty for all years following 1958 until water-supply wells TT-23 and TT-26 were removed from service in February 1985.[27]

Because of contaminated groundwater, water-supply well TT-26 was removed from regular service during February 1985 (Maslia et al. 2007, Table A6). This caused an immediate reduction in the PCE concentration in finished water at the Tarawa Terrace WTP because of the dilution of contaminated WTP water with water from other water-supply wells that were not contaminated or were contaminated with much lower concentrations of PCE than was water-supply well TT-26. As a result, PCE concentrations in finished water at the Tarawa Terrace WTP during February 1985–February 1987 (when the WTP was permanently closed) were significantly reduced compared with January 1985 concentrations (Maslia et al. 2007, Figure A18). Probabilistic type curves representing the complementary cumulative probability function for selected months during January 1985–February 1987 shown in Figure I28*b* also confirm this observation. For example, using the procedure described previously, the probability of exceeding the current MCL for PCE of 5 µg/L during February 1985 is about 10% (point F in Figure I28*b*), compared to a probability of 39% during January 1958 and a probability of greater than 99.8% during January 1985.

The probability type curves shown in Figure I28 also can be used to ascertain uncertainty and variability associated with simulated PCE concentrations in finished water at the Tarawa Terrace WTP. For example, referring to points B and C in Figure I28*a*, during January 1958, there is a 97.5% probability that the concentration of PCE in finished water at the Tarawa Terrace WTP exceeded 2 µg/L (point B), and correspondingly, a 2.5% probability that the concentration exceeded 8 µg/L (point C). Thus, during January 1958, 95% of MC simulation results indicate that the concentration of PCE in finished water at the Tarawa Terrace WTP was in the range of 2–8 µg/L.[28] Stated in terms of uncertainty and variability, during January 1958, the uncertainty is 5% (100% minus 95% of all MC simulation results), and the corresponding variability in PCE concentration in finished water at the Tarawa Terrace WTP is 2–8 µg/L. As a comparison, this same analysis is conducted for January 1968 (points D and E). For simulated conditions existing during January 1968 (the start of the epidemiological case-control study), 95% of MC simulation results indicate that the concentration of PCE in finished water at the Tarawa Terrace WTP was in the range of 40–80 µg/L. Stated in terms of uncertainty and variability, during January 1968, the uncertainty is 5% (100% minus 95% of all MC simulation results), and the corresponding variability in PCE concentration in finished water at the Tarawa Terrace WTP is 40–80 µg/L.

[27] Except for July and August 1980 and January and February 1983 when water-supply well TT-26 was out of service—see Figure A18 in Maslia et al. (2007).

[28] In this example, point B (Figure I28*a*) represents 97.5 percent of Monte Carlo simulations, and point C represents 2.5 percent of Monte Carlo simulations. Thus, the range of results representing 95 percent of Monte Carlo simulations is obtained by subtracting the probability-axis value of point C from point B or 97.5%–2.5%.

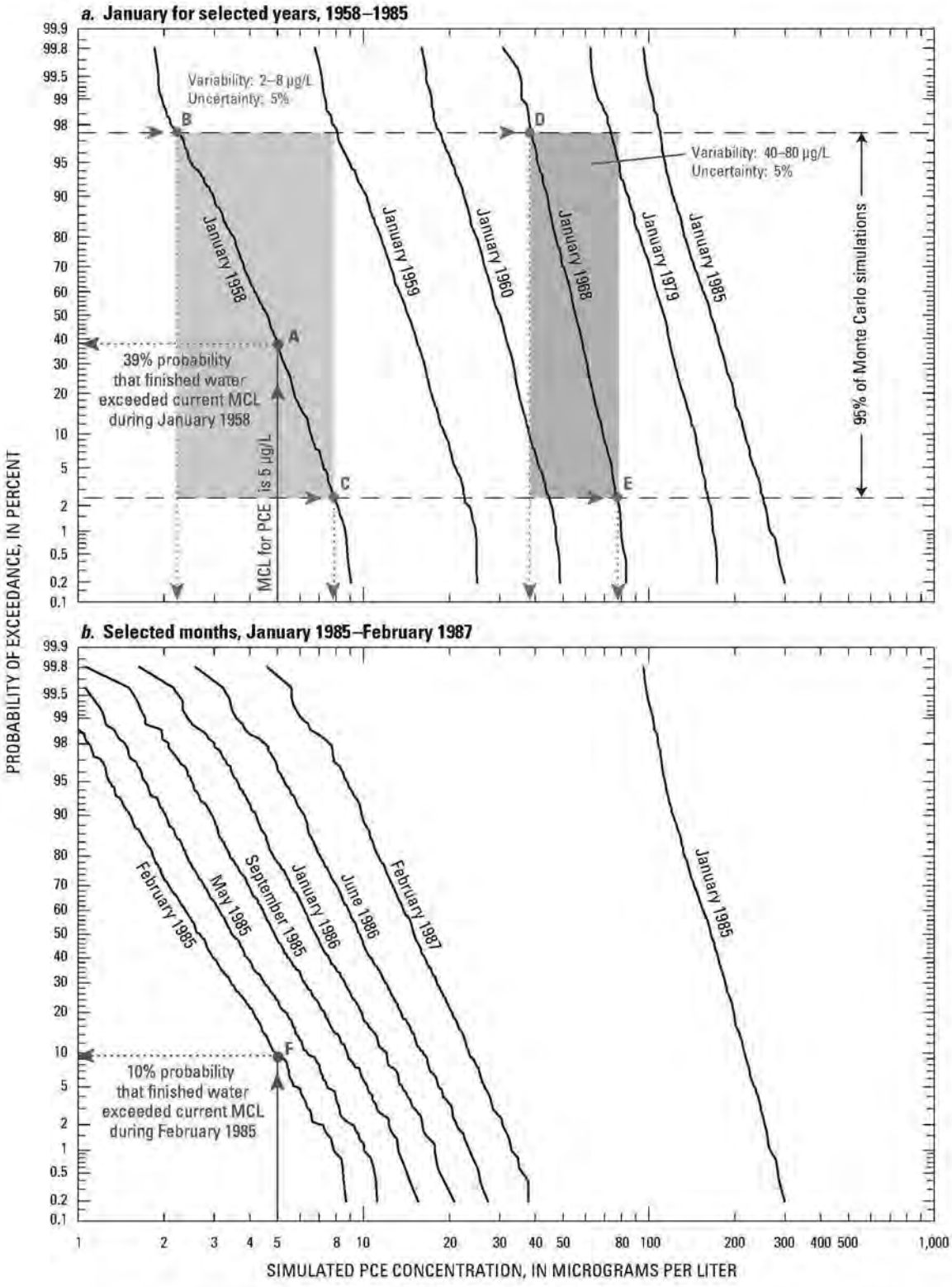



**Figure I28.** Probabilities of exceeding tetrachloroethylene concentrations in finished water at the water treatment plant derived from scenario 1 (pumping uncertainty excluded) probabilistic analysis using Monte Carlo simulation for *(a)* selected years, 1958–1985, and *(b)* selected months, January 1985–February 1987, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina (see text for discussion of points A–F). [PCE, tetrachloroethylene; MCL, maximum contaminant level; µg/L, micrograms per liter; %, percent]

The probabilistic analysis conducted using MC simulation was applied to the entire period of operation of the Tarawa Terrace WTP (January 1953–February 1987). The PCE concentration in finished water determined using the deterministic analysis (single-value parameter input and output) also can be expressed and presented in terms of a range of probabilities for the entire duration of WTP operations. Figure I29 shows the concentration of PCE in finished water at the Tarawa Terrace WTP in terms of the MC simulation results. Several results shown on this graph are worthy of further explanation.

1. The range of PCE concentrations derived from the probabilistic analysis using MC simulation is shown as a band of solutions in Figure I29 and represents 95% of all simulated results.
2. The current MCL for PCE (5 µg/L) was first exceeded in finished water during October 1957–August 1958; these solutions include November 1957, the exceedance date determined using the calibrated fate and transport model (Faye 2008), which is a deterministic modeling analysis approach.
3. The PCE concentration in Tarawa Terrace WTP finished water during January 1985, simulated using the probabilistic analysis, ranges from about 110–251 µg/L (95 percent of Monte Carlo simulations; Appendix I5). This range includes the maximum calibrated value of 183 µg/L (derived without considering uncertainty and variability using MT3DMS) and the maximum measured value of 215 µg/L (Faye 2008).

Results of the probabilistic analysis, which were obtained by using MC simulation with pumping uncertainty excluded (scenario 1), quantitatively define the uncertainty and variability of the deterministically derived results reported by Faye and Valenzuela (2007) and Faye (2008). These probabilistic results provide additional confidence that the deterministically derived results (for example, the historically reconstructed PCE concentrations in Tarawa Terrace finished water) are reasonable and conform well to field observations and data.

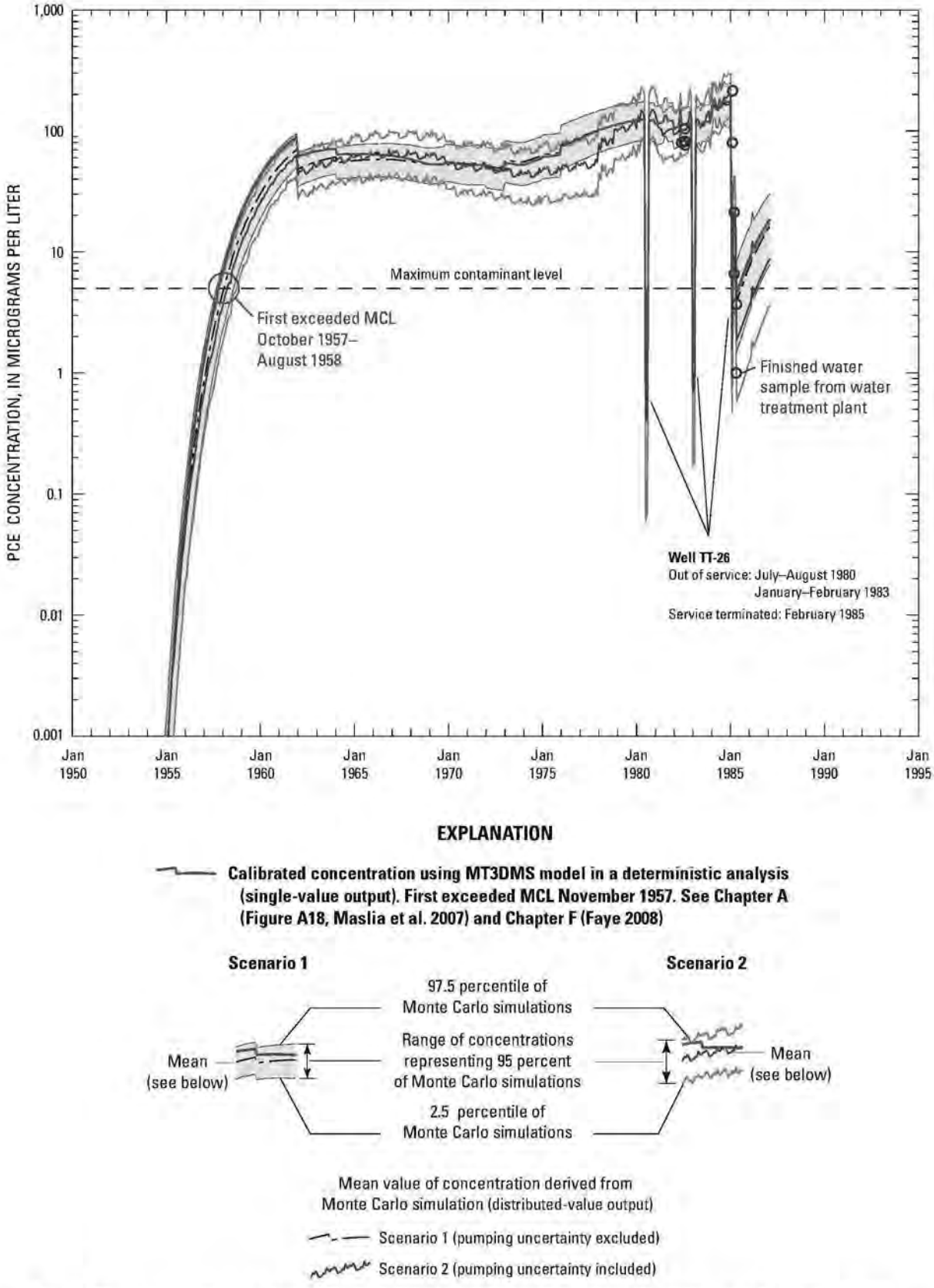



**Figure I29.** Concentrations of tetrachloroethylene in finished water at the water treatment plant derived from scenario 1 (pumping uncertainty excluded) and scenario 2 (pumping uncertainty included) probabilistic analyses using Monte Carlo simulation, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.
[See Appendix I5 for tabular listing; PCE, tetrachloroethylene; MCL, maximum contaminant level]

## Scenario 2: Pumping Uncertainty Included

For the scenario 2 probabilistic analysis, pumping was characterized as an uncertain and varying input parameter (for example, Figure I24). For this scenario, probabilistic analysis results for finished water at the Tarawa Terrace WTP also are shown as a series of histograms for the same selected times used for scenario 1 results: January 1958, January 1968, January 1979, and January 1985 (Figure I30). These histograms show the probability of a range of PCE-concentration values occurring during a specific month and year. The histograms of PCE concentrations in finished water under scenario 1 (pumping uncertainty excluded) and scenario 2 (pumping uncertainty included) are similar when compared to the theoretical normal distribution fit to MC simulation results. However, under scenario 2 conditions, with the exception of results for January 1958, the range in PCE concentrations for 95% of all MC simulation results ($P_{97.5}$ minus $P_{2.5}$) indicate greater variation. For example, for January 1979, the range of 95% of all MC simulation results is 107 µg/L for scenario 2 compared with a corresponding variation of 87 µg/L for scenario 1. Similarly, for January 1985, the range of 95% of all MC simulation results is 170 µg/L for scenario 2 compared with a corresponding range of 141 µg/L for scenario 1. This increase in variation is most likely a consequence of characterizing pumping as an uncertain input parameter (scenario 2 conditions) rather than as a known quantity (scenario 1 conditions).

The probabilistic analysis conducted using MC simulation for scenario 2 conditions was applied to the entire period of operation of the Tarawa Terrace WTP (January 1953–February 1987). Similar to scenario 1, scenario 2 results also can be expressed and presented in terms of a range of probabilities for the entire duration of WTP operations. Figure I29 shows the concentration of PCE in finished water at the Tarawa Terrace WTP in terms of the MC simulation results, and comparisons can be made between scenario 1 and scenario 2 results. Tabular values for both scenario 1 and scenario 2 results in terms of the $P_{2.5}$, $P_{50}$, and $P_{97.5}$ values and comparisons with the deterministically calibrated values of PCE in finished water at the Tarawa Terrace WTP derived using the deterministic modeling analysis (Faye 2008) are listed in Appendix I5. Several results shown on Figure I29 are worthy of further explanation:

1. The range of PCE concentrations derived from the probabilistic analysis using MC simulations for scenario 1 and scenario 2 represent 95% of all possible results.

2. Both scenario 1 and scenario 2 indicated a date range for first exceeding the MCL for PCE (5 µg/L) of October 1957–August 1985; this range also includes the date of November 1957, derived using the deterministic modeling analysis (Faye 2008).

3. The PCE concentration in Tarawa Terrace WTP finished water during January 1985, simulated using the scenario 2 probabilistic analysis, ranges from 123–293 µg/L (95 percent of Monte Carlo simulations—see Appendix I5). As with scenario 1 results, this range includes the maximum calibrated value of 183 µg/L (derived without considering uncertainty and variability using MT3DMS) and the maximum measured value of 215 µg/L (Faye 2008).

Calibrated time-varying PCE concentrations in finished water at the Tarawa Terrace WTP (Maslia et al. 2007; Faye 2008), mean values of MC simulation results from scenario 1 (pumping uncertainty excluded), and mean values of MC simulation results from scenario 2 (pumping uncertainty included) are shown for comparison in Figure I31. Results of these comparisons indicate that the PCE concentration in finished water exceeded the current MCL for PCE of 5 µg/L during February 1958 for scenario 1 and during April 1958 for scenario 2. Recall, that for the calibrated model (single-valued, deterministic results), PCE concentration in finished water exceeded the current MCL for PCE of 5 µg/L during November 1957 (Figure I31, Inset A). Thus, compared to the calibrated, single-valued, deterministic results, accounting for input parameter uncertainty and excluding pumping uncertainty (scenario 1) resulted in a delay of 3 months (November 1957–February 1958) before finished water at the WTP exceeded the current MCL for PCE. When pumping uncertainty is included as a variant (scenario 2), the delay was 5 months (November 1957–April 1958), when compared with calibrated model results.

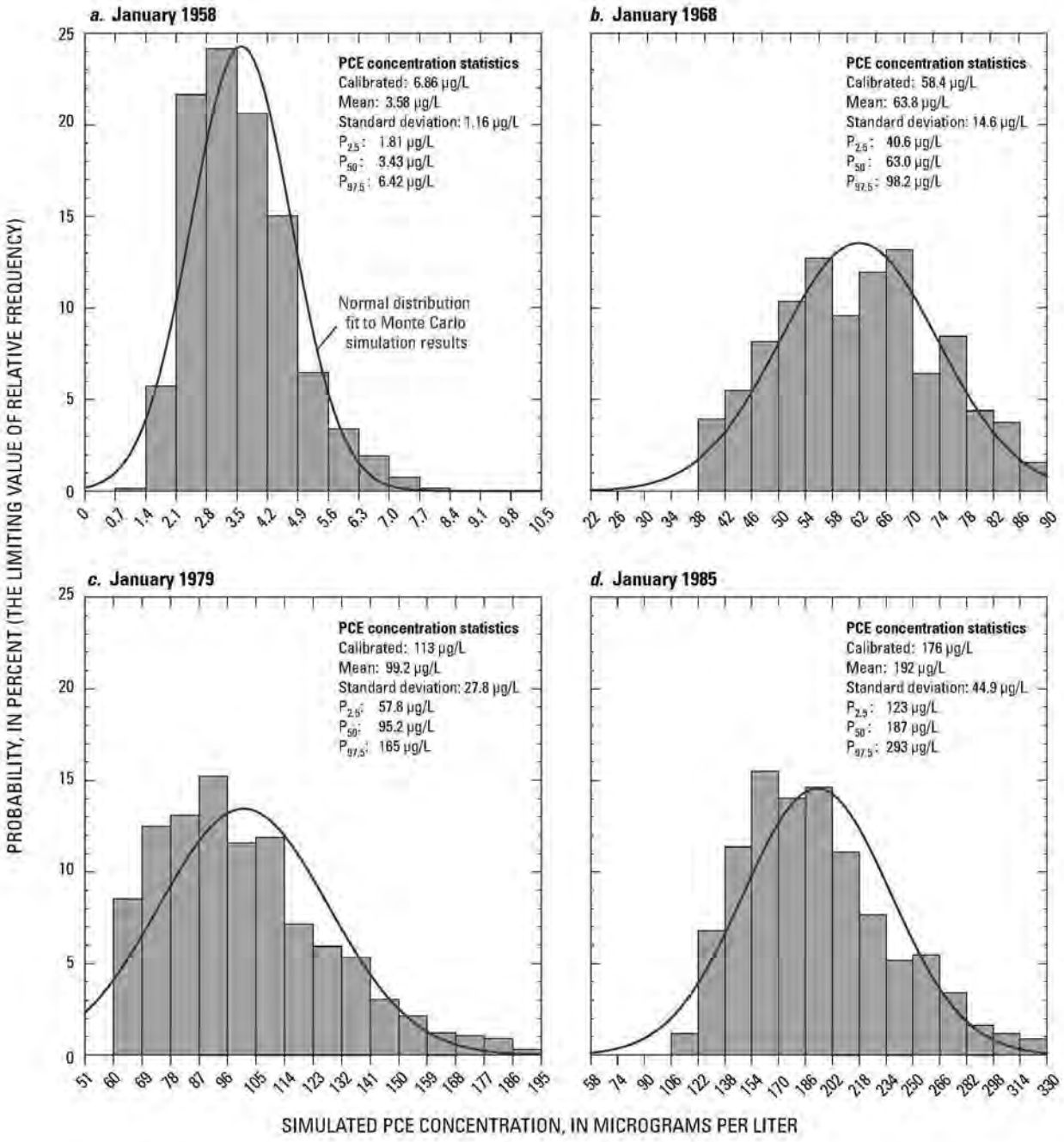



**Figure I30.** Probability of occurrence of tetrachloroethylene contamination in finished water at the water treatment plant derived from scenario 2 (pumping uncertainty included) probabilistic analysis using Monte Carlo simulation for *(a)* January 1958, *(b)* January 1968, *(c)* January 1979, and *(d)* January 1985, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; µg/L, micrograms per liter; $P_{2.5}$, $P_{50}$, and $P_{97.5}$ concentrations at 2.5, 50, and 97.5 percent, respectively; calibrated concentration from Maslia et al. 2007, Appendix A2]

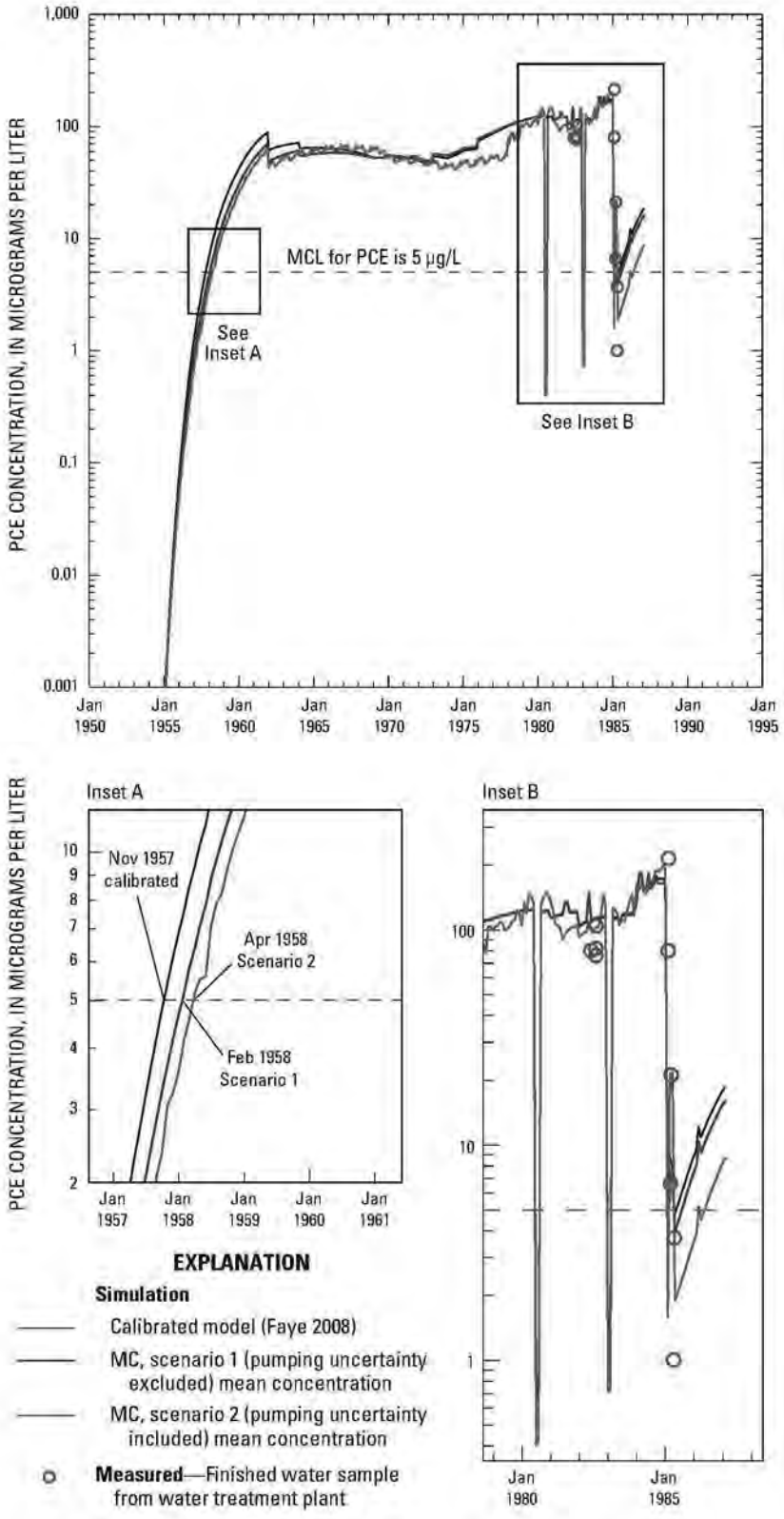



**Figure I31.** Concentration of tetrachloroethylene in finished water at the water treatment plant derived from deterministic (calibrated model) and probabilistic (Monte Carlo simulation) analysis, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [PCE, tetrachloroethylene; MCL, maximum contaminant level; µg/L, micrograms per liter; MC, Monte Carlo]

A series of probabilistic type curves, such as those shown in Figure I28, also were constructed for results of scenario 2. As previously explained, these type curves can be used to estimate the probability that a specified PCE concentration (for example, the MCL of 5 µg/L) was exceeded. Probabilistic type curves derived from results of scenario 2 (pumping uncertainty included) are plotted along with results from scenario 1 (pumping uncertainty excluded) in Figure I32. Using the procedure previously described for scenario 1, the probability that the current MCL for PCE (5 µg/L) is exceeded for a given date is determined as follows for scenario 2 results.

1. Locate the scenario 2 probabilistic type curve for January 1958 in Figure I32.
2. Locate the 5 µg/L PCE concentration along the x-axis of the graph in Figure I32.
3. Follow the vertical line until it intersects with the January 1958 complementary cumulative probability function type curve for scenario 2 (point A, Figure I32).
4. Follow the horizontal line until it intersects the y-axis—for the scenario 2 example, 11%.

The same procedure is used to determine the probability of exceeding the 5 µg/L PCE concentration for scenario 1 results (pumping uncertainty excluded). For this scenario, it is 39%. Thus, when including pumping uncertainty (scenario 2) as a model parameter of variation, there is about a fourfold reduction in the probability of exceeding the MCL for PCE in finished water at the Tarawa Terrace WTP during January 1958.

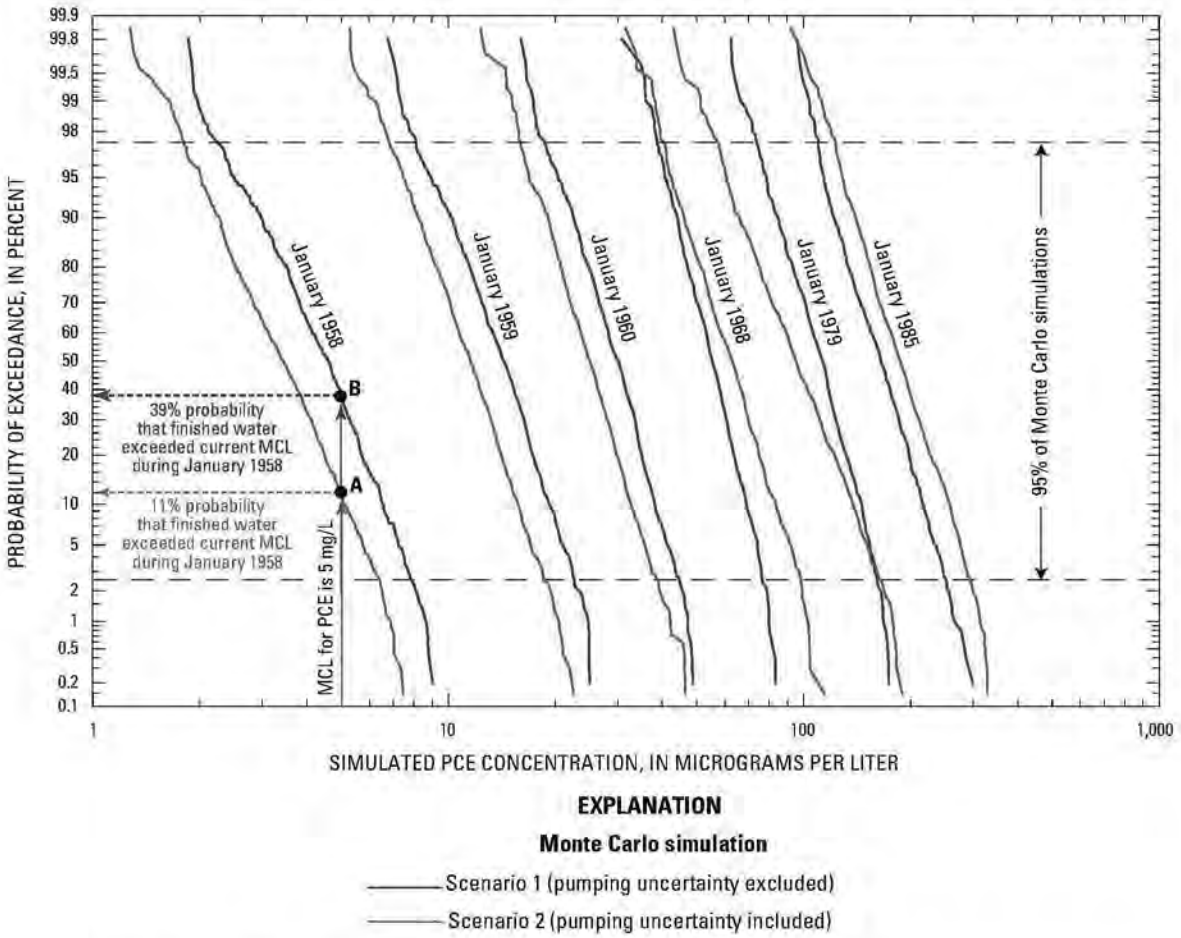



**Figure I32.** Probabilities of exceeding tetrachloroethylene concentration in finished water at the water treatment plant derived from probabilistic analysis (Monte Carlo simulation) with pumping uncertainty excluded (scenario 1) and included (scenario 2), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [See text for discussion of points A and B; PCE, tetrachloroethylene; MCL, maximum contaminant level; µg/L, micrograms per liter; %, percent]

# Summary and Conclusions

This chapter (Chapter I) of the Tarawa Terrace report series was written to provide detailed and specific information relative to model parameter sensitivity, variability, and uncertainty associated with simulations of groundwater flow, contaminant fate and transport, and distribution of drinking water. The literature abounds with a plethora of books, research articles, and conference proceedings specifically dedicated to the topic of sensitivity, variability, uncertainty, and probabilistic analysis techniques. Some of these references are cited in the "References" section of this report. It is not the focus of this report, however, to develop an all encompassing dissertation on the aforementioned topics. Rather, the aim of this chapter report is to provide readers with an understanding of how parameter sensitivity, variability, and uncertainty have been taken into account and investigated in the course of assessing deterministically derived calibrated model results for Tarawa Terrace and vicinity. These calibrated model results are based on the application of groundwater-flow, contaminant fate and transport, and water-distribution system models described in the Chapter A (Maslia et al. 2007), Chapter C (Faye and Valenzuela 2007), Chapter F (Faye 2008), and Chapter J (Sautner et al. In press 2009) reports. Results also are based on associated data and information described in other reports—Chapter B (Faye 2007), Chapter D (Lawrence 2007), Chapter E (Faye and Green 2007), Chapter G (Jang and Aral 2008), and Chapter H (Wang and Aral 2008).

The approach used in developing the deterministically derived calibrated groundwater-flow and contaminant fate and transport models relied solely on available information (current and historical) to develop the geohydrologic framework and conceptual models of groundwater flow and contaminant fate and transport. A time-consuming and costly drilling program to gather additional site data was not part of this investigation. Thus, in addition to parameter variability in the study area, relying on available data and information also leads to parameter uncertainty, owing in part to the paucity of historical information and data.

To investigate model input parameter sensitivity, variability, and uncertainty, and model output variability and uncertainty, several methods were used. These methods ranged from the less sophisticated one-at-a-time parameter variation wherein a selected input parameter was independently varied to assess sensitivity, to a more complex parameterization using the advanced, nonlinear parameter estimation package PEST, to sophisticated probabilistic techniques that rely on numerical methods such as sequential Gaussian (SG) simulation, pseudo-random number generators (PRNGs), and Monte Carlo (MC) simulation to investigate parameter input and output uncertainty. Each of the methods has advantages and disadvantages. For example, varying one input parameter at a time is computationally efficient and provides some qualitative insight into the relative importance of selected model parameters. A probabilistic analysis, on the other hand, can be computationally expensive, requiring many hours to many days to conduct an MC simulation; however, it does provide detailed quantitative results about the range and likelihood (probability) of model outputs. This quantitative information is needed by epidemiologists to assess the reliability of historically reconstructed drinking water concentrations as part of the case-control epidemiological study. The methods presented in this report are summarized below:

1. a sensitivity analysis conducted using parameters of the groundwater-flow and contaminant fate and transport models—this sensitivity analysis included 11 parameters associated with the groundwater-flow model and 7 parameters associated with the contaminant fate and transport model;
2. a sensitivity analysis conducted to quantify the effect of the finite-difference grid cell size on groundwater-flow model output;
3. a sensitivity analysis conducted to quantify the effect of time-step size on contaminant fate and transport model output;
4. a sensitivity analysis conducted to quantify the relative importance of water-distribution system model parameters by conducting analyses of storage-tank mixing models and by using the parameter estimation package, PEST; and
5. Monte Carlo analyses using selected groundwater-flow and contaminant fate and transport model parameters with and without considering pumping uncertainty.

The sensitivity analysis method was used in this study to ascertain the dependency of model output, such as tetrachloroethylene (PCE) concentration in finished water at the Tarawa Terrace water treatment plant (WTP), on certain model input parameters (for example, horizontal hydraulic conductivity or mass-loading rate). The sensitivity analysis approach used is referred to as a one-at-a-time design or experiment and was conducted by changing the values of input parameters of the calibrated models one at a time and then quantifying the variation in the output parameter (Tables I5–I7; Figures I4–I6). Results from these sensitivity analyses indicated that horizontal hydraulic conductivity was the most sensitive parameter for the groundwater-flow model (Figure I4*a*, *b*) and reaction rate and mass-loading rate were the most sensitive parameters for the contaminant fate and transport model (Figure I4*c*, *d*).

Properties of numerical models such as the design of the computational grid (cell size) and temporal discretization (time-step size) also can have an effect on model output, and quantifying and understanding the effect of the aforementioned numerical properties on output variables are important. Therefore, sensitivity analyses were conducted on the groundwater-flow and contaminant fate and transport models by varying the calibrated model cell size and time-step size (Figure I8 and Table I8, respectively). Results of the cell-size sensitivity analysis indicated that refining the calibrated model grid from cell sizes of 50 ft per side to 25 ft per side did not appreciably provide improved accuracy of computation in terms of simulated drawdown at water-supply wells (Figure I8). Refining time-step sizes from 30 and 31 days used in the calibrated

models to 1 day indicated that PCE concentrations at water-supply wells TT-23 and TT-26 were unaffected by numerical oscillations that could be caused by inappropriate temporal discretization (Table I8).

Two types of sensitivity analyses were conducted on results obtained from applying the EPANET 2 model (Rossman 2000) to the Tarawa Terrace and Holcomb Boulevard water-distribution systems. These analyses consisted of ascertaining the effect of: (1) storage-tank mixing model choice and (2) sensitivity of the model to material roughness coefficients (C-factor) and demand-pattern factors using the advanced parameter estimation modeling package, PEST (Doherty 2005). Sensitivity analysis results comparing four storage-tank models (continuous stirred-tank reactor; two-compartment storage tank; first-in, first-out plug-flow storage tank; and last-in, first-out plug-flow storage tank) with measured data indicated that the choice of mixing model does make a difference (Figures I12 and I13) and that water-quality dynamics associated with monitoring locations and source characterization also can affect modeling results. Using PEST to estimate and optimize C-factor values indicated that the Tarawa Terrace water-distribution system model is relatively insensitive to C-factor values (Table I9). Still, the model was more sensitive to polyvinyl chloride pipe C-factor variation than to cast iron pipe C-factor variation (Figure I14). With respect to demand-pattern factors, PEST was used to optimize values by minimizing the sum of squared differences between measured and simulated hydraulic head. Overall, the PEST-derived demand-pattern factors resulted in lower root-mean-square values, greater correlation coefficients, and closer matches between measured and simulated hydraulic heads in the storage tanks (Figure I16 and Table I10).

A probabilistic analysis was used to generate uncertainties in model inputs (for example, horizontal hydraulic conductivity) so that estimates of uncertainty and variability in model output (for example, PCE concentration in finished water at the Tarawa Terrace WTP) could be made. MC simulation was used to quantify model uncertainty and variability. In the probabilistic analysis, selected input parameters of the deterministically derived calibrated groundwater-flow and contaminant fate and transport models were characterized using the SG simulation and MC simulation methods. Results were obtained in terms of distributed-value output that was used to assess model uncertainty and parameter variability. Customized computer codes were developed for incorporating the two-stage MC simulation process into the Tarawa Terrace models (Figure I18). The probabilistic analysis described herein can be summarized in four steps: (1) selection of uncertain input parameters; (2) generation of uncertain input parameters using SG simulation, PRNG, or statistical analysis of historical pumping variation; (3) incorporating the statistical distributions of input parameters into the groundwater-flow and contaminant fate and transport models; and (4) using MC simulation to obtain physically plausible distributions of model output (that is, potentiometric heads, groundwater velocities, PCE concentrations in groundwater, and PCE concentrations in finished water at the Tarawa Terrace WTP).

For the probabilistic analysis, eight input parameters were assumed to be uncertain and variable: (1) horizontal hydraulic conductivity, (2) infiltration, (3) distribution coefficient, (4) bulk density, (5) effective porosity, (6) reaction rate, (7) mass-loading rate, and (8) longitudinal dispersivity (Table I15). Two MC simulation scenarios were investigated. For scenario 1, water-supply well pumping uncertainty was excluded from the probabilistic analysis; for scenario 2, water-supply well pumping uncertainty was included in the probabilistic analysis (Figure I24).

For scenario 1 (pumping uncertainty excluded), 95% of MC simulation results indicate the maximum contaminant level for PCE of 5 µg/L was first exceeded in finished water during October 1957–August 1958 (Figure I29; Appendix I5). For scenario 2 (pumping uncertainty included) 95% of MC simulation results indicate the current MCL for PCE of 5 µg/L was first exceeded in finished water during November 1957–October 1958 (Appendix I5). Furthermore, results for both scenario 1 and scenario 2 show the PCE concentration in finished water during January 1985, simulated using the probabilistic analysis, ranged from about 110 to 293 µg/L (95% of MC simulations, Appendix I5). This range includes the maximum calibrated value of 183 µg/L (derived without considering uncertainty and variability using MT3DMS) and the maximum measured value of 215 µg/L (Faye 2008). Therefore, these probabilistic analysis results, obtained by using MC simulation and including and excluding pumping uncertainty, provide additional confidence that the historically reconstructed PCE concentrations determined by Faye (2008) using the single-valued deterministic approach are reasonable and conform well to field observations and data.

Based on the results from the probabilistic analyses using a two-stage MC simulation approach, the following conclusions are made.

- PCE concentrations in finished water at the Tarawa Terrace WTP deterministically derived from the calibrated model (Faye 2008) are contained within the 95 percentile range ($P_{2.5}$–$P_{97.5}$) of PCE results obtained from the probabilistically derived MC simulation results (Appendix I5).
- Finished water delivered by the Tarawa Terrace WTP exceeded the current MCL for PCE of 5 µg/L as early as October 1957 and as late as October 1958 (Appendix I5) when considering pumping as both a certain and uncertain model input parameter.
- The PCE concentration in Tarawa Terrace WTP finished water during January 1985, simulated using scenario 1 probabilistic analysis (pumping uncertainty excluded), ranges from about 110 to 251 µg/L (95% of MC simulations). Using scenario 2 probabilistic analysis (pumping uncertainty included), the PCE concentration ranges from about 123 to 293 µg/L (95% of MC simulations) for January 1985. These ranges include the calibrated value of 183 µg/L (deterministic, single-value output reported in Maslia et al. [2007]) and the maximum measured value of 215 µg/L (Faye 2008).

## Acknowledgments

A study of this complexity and magnitude is dependent upon the assistance, input, and suggestions of many colleagues. Thus, the authors of this report and all other chapter reports acknowledge the managers and staff of the U.S. Geological Survey Water Science Centers in Raleigh, North Carolina, and Atlanta, Georgia. In particular, the contributions of Melinda J. Chapman, Douglas A. Harned, and Stephen S. Howe are acknowledged for providing the majority of well, water-level, and pumpage data used in this study. Keith W. McFadden and Jonathan W. Musser are acknowledged for assistance with spatial analyses in preparing illustrations and with developing geodatabases, Web-based applications, and the querying system contained on the electronic media accompanying this report. Gregory C. Mayer and Edward H. Martin also are acknowledged for their administrative assistance.

The authors acknowledge the staff of the Environmental Management Division, U.S. Marine Corps Base Camp Lejeune, North Carolina. In particular, Scott A. Brewer, Brynn Ashton, Scott R. Williams, and Rick Cheng for their assistance and cooperation during the course of this study, especially for providing a large number of technical reports, maps, and historical documents, which summarize the results of groundwater remedial investigations at and in the vicinity of Tarawa Terrace.

The authors acknowledge the contributions of the U.S. Environmental Protection Agency, Region IV, Atlanta, Georgia, for providing reports and documents summarizing the results of investigations of groundwater contamination in the vicinity of ABC One-Hour Cleaners and in the northern part of Tarawa Terrace.

The authors acknowledge colleagues at ATSDR, Eastern Research Group, Inc., the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, and the Oak Ridge Institute for Science and Education for providing assistance and advice with all aspects of this study.

Thomas M. Plummer, Commander, U.S. Public Health Service, Indian Health Service, U.S. Department of Health and Human Services, assisted with planning, field instrumentation, and conducting tests of water-distribution systems serving Camp Lejeune, August 18–28, 2004.

Caryl J. Wipperfurth and Kimberly A. Waltenbaugh, U.S. Geological Survey Enterprise Publishing Network, assisted with the preparation of text, illustrations, and electronic media.

## Availability of Model Input Data Files and Simulation Results

Calibrated model input data files developed for simulating predevelopment groundwater flow, transient groundwater flow, the fate and transport of PCE as a single species, and the distribution of water and contaminants in a water-distribution system are provided with this report in a CD–ROM format. Input files and selected output files used with the parameter estimation model, PEST, also are provided on the CD–ROM. Public-domain model codes used with these input files are available on the Internet at the following Web sites:

- Predevelopment and transient groundwater flow
  - Model code: MODFLOW-96 and MODFLOW-2000
  - Web site: *http://water.usgs.gov/nrp/gwsoftware/modflow.html*
- Fate and transport of PCE as a single species
  - Model code: MT3DMS
  - Web site: *http://hydro.geo.ua.edu/*
- Distribution of water and contaminants in a water-distribution system
  - Model code: EPANET 2
  - Web site: *http://www.epa.gov/nrmrl/wswrd/epanet.html*
- Model-independent parameter estimation
  - Model code: PEST
  - Web site: *http://www.sspa.com/pest/*

Readers desiring information about the model input data files contained on the CD-ROM or simulation results may also contact the Project Officer of ATSDR's Exposure-Dose Reconstruction Program at the following address:

Morris L. Maslia, P.E., D.WRE, DEE
Agency for Toxic Substances and Disease Registry
4770 Buford Highway, N.E., Mail Stop F-59
Atlanta, Georgia 30341-3717
Telephone: (770) 488-3842
Fax: (770) 488-1536
Email: *mmaslia@cdc.gov*

## References


Absoft Pro FORTRAN v10.0. Absoft Corporation. Rochester Hills, MI. 2005. [cited 2008 July 30]; Available from *http://www.absoft.com/*

Anderson MP, and Woessner WW. Applied Groundwater Modeling. San Diego, CA: Academic Press, Inc.; 1992.

Barnes R. Variogram Tutorial. Golden Software, Inc. Golden, CO. 2003. [cited 2008 August 2]; Available from *http://www.goldensoftware.com/variogramTutorial.pdf*

Boulos PF, Grayman WM, Bowcock RW, Clapp JW, Rossman LA, Clark RM, Deininger RA, and Dhingra AK. Hydraulic Mixing and Free Chlorine Residual in Reservoirs. Journal of the American Water Works Association. 1996; 88(7):48–59.

Boulos PF, Lansey KE, and Karney BW. Comprehensive Water Distribution System Analysis Handbook for Engineers and Planners. Pasadena, CA: MWH Soft; 2006.

Cesario L. Modeling, Analysis, and Design of Water Distribution Systems. Denver, CO: American Water Works Association; 1995.

Chiang W-H, and Kinzelbach W. 3D-Groundwater Modeling with PMWIN: A Simulation System for Modeling Groundwater Flow and Pollution. New York: Springer-Verlag Berlin Heidelberg; 2001.

Clark RM, and Grayman WM. Modeling Water Quality in Drinking Water Distribution Systems. Denver, CO: American Water Works Association; 1998.

CLW, Camp Lejeune Water Documents, 0001–8761 (not consecutively available), provided on DVD format, in Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove FJ, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter A: Summary of Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Cooley RL. A Method for Estimating Parameters and Assessing Reliability for Models of Steady-State Groundwater Flow, 1. Theory and Numerical Properties. Water Resources Research. 1977;13(2):318–324.

Cooley RL. A Method for Estimating Parameters and Assessing Reliability for Models of Steady-State Groundwater Flow, 2. Application of Statistical Analysis. Water Resources Research. 1979;15(3):603–617.

Cooley RL. Comparison of Several Methods of Solving Nonlinear Regression Groundwater Flow Problems. Water Resources Research. 1985; 21(10):1525–1538.

Cowles MK, and Carlin BP. Markov Chain Monte Carlo Convergence Diagnostics: A Comparative Review. Journal of the American Statistical Association. 1996;91:883–904.

Cullen AC, and Frey HC. Probabilistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs. New York: Plenum Press; 1999.

Daus AD, and Frind EO. An Alternating Direction Galerkin Technique for Simulation of Contaminant Transport in Complex Ground Water Systems. Water Resources Research. 1985;21(5):653–654.

Davis JC. Statistics and Data Analysis in Geology. 2nd ed. New York: John Wiley & Sons; 1973.

Deutsch CV, and Journel AG. GSLIB Geostatistical Software Library and User's Guide. 2nd ed. New York: Oxford University Press; 1998.

Doherty J. Groundwater Data Utilities/Part B: Program Descriptions. 2005. [cited 2007 January 31]; Available from *http://www.sspa.com/pest/utilities.shtml*

ECG, Inc. Marine Corps Base Camp Lejeune and Marine Corps Air Station, New River, Water Conservation Analysis. Vienna, VA: ECG, Inc.; 1999.

Faye RE. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter B: Geohydrologic Framework of the Castle Hayne Aquifer System. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Faye RE. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE). Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008.

Faye RE, and Green JW Jr. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter E: Occurrence of Contaminants in Groundwater. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

## References


Faye RE, and Valenzuela C. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter C: Simulation of Groundwater Flow. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Gelhar LW, Welty C, and Rehfeldt KR. A Critical Review of Data on Field-Scale Dispersion in Aquifers. Water Resources Research. 1992;28(7):1955–1973.

Golden Software, Inc. Surfer User's Guide. Golden, CO: Golden Software, Inc.; 1999.

Grayman WM, and Clark RM. Using Computer Models to Determine the Effect of Storage on Water Quality. Journal of the American Water Works Association. 1993;85(7):67–77.

Grayman WM, Deininger RA, Green A, Boulos PF, Bowcock RW, and Godwin CC. Water Quality and Mixing Models for Tanks and Reservoirs. Journal of the American Water Works Association. 1996;88(7):60–73.

Grayman WM, Rossman LA, Deininger RA, Smith CD, Arnold CN, and Smith JF. Mixing and Aging of Water in Distribution System Storage Facilities. Journal of the American Water Works Association. 2004;96(9):70–80.

Grayman WM, Maslia ML, and Sautner JB. Calibrating Distribution System Models with Fire-Flow Tests. Opflow, American Water Works Association. 2006 April:32(4)10–12.

Harbaugh AW, Banta ER, Hill MC, and McDonald MG. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process. Reston, VA: U.S. Geological Survey Open-File Report 00–92; 2000.

Harbaugh AW, and McDonald MG. Programmer's Documentation for MODFLOW-96, an Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. Reston, VA: U.S. Geological Survey Open-File Report 96–486; 1996.

Henry Von Oesen and Associates, Inc. Study of Two Water Plants, Tarawa Terrace-Montford Point, Camp Lejeune, North Carolina: Henry Von Oesen and Associates, Inc.; 1979.

Hill MC, and Tiedman CR. Effective Groundwater Model Calibration. Hoboken, NJ: John Wiley & Sons; 2007.

Hoffman F. Retardation of Volatile Organic Compounds in Groundwater in Low Organic Carbon Sediments—Interim Report. Oak Ridge, TN: U.S. Department of Energy, Lawrence Livermore National Laboratory; 1995.

Howard PH, Boethling RS, and Jarvis WF. Handbook of Environmental Degradation Rates 1st ed. Ann Arbor, MI: Lewis Publishers; 1991.

IMSL. FORTRAN Numerical Library, V 5. Visual Numerics, Inc. San Ramon, CA. 2003. [cited: 2008 July 30]; Available from *http://www.visualnumerics.com*

Jang W, and Aral MM. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter G: Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008.

Kennedy MS, Moegling S, Sarikelle S, and Suravallop K. Assessing the Effects of Storage Tank Design on Water Quality. Journal of the American Water Works Association. 1993:85(7)78–88.

Kitanidis PK. Introductions to Geostatistics Application in Hydrogeology. New York, NY: Cambridge University Press; 1997.

Lawrence SJ. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter D: Properties of Degradation Pathways of Common Organic Compounds in Groundwater. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Maslia ML. Expert Peer Review Panel Evaluating ATSDR's Water-Modeling Activities in Support of the Current Study of Childhood Birth Defects and Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina: Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2005.

Maslia ML and Aral MM. Analytical Contaminant Transport Analysis System (ACTS)—Multimedia Environmental Fate and Transport. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management. 2004 July:181–198.

Maslia ML, Sautner JB, and Aral MM. Analysis of the 1998 Water-Distribution System Serving the Dover Township Area, New Jersey: Field-Data Collection Activities and Water-Distribution System Modeling. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2000.

Maslia ML, Sautner JB, Aral MM, Gillig RE, Reyes JJ, and Williams RC. Historical Reconstruction of the Water-Distribution System Serving the Dover Township Area, New Jersey: January 1962–December 1996. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2001 October.

Maslia ML, Sautner JB, Valenzuela C, Bove FJ, and Aral MM. Field Data Collection Activities for Water-Distribution Systems Serving Marine Corps Base Camp Lejeune, North Carolina. Preliminary Test and Tracer Study of the Hadnot Point Water-Distribution System: Draft Work Plan. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2004.

Maslia ML, Sautner JB, Valenzuela C, Grayman WM, Aral MM, and Green JW Jr. Use of Continuous Recording Water-Quality Monitoring Equipment for Conducting Water-Distribution System Tracer Tests: The Good, the Bad, and the Ugly. Proceedings: World Environmental and Water Resources Congress; 2005 May 15–19; Anchorage, AK; 2005.

Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove F, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter A: Summary of Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Maslia ML, Sautner JB, Faye RE, Suárez-Soto RJ, Aral MM, Grayman WM, Jang W, Wang J, Bove F, Ruckart PZ, Valenzuela C, Green JW Jr, and Krueger AL. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter K: Supplemental Information. Atlanta, GA: Agency for Toxic Substances and Disease Registry; In press 2009.

Masters GM. Introduction to Environmental Engineering and Science. 2nd ed. Upper Saddle River, NJ: Prentice Hall; 1998.

Molak V. Fundamentals of Risk Analysis and Risk Management. Boca Raton, FL: Lewis Publishers; 1997.

Morris DA, and Johnson AI. Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948–60. Washington, DC: U.S. Geological Survey Water-Supply Paper 1839–D; 1967.

North Carolina Rural Economic Development Center. Water 2030 Report North Carolina Water Supply and Demand, 2005–2030. 2006. [cited 14 August 2008]; Available from *http://www.ncruralcenter.org/pubs/*

Nyhoff L, and Leestma S. FORTRAN 77 for Engineers and Scientists, with an Introduction to FORTRAN 90. 4th ed. Upper Saddle River, New Jersey: Prentice Hall; 1996.

Olea RA. Geostatistics for Engineers and Earth Scientists. Boston, MA: Kluwer Academic Publishers; 1999.

Palisade Corporation. @RISK Advanced Risk Analysis for Spreadsheets. Newfield, NY: Palisade Corporation; 2004. p. 503.

Palisade Corporation. Guide to Using @RISK: Risk Analysis and Simulation Add-In for Microsoft® Excel. Version 5.0. Ithica, NY; May 2008.

Pankow JF, and Cherry JA. Dense Chlorinated Solvents and Other DNAPLs in Groundwater: History, Behavior, and Remediation: Waterloo Press; 1996.

Roberts PJW, and Tian X. Application of Three-Dimensional Laser-Induced Fluorescence to Stratified Turbulent Mixing Process. Proceedings: American Society of Civil Engineers, Hydraulic Measurements and Experimental Methods Conference, 2002 July 28–August 1, Estes Park, CO.

Roberts PWJ, Tian X, Soitropoulos F, and Duer M. Physical Modeling of Mixing in Water Storage Tanks. Denver, CO: American Water Works Association Research Foundation Report; 2005.

Rogers JF, Kilough GG, Thompson SJ, Addy CL, McKeown RE, and Cowen DJ. Estimating Environmental Exposures to Sulfur Dioxide from Multiple Industrial Sources for a Case-Control Study. Journal of Exposure Analysis and Environmental Epidemiology. 1999;9:535–545.

Rossman LA. EPANET 2 Users Manual. Cincinnati: U.S. Environmental Protection Agency, Nation Risk Management Research Laboratory, Report No.: EPA/600–R–00/057; 2000 September.

Rossman LA, and Grayman WM. Scale-Model Studies of Mixing on Drinking Water Storage Tanks. Journal of Environmental Engineering, American Society of Civil Engineers. 1999;125(8):755–761.

Saltelli A, Chan K, and Scott EM, eds. Sensitivity Analysis. Chichester, England: John Wiley & Sons, Ltd; 2000.

Sautner JB, Maslia ML, Valenzuela C, Grayman WM, Aral MM, and Green JW Jr. Field Testing of Water-Distribution Systems at the U.S. Marine Corps Base Camp Lejeune, North Carolina, in Support of an Epidemiologic Study. Proceedings: World Environmental and Water Resources Congress; 2005 May 15–19, Anchorage, AK.

Sautner JB, Maslia ML, and Grayman WM. Storage Tank Mixing Models: Comparison of Tracer Data with Model Simulation. Proceedings: World Environmental and Water Resources Congress; 2007 May 15–19, Tampa, FL.

## References


Sautner JB, Valenzuela C, Maslia ML, and Grayman WM. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter J: Field Tests, Data Analyses, and Simulation of Distribution of Drinking Water. Atlanta, GA: Agency for Toxic Substances and Disease Registry; In press 2009.

Schnoor JL. Environmental Modeling. New York: John Wiley & Sons, Inc.; 1996.

Schwartz FW, and Zhang H. Fundamentals of Ground Water. New York: John Wiley & Sons, Inc.; 2003.

Tung Y-K, and Yen B-C. Hydrosystems Engineering Uncertainty Analysis. New York: McGraw-Hill; 2005.

Uner E. Generating Random Numbers. 2004. [cited 2008 August 1]; Available from *http://www.embedded.com/columns*

U.S. Environmental Protection Agency (USEPA). Guiding Principles for Monte Carlo Analysis. Washington, DC: U.S. Environmental Protection Agency, Report No.: EPA 630–R–97–001; 1997 March.

Walski TM. Analysis of Water Distribution Systems. Malabar, FL: Krieger Publishing Company; 1992.

Walski TM, Chase DV, and Savic DA. Water Distribution Modeling, 1st ed. Waterbury, CT: Haestad Press; 2001.

Wang J, and Aral MM. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter H: Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008.

Wikipedia. The Free Encyclopedia. Pseudorandom Number Generator. 2008. [cited: 2008 August 1]; Available from *http://en.wikipedia.org/wiki/Pseudorandom_random_generator*

Zhang D. Stochastic Methods for Flow in Porous Media: Coping with Uncertainties. San Diego, CA: Academic Press; 2002.

Zheng C, and Wang PP. MT3DMS: A Modular Three-Dimensional Multi-Species Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems: Documentation and User's Guide. Vicksburg, MS: U.S. Army Engineer Research and Development Center; 1999. Report No.: SERDP-99.

# Appendixes

**Appendix I1.** Simulation stress periods and corresponding month and year.

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

| Stress period | Month and year | Stress period | Month and year | Stress period | Month and year | Stress period | Month and year | Stress period | Month and year | Stress period | Month and year |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Jan 1951 | 49 | Jan 1955 | 97 | Jan 1959 | 145 | Jan 1963 | 193 | Jan 1967 | 241 | Jan 1971 |
| 2 | Feb 1951 | 50 | Feb 1955 | 98 | Feb 1959 | 146 | Feb 1963 | 194 | Feb 1967 | 242 | Feb 1971 |
| 3 | Mar 1951 | 51 | Mar 1955 | 99 | Mar 1959 | 147 | Mar 1963 | 195 | Mar 1967 | 243 | Mar 1971 |
| 4 | Apr 1951 | 52 | Apr 1955 | 100 | Apr 1959 | 148 | Apr 1963 | 196 | Apr 1967 | 244 | Apr 1971 |
| 5 | May 1951 | 53 | May 1955 | 101 | May 1959 | 149 | May 1963 | 197 | May 1967 | 245 | May 1971 |
| 6 | June 1951 | 54 | June 1955 | 102 | June 1959 | 150 | June 1963 | 198 | June 1967 | 246 | June 1971 |
| 7 | July 1951 | 55 | July 1955 | 103 | July 1959 | 151 | July 1963 | 199 | July 1967 | 247 | July 1971 |
| 8 | Aug 1951 | 56 | Aug 1955 | 104 | Aug 1959 | 152 | Aug 1963 | 200 | Aug 1967 | 248 | Aug 1971 |
| 9 | Sept 1951 | 57 | Sept 1955 | 105 | Sept 1959 | 153 | Sept 1963 | 201 | Sept 1967 | 249 | Sept 1971 |
| 10 | Oct 1951 | 58 | Oct 1955 | 106 | Oct 1959 | 154 | Oct 1963 | 202 | Oct 1967 | 250 | Oct 1971 |
| 11 | Nov 1951 | 59 | Nov 1955 | 107 | Nov 1959 | 155 | Nov 1963 | 203 | Nov 1967 | 251 | Nov 1971 |
| 12 | Dec 1951 | 60 | Dec 1955 | 108 | Dec 1959 | 156 | Dec 1963 | 204 | Dec 1967 | 252 | Dec 1971 |
| 13 | Jan 1952 | 61 | Jan 1956 | 109 | Jan 1960 | 157 | Jan 1964 | 205 | Jan 1968 | 253 | Jan 1972 |
| 14 | Feb 1952 | 62 | Feb 1956 | 110 | Feb 1960 | 158 | Feb 1964 | 206 | Feb 1968 | 254 | Feb 1972 |
| 15 | Mar 1952 | 63 | Mar 1956 | 111 | Mar 1960 | 159 | Mar 1964 | 207 | Mar 1968 | 255 | Mar 1972 |
| 16 | Apr 1952 | 64 | Apr 1956 | 112 | Apr 1960 | 160 | Apr 1964 | 208 | Apr 1968 | 256 | Apr 1972 |
| 17 | May 1952 | 65 | May 1956 | 113 | May 1960 | 161 | May 1964 | 209 | May 1968 | 257 | May 1972 |
| 18 | June 1952 | 66 | June 1956 | 114 | June 1960 | 162 | June 1964 | 210 | June 1968 | 258 | June 1972 |
| 19 | July 1952 | 67 | July 1956 | 115 | July 1960 | 163 | July 1964 | 211 | July 1968 | 259 | July 1972 |
| 20 | Aug 1952 | 68 | Aug 1956 | 116 | Aug 1960 | 164 | Aug 1964 | 212 | Aug 1968 | 260 | Aug 1972 |
| 21 | Sept 1952 | 69 | Sept 1956 | 117 | Sept 1960 | 165 | Sept 1964 | 213 | Sept 1968 | 261 | Sept 1972 |
| 22 | Oct 1952 | 70 | Oct 1956 | 118 | Oct 1960 | 166 | Oct 1964 | 214 | Oct 1968 | 262 | Oct 1972 |
| 23 | Nov 1952 | 71 | Nov 1956 | 119 | Nov 1960 | 167 | Nov 1964 | 215 | Nov 1968 | 263 | Nov 1972 |
| 24 | Dec 1952 | 72 | Dec 1956 | 120 | Dec 1960 | 168 | Dec 1964 | 216 | Dec 1968 | 264 | Dec 1972 |
| 25 | Jan 1953 | 73 | Jan 1957 | 121 | Jan 1961 | 169 | Jan 1965 | 217 | Jan 1969 | 265 | Jan 1973 |
| 26 | Feb 1953 | 74 | Feb 1957 | 122 | Feb 1961 | 170 | Feb 1965 | 218 | Feb 1969 | 266 | Feb 1973 |
| 27 | Mar 1953 | 75 | Mar 1957 | 123 | Mar 1961 | 171 | Mar 1965 | 219 | Mar 1969 | 267 | Mar 1973 |
| 28 | Apr 1953 | 76 | Apr 1957 | 124 | Apr 1961 | 172 | Apr 1965 | 220 | Apr 1969 | 268 | Apr 1973 |
| 29 | May 1953 | 77 | May 1957 | 125 | May 1961 | 173 | May 1965 | 221 | May 1969 | 269 | May 1973 |
| 30 | June 1953 | 78 | June 1957 | 126 | June 1961 | 174 | June 1965 | 222 | June 1969 | 270 | June 1973 |
| 31 | July 1953 | 79 | July 1957 | 127 | July 1961 | 175 | July 1965 | 223 | July 1969 | 271 | July 1973 |
| 32 | Aug 1953 | 80 | Aug 1957 | 128 | Aug 1961 | 176 | Aug 1965 | 224 | Aug 1969 | 272 | Aug 1973 |
| 33 | Sept 1953 | 81 | Sept 1957 | 129 | Sept 1961 | 177 | Sept 1965 | 225 | Sept 1969 | 273 | Sept 1973 |
| 34 | Oct 1953 | 82 | Oct 1957 | 130 | Oct 1961 | 178 | Oct 1965 | 226 | Oct 1969 | 274 | Oct 1973 |
| 35 | Nov 1953 | 83 | Nov 1957 | 131 | Nov 1961 | 179 | Nov 1965 | 227 | Nov 1969 | 275 | Nov 1973 |
| 36 | Dec 1953 | 84 | Dec 1957 | 132 | Dec 1961 | 180 | Dec 1965 | 228 | Dec 1969 | 276 | Dec 1973 |
| 37 | Jan 1954 | 85 | Jan 1958 | 133 | Jan 1962 | 181 | Jan 1966 | 229 | Jan 1970 | 277 | Jan 1974 |
| 38 | Feb 1954 | 86 | Feb 1958 | 134 | Feb 1962 | 182 | Feb 1966 | 230 | Feb 1970 | 278 | Feb 1974 |
| 39 | Mar 1954 | 87 | Mar 1958 | 135 | Mar 1962 | 183 | Mar 1966 | 231 | Mar 1970 | 279 | Mar 1974 |
| 40 | Apr 1954 | 88 | Apr 1958 | 136 | Apr 1962 | 184 | Apr 1966 | 232 | Apr 1970 | 280 | Apr 1974 |
| 41 | May 1954 | 89 | May 1958 | 137 | May 1962 | 185 | May 1966 | 233 | May 1970 | 281 | May 1974 |
| 42 | June 1954 | 90 | June 1958 | 138 | June 1962 | 186 | June 1966 | 234 | June 1970 | 282 | June 1974 |
| 43 | July 1954 | 91 | July 1958 | 139 | July 1962 | 187 | July 1966 | 235 | July 1970 | 283 | July 1974 |
| 44 | Aug 1954 | 92 | Aug 1958 | 140 | Aug 1962 | 188 | Aug 1966 | 236 | Aug 1970 | 284 | Aug 1974 |
| 45 | Sept 1954 | 93 | Sept 1958 | 141 | Sept 1962 | 189 | Sept 1966 | 237 | Sept 1970 | 285 | Sept 1974 |
| 46 | Oct 1954 | 94 | Oct 1958 | 142 | Oct 1962 | 190 | Oct 1966 | 238 | Oct 1970 | 286 | Oct 1974 |
| 47 | Nov 1954 | 95 | Nov 1958 | 143 | Nov 1962 | 191 | Nov 1966 | 239 | Nov 1970 | 287 | Nov 1974 |
| 48 | Dec 1954 | 96 | Dec 1958 | 144 | Dec 1962 | 192 | Dec 1966 | 240 | Dec 1970 | 288 | Dec 1974 |

**Appendix I1.** Simulation stress periods and corresponding month and year.—Continued

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

| Stress period | Month and year | Stress period | Month and year | Stress period | Month and year | Stress period | Month and year | Stress period | Month and year |
|---|---|---|---|---|---|---|---|---|---|
| 289 | Jan 1975 | 337 | Jan 1979 | 385 | Jan 1983 | 433 | Jan 1987 | 481 | Jan 1991 |
| 290 | Feb 1975 | 338 | Feb 1979 | 386 | Feb 1983 | 434 | Feb 1987 | 482 | Feb 1991 |
| 291 | Mar 1975 | 339 | Mar 1979 | 387 | Mar 1983 | 435 | Mar 1987 | 483 | Mar 1991 |
| 292 | Apr 1975 | 340 | Apr 1979 | 388 | Apr 1983 | 436 | Apr 1987 | 484 | Apr 1991 |
| 293 | May 1975 | 341 | May 1979 | 389 | May 1983 | 437 | May 1987 | 485 | May 1991 |
| 294 | June 1975 | 342 | June 1979 | 390 | June 1983 | 438 | June 1987 | 486 | June 1991 |
| 295 | July 1975 | 343 | July 1979 | 391 | July 1983 | 439 | July 1987 | 487 | July 1991 |
| 296 | Aug 1975 | 344 | Aug 1979 | 392 | Aug 1983 | 440 | Aug 1987 | 488 | Aug 1991 |
| 297 | Sept 1975 | 345 | Sept 1979 | 393 | Sept 1983 | 441 | Sept 1987 | 489 | Sept 1991 |
| 298 | Oct 1975 | 346 | Oct 1979 | 394 | Oct 1983 | 442 | Oct 1987 | 490 | Oct 1991 |
| 299 | Nov 1975 | 347 | Nov 1979 | 395 | Nov 1983 | 443 | Nov 1987 | 491 | Nov 1991 |
| 300 | Dec 1975 | 348 | Dec 1979 | 396 | Dec 1983 | 444 | Dec 1987 | 492 | Dec 1991 |
| 301 | Jan 1976 | 349 | Jan 1980 | 397 | Jan 1984 | 445 | Jan 1988 | 493 | Jan 1992 |
| 302 | Feb 1976 | 350 | Feb 1980 | 398 | Feb 1984 | 446 | Feb 1988 | 494 | Feb 1992 |
| 303 | Mar 1976 | 351 | Mar 1980 | 399 | Mar 1984 | 447 | Mar 1988 | 495 | Mar 1992 |
| 304 | Apr 1976 | 352 | Apr 1980 | 400 | Apr 1984 | 448 | Apr 1988 | 496 | Apr 1992 |
| 305 | May 1976 | 353 | May 1980 | 401 | May 1984 | 449 | May 1988 | 497 | May 1992 |
| 306 | June 1976 | 354 | June 1980 | 402 | June 1984 | 450 | June 1988 | 498 | June 1992 |
| 307 | July 1976 | 355 | July 1980 | 403 | July 1984 | 451 | July 1988 | 499 | July 1992 |
| 308 | Aug 1976 | 356 | Aug 1980 | 404 | Aug 1984 | 452 | Aug 1988 | 500 | Aug 1992 |
| 309 | Sept 1976 | 357 | Sept 1980 | 405 | Sept 1984 | 453 | Sept 1988 | 501 | Sept 1992 |
| 310 | Oct 1976 | 358 | Oct 1980 | 406 | Oct 1984 | 454 | Oct 1988 | 502 | Oct 1992 |
| 311 | Nov 1976 | 359 | Nov 1980 | 407 | Nov 1984 | 455 | Nov 1988 | 503 | Nov 1992 |
| 312 | Dec 1976 | 360 | Dec 1980 | 408 | Dec 1984 | 456 | Dec 1988 | 504 | Dec 1992 |
| 313 | Jan 1977 | 361 | Jan 1981 | 409 | Jan 1985 | 457 | Jan 1989 | 505 | Jan 1993 |
| 314 | Feb 1977 | 362 | Feb 1981 | 410 | Feb 1985 | 458 | Feb 1989 | 506 | Feb 1993 |
| 315 | Mar 1977 | 363 | Mar 1981 | 411 | Mar 1985 | 459 | Mar 1989 | 507 | Mar 1993 |
| 316 | Apr 1977 | 364 | Apr 1981 | 412 | Apr 1985 | 460 | Apr 1989 | 508 | Apr 1993 |
| 317 | May 1977 | 365 | May 1981 | 413 | May 1985 | 461 | May 1989 | 509 | May 1993 |
| 318 | June 1977 | 366 | June 1981 | 414 | June 1985 | 462 | June 1989 | 510 | June 1993 |
| 319 | July 1977 | 367 | July 1981 | 415 | July 1985 | 463 | July 1989 | 511 | July 1993 |
| 320 | Aug 1977 | 368 | Aug 1981 | 416 | Aug 1985 | 464 | Aug 1989 | 512 | Aug 1993 |
| 321 | Sept 1977 | 369 | Sept 1981 | 417 | Sept 1985 | 465 | Sept 1989 | 513 | Sept 1993 |
| 322 | Oct 1977 | 370 | Oct 1981 | 418 | Oct 1985 | 466 | Oct 1989 | 514 | Oct 1993 |
| 323 | Nov 1977 | 371 | Nov 1981 | 419 | Nov 1985 | 467 | Nov 1989 | 515 | Nov 1993 |
| 324 | Dec 1977 | 372 | Dec 1981 | 420 | Dec 1985 | 468 | Dec 1989 | 516 | Dec 1993 |
| 325 | Jan 1978 | 373 | Jan 1982 | 421 | Jan 1986 | 469 | Jan 1990 | 517 | Jan 1994 |
| 326 | Feb 1978 | 374 | Feb 1982 | 422 | Feb 1986 | 470 | Feb 1990 | 518 | Feb 1994 |
| 327 | Mar 1978 | 375 | Mar 1982 | 423 | Mar 1986 | 471 | Mar 1990 | 519 | Mar 1994 |
| 328 | Apr 1978 | 376 | Apr 1982 | 424 | Apr 1986 | 472 | Apr 1990 | 520 | Apr 1994 |
| 329 | May 1978 | 377 | May 1982 | 425 | May 1986 | 473 | May 1990 | 521 | May 1994 |
| 330 | June 1978 | 378 | June 1982 | 426 | June 1986 | 474 | June 1990 | 522 | June 1994 |
| 331 | July 1978 | 379 | July 1982 | 427 | July 1986 | 475 | July 1990 | 523 | July 1994 |
| 332 | Aug 1978 | 380 | Aug 1982 | 428 | Aug 1986 | 476 | Aug 1990 | 524 | Aug 1994 |
| 333 | Sept 1978 | 381 | Sept 1982 | 429 | Sept 1986 | 477 | Sept 1990 | 525 | Sept 1994 |
| 334 | Oct 1978 | 382 | Oct 1982 | 430 | Oct 1986 | 478 | Oct 1990 | 526 | Oct 1994 |
| 335 | Nov 1978 | 383 | Nov 1982 | 431 | Nov 1986 | 479 | Nov 1990 | 527 | Nov 1994 |
| 336 | Dec 1978 | 384 | Dec 1982 | 432 | Dec 1986 | 480 | Dec 1990 | 528 | Dec 1994 |

**Appendix I2.** Initial estimated and PEST-derived demand-pattern factors used in water-distribution system model simulations, September 22–October 12, 2004, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]

[PEST, parameter estimation modeling software developed by Doherty (2005); —, not applicable]

| September 22 | | | September 24 | | | September 26 | | | September 28 | | | September 30 | | | October 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST |
| 0000 | — | — | 0000 | 0.12 | 0.41 | 0000 | 1.70 | 1.13 | 0000 | 1.31 | [2]1.84 | 0000 | 0.96 | 0.99 | 0000 | 1.59 | 1.46 |
| 0100 | — | — | 0100 | 0.15 | 0.45 | 0100 | 0.00 | 0.00 | 0100 | 0.00 | 0.00 | 0100 | 0.35 | 0.36 | 0100 | 0.00 | 0.00 |
| 0200 | — | — | 0200 | 0.61 | 0.52 | 0200 | 0.02 | 0.01 | 0200 | 0.28 | 0.05 | 0200 | 0.02 | 0.07 | 0200 | 0.00 | 0.00 |
| 0300 | — | — | 0300 | 0.45 | 0.40 | 0300 | 0.10 | 0.29 | 0300 | 0.61 | 0.83 | 0300 | 0.80 | 0.41 | 0300 | 0.12 | 0.27 |
| 0400 | — | — | 0400 | 0.39 | 0.70 | 0400 | 0.32 | 0.84 | 0400 | 0.85 | 0.32 | 0400 | 1.86 | 1.77 | 0400 | 0.20 | 0.56 |
| 0500 | — | — | 0500 | 1.69 | 1.04 | 0500 | 1.27 | 0.77 | 0500 | 0.67 | 0.93 | 0500 | 1.89 | 1.86 | 0500 | 0.51 | 0.19 |
| 0600 | 1.75 | 1.77 | 0600 | 0.66 | 0.62 | 0600 | 0.25 | 0.00 | 0600 | 1.32 | 1.90 | 0600 | 1.89 | 1.89 | 0600 | 0.74 | 1.01 |
| 0700 | 1.30 | 0.98 | 0700 | 1.09 | 0.79 | 0700 | 0.58 | 0.45 | 0700 | 0.81 | 0.86 | 0700 | 1.89 | 1.89 | 0700 | 1.14 | 1.37 |
| 0800 | 0.22 | 0.00 | 0800 | 1.25 | 1.61 | 0800 | 1.29 | 2.05 | 0800 | 0.78 | 0.74 | 0800 | 1.89 | 1.89 | 0800 | 1.17 | 0.96 |
| 0900 | 0.98 | 1.06 | 0900 | 1.66 | 1.83 | 0900 | 1.51 | 2.07 | 0900 | 1.26 | 0.96 | 0900 | 1.91 | 1.94 | 0900 | 1.50 | 1.47 |
| 1000 | 1.41 | 1.50 | 1000 | 1.78 | 2.45 | 1000 | 1.29 | 1.01 | 1000 | 1.17 | 0.87 | 1000 | 0.42 | 0.85 | 1000 | 2.60 | 1.88 |
| 1100 | 0.98 | 1.08 | 1100 | 1.27 | 1.55 | 1100 | 2.01 | 1.79 | 1100 | 1.13 | 1.62 | 1100 | 1.34 | 0.71 | 1100 | 1.40 | 1.53 |
| 1200 | 1.18 | 1.12 | 1200 | 1.11 | 0.41 | 1200 | 0.97 | 0.75 | 1200 | 1.02 | 0.75 | 1200 | 1.00 | 1.05 | 1200 | 1.46 | 1.31 |
| 1300 | 1.64 | 1.40 | 1300 | 1.21 | 1.60 | 1300 | 0.82 | 1.27 | 1300 | 1.19 | 0.98 | 1300 | 0.96 | 0.70 | 1300 | 1.29 | 1.14 |
| 1400 | 0.70 | 0.74 | 1400 | 1.64 | 2.03 | 1400 | 1.36 | 0.75 | 1400 | 0.94 | 1.24 | 1400 | 1.33 | 1.24 | 1400 | 1.21 | 1.17 |
| 1500 | 0.47 | 1.18 | 1500 | 0.62 | 0.86 | 1500 | 1.36 | 1.53 | 1500 | 1.47 | 1.44 | 1500 | 1.09 | 1.08 | 1500 | 1.03 | 1.21 |
| 1600 | 1.39 | 1.15 | 1600 | 0.83 | 0.73 | 1600 | 1.38 | 1.80 | 1600 | 1.04 | 0.87 | 1600 | 0.89 | 0.67 | 1600 | 0.95 | 0.86 |
| 1700 | 1.11 | 0.95 | 1700 | 1.50 | 0.53 | 1700 | 0.94 | 0.70 | 1700 | 0.96 | 1.17 | 1700 | 0.77 | 2.01 | 1700 | 1.55 | 1.41 |
| 1800 | 1.37 | 1.26 | 1800 | 2.14 | 1.85 | 1800 | 0.67 | 1.67 | 1800 | 1.24 | 0.88 | 1800 | 0.42 | 0.88 | 1800 | 0.86 | 0.52 |
| 1900 | 1.74 | 1.57 | 1900 | 1.51 | 2.44 | 1900 | 0.45 | 1.44 | 1900 | 1.51 | 2.03 | 1900 | 1.59 | 1.50 | 1900 | 1.03 | 1.31 |
| 2000 | 1.09 | 1.38 | 2000 | 0.41 | 0.00 | 2000 | 2.25 | 0.38 | 2000 | 1.37 | 1.44 | 2000 | 1.74 | 1.47 | 2000 | 1.54 | 1.30 |
| 2100 | 1.33 | 1.04 | 2100 | 0.91 | 0.26 | 2100 | 1.29 | 1.66 | 2100 | 1.14 | 0.52 | 2100 | 1.89 | 1.77 | 2100 | 1.89 | 1.73 |
| 2200 | 0.97 | 0.55 | 2200 | 1.36 | 2.36 | 2200 | 0.83 | 0.28 | 2200 | 1.04 | 0.80 | 2200 | 1.89 | 1.85 | 2200 | 1.86 | 1.77 |
| 2300 | 0.00 | 0.00 | 2300 | 0.00 | 0.00 | 2300 | 0.78 | 0.88 | 2300 | 0.20 | 0.46 | 2300 | 1.89 | 1.88 | 2300 | 1.68 | 1.59 |

| September 23 | | | September 25 | | | September 27 | | | September 29 | | | October 1 | | | October 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST |
| 0000 | 0.00 | 0.00 | 0000 | 0.65 | 0.00 | 0000 | 0.38 | 0.00 | 0000 | 1.87 | 2.14 | 0000 | 1.86 | 1.83 | 0000 | 0.00 | 0.00 |
| 0100 | 0.00 | 0.00 | 0100 | 0.69 | 1.23 | 0100 | 0.39 | 0.33 | 0100 | 0.00 | 0.00 | 0100 | 1.89 | 1.87 | 0100 | 0.02 | 0.00 |
| 0200 | 0.02 | 0.00 | 0200 | 0.56 | 0.00 | 0200 | 0.56 | 0.99 | 0200 | 0.15 | 0.00 | 0200 | 1.89 | 1.89 | 0200 | 0.15 | 0.39 |
| 0300 | 0.15 | 0.40 | 0300 | 1.17 | 1.62 | 0300 | 0.41 | 0.00 | 0300 | 0.12 | 0.07 | 0300 | 0.43 | 0.26 | 0300 | 0.17 | 0.50 |
| 0400 | 0.27 | 0.72 | 0400 | 0.00 | 0.49 | 0400 | 0.78 | 1.11 | 0400 | 0.26 | 0.00 | 0400 | 0.25 | 0.00 | 0400 | 0.93 | 0.68 |
| 0500 | 0.74 | 0.56 | 0500 | 0.31 | 0.00 | 0500 | 0.96 | 1.33 | 0500 | 0.30 | 0.45 | 0500 | 1.14 | 0.46 | 0500 | 0.20 | 0.32 |
| 0600 | 1.62 | 1.34 | 0600 | 0.00 | 0.00 | 0600 | 0.97 | 1.03 | 0600 | 1.23 | 1.12 | 0600 | 0.80 | 0.78 | 0600 | 0.51 | 0.31 |
| 0700 | 0.74 | 0.25 | 0700 | 0.10 | 0.27 | 0700 | 0.94 | 0.82 | 0700 | 0.95 | 1.30 | 0700 | 1.18 | 1.59 | 0700 | 0.77 | 0.99 |
| 0800 | 0.84 | 1.29 | 0800 | 2.11 | 1.61 | 0800 | 0.72 | 0.53 | 0800 | 0.84 | 0.07 | 0800 | 0.67 | 0.18 | 0800 | 1.45 | 1.38 |
| 0900 | 1.36 | 1.60 | 0900 | 1.52 | 1.53 | 0900 | 0.98 | 0.63 | 0900 | 0.00 | 0.33 | 0900 | 0.93 | 1.40 | 0900 | 1.54 | 1.72 |
| 1000 | 1.82 | 1.65 | 1000 | 1.66 | 1.63 | 1000 | 0.90 | 1.23 | 1000 | 0.70 | 1.25 | 1000 | 1.39 | 1.57 | 1000 | 1.71 | 1.79 |
| 1100 | 1.33 | 1.94 | 1100 | 1.39 | 1.39 | 1100 | 1.51 | 1.72 | 1100 | 1.20 | 1.20 | 1100 | 1.41 | 1.65 | 1100 | 1.79 | 1.86 |
| 1200 | 1.30 | 1.96 | 1200 | 1.46 | 1.38 | 1200 | 1.04 | 0.24 | 1200 | 2.18 | 2.35 | 1200 | 1.91 | 1.88 | 1200 | 1.31 | 1.88 |
| 1300 | 1.70 | 1.75 | 1300 | 1.80 | 1.74 | 1300 | 0.85 | 1.33 | 1300 | 0.93 | 0.78 | 1300 | 1.35 | 1.95 | 1300 | 1.37 | 1.32 |
| 1400 | 0.85 | 0.91 | 1400 | 0.00 | 0.57 | 1400 | 1.20 | 1.06 | 1400 | 0.52 | 1.29 | 1400 | 1.86 | 1.85 | 1400 | 1.00 | 1.20 |
| 1500 | 0.88 | 0.97 | 1500 | 1.13 | 1.19 | 1500 | 0.89 | 1.34 | 1500 | 0.37 | 1.17 | 1500 | 1.89 | 1.88 | 1500 | 1.62 | 1.45 |
| 1600 | 2.00 | 1.16 | 1600 | 0.78 | 0.99 | 1600 | 1.22 | 0.77 | 1600 | 2.40 | 0.86 | 1600 | 1.89 | 1.88 | 1600 | 1.72 | 1.40 |
| 1700 | 1.77 | 1.52 | 1700 | 1.49 | 1.04 | 1700 | 1.35 | 1.68 | 1700 | 2.03 | 2.00 | 1700 | 1.86 | 1.83 | 1700 | 1.40 | 1.54 |
| 1800 | 0.73 | 0.96 | 1800 | 1.64 | 1.34 | 1800 | 1.25 | 1.55 | 1800 | 0.00 | 0.46 | 1800 | 1.89 | 1.88 | 1800 | 1.12 | 1.42 |
| 1900 | 1.21 | 1.26 | 1900 | 0.74 | 1.16 | 1900 | 0.83 | 1.18 | 1900 | 0.70 | 1.81 | 1900 | 1.22 | 1.15 | 1900 | 1.10 | 1.20 |
| 2000 | 2.10 | 1.70 | 2000 | 1.25 | 0.94 | 2000 | 1.63 | 1.05 | 2000 | 0.74 | 0.77 | 2000 | 0.89 | 0.92 | 2000 | 1.59 | 1.36 |
| 2100 | 2.85 | 2.69 | 2100 | 0.27 | 0.33 | 2100 | 1.31 | 1.09 | 2100 | 1.91 | 1.18 | 2100 | 1.89 | 2.03 | 2100 | 1.50 | 1.43 |
| 2200 | 0.18 | 0.00 | 2200 | 0.85 | 0.85 | 2200 | 1.18 | 1.24 | 2200 | 0.37 | 0.00 | 2200 | 1.86 | 1.87 | 2200 | 1.07 | 0.77 |
| 2300 | 0.00 | 0.06 | 2300 | 0.24 | 0.00 | 2300 | 0.77 | 0.27 | 2300 | 0.84 | 0.62 | 2300 | 1.89 | 1.87 | 2300 | 0.30 | 0.57 |

**Appendix I2.** Initial estimated and PEST-derived demand-pattern factors used in water-distribution system model simulations, September 22–October 12, 2004, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.[1]—Continued

[PEST, parameter estimation modeling software developed by Doherty (2005); —, not applicable]

| October 4 | | | October 6 | | | October 8 | | | October 10 | | | October 12 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST |
| 0000 | 0.69 | 0.41 | 0000 | 0.58 | 0.91 | 0000 | 1.03 | 0.66 | 0000 | 1.79 | 2.02 | 0000 | 0.23 | 0.00 |
| 0100 | 0.17 | 0.29 | 0100 | 0.70 | 0.41 | 0100 | 0.15 | 0.01 | 0100 | 0.05 | 0.01 | 0100 | 0.19 | 0.00 |
| 0200 | 1.03 | 0.71 | 0200 | 0.12 | 0.16 | 0200 | 0.25 | 0.69 | 0200 | 0.05 | [3]0.13 | 0200 | 0.10 | 0.07 |
| 0300 | 0.20 | 0.23 | 0300 | 0.71 | 0.61 | 0300 | 0.86 | 0.60 | 0300 | 0.73 | 0.18 | 0300 | 0.12 | 0.35 |
| 0400 | 0.72 | 0.98 | 0400 | 0.54 | 0.65 | 0400 | 0.15 | 0.19 | 0400 | 0.07 | 0.00 | 0400 | 0.47 | 0.96 |
| 0500 | 1.53 | 1.14 | 0500 | 0.83 | 0.54 | 0500 | 0.79 | 0.50 | 0500 | 0.15 | 0.29 | 0500 | 1.20 | 1.16 |
| 0600 | 1.01 | 0.78 | 0600 | 0.63 | 1.15 | 0600 | 0.57 | 1.20 | 0600 | 0.17 | 0.50 | 0600 | 1.10 | 0.94 |
| 0700 | 1.18 | 1.21 | 0700 | 1.59 | 1.50 | 0700 | 1.62 | 1.07 | 0700 | 0.81 | 0.59 | 0700 | 0.66 | 0.27 |
| 0800 | 1.12 | 1.53 | 0800 | 1.24 | 1.57 | 0800 | 0.97 | 0.84 | 0800 | 0.66 | 1.14 | 0800 | 0.42 | 0.91 |
| 0900 | 1.23 | 1.01 | 0900 | 0.85 | 0.82 | 0900 | 0.82 | 1.58 | 0900 | 1.92 | 1.52 | 0900 | 1.40 | 1.36 |
| 1000 | 1.01 | 0.73 | 1000 | 0.96 | 0.70 | 1000 | 1.24 | 0.83 | 1000 | 1.39 | 1.36 | 1000 | 1.47 | 1.60 |
| 1100 | 1.05 | 1.57 | 1100 | 0.99 | 1.28 | 1100 | 1.23 | 1.30 | 1100 | 1.76 | 1.80 | 1100 | 1.34 | 1.34 |
| 1200 | 1.49 | 1.23 | 1200 | 1.48 | 1.41 | 1200 | 1.64 | 1.40 | 1200 | 1.91 | 1.92 | 1200 | 0.66 | 0.36 |
| 1300 | 0.81 | 1.26 | 1300 | 0.89 | 0.78 | 1300 | 0.94 | 0.88 | 1300 | 0.13 | 0.86 | 1300 | 0.62 | 1.41 |
| 1400 | 1.12 | 0.84 | 1400 | 0.95 | 1.12 | 1400 | 0.42 | 0.92 | 1400 | 0.30 | 0.76 | 1400 | 1.59 | 0.93 |
| 1500 | 0.86 | 0.53 | 1500 | 0.71 | 0.84 | 1500 | 0.91 | 1.02 | 1500 | 1.24 | 1.53 | 1500 | 0.94 | 0.39 |
| 1600 | 1.17 | 1.35 | 1600 | 1.37 | 1.24 | 1600 | 1.28 | 1.04 | 1600 | 0.86 | 0.81 | 1600 | 0.62 | 1.38 |
| 1700 | 1.49 | 1.40 | 1700 | 1.61 | 1.51 | 1700 | 0.74 | 0.78 | 1700 | 1.13 | 1.18 | 1700 | 1.35 | 1.24 |
| 1800 | 1.68 | 1.68 | 1800 | 1.39 | 1.14 | 1800 | 1.16 | 0.99 | 1800 | 1.01 | 1.04 | 1800 | 0.71 | 0.30 |
| 1900 | 1.11 | 1.58 | 1900 | 0.90 | 0.81 | 1900 | 0.66 | 0.59 | 1900 | 0.88 | 0.77 | 1900 | 0.74 | 1.66 |
| 2000 | 1.03 | 0.75 | 2000 | 0.99 | 1.65 | 2000 | 0.62 | 0.81 | 2000 | 1.02 | 0.89 | 2000 | 0.40 | 1.33 |
| 2100 | 1.11 | 1.14 | 2100 | 1.54 | 1.37 | 2100 | 1.08 | 0.92 | 2100 | 0.64 | 0.78 | 2100 | 1.86 | 1.17 |
| 2200 | 1.31 | 1.07 | 2200 | 1.01 | 1.24 | 2200 | 0.51 | 0.51 | 2200 | 0.79 | 0.61 | 2200 | 1.27 | 0.40 |
| 2300 | 0.22 | 0.31 | 2300 | 0.71 | 0.28 | 2300 | 0.82 | 0.68 | 2300 | 0.66 | 0.33 | 2300 | 0.59 | 0.19 |

| October 5 | | | October 7 | | | October 9 | | | October 11 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST | Hour | Initial | PEST |
| 0000 | 0.86 | 0.59 | 0000 | 0.17 | 0.19 | 0000 | 0.40 | 0.44 | 0000 | 0.43 | 0.08 |
| 0100 | 0.20 | 0.33 | 0100 | 0.48 | 0.26 | 0100 | 0.22 | 0.61 | 0100 | 0.12 | 0.24 |
| 0200 | 0.33 | 0.44 | 0200 | 0.43 | 0.55 | 0200 | 0.61 | 0.33 | 0200 | 0.12 | 0.37 |
| 0300 | 0.53 | 0.44 | 0300 | 0.25 | 0.68 | 0300 | 0.12 | 0.17 | 0300 | 0.68 | 0.90 |
| 0400 | 0.98 | 0.91 | 0400 | 1.19 | 0.85 | 0400 | 1.04 | 0.79 | 0400 | 1.79 | 0.74 |
| 0500 | 1.06 | 1.13 | 0500 | 0.57 | 1.06 | 0500 | 0.87 | 0.46 | 0500 | 0.24 | 0.30 |
| 0600 | 1.15 | 0.80 | 0600 | 1.29 | 1.12 | 0600 | 0.15 | 0.12 | 0600 | 0.39 | 0.26 |
| 0700 | 0.50 | 1.02 | 0700 | 0.86 | 0.41 | 0700 | 0.68 | 0.68 | 0700 | 0.64 | 0.75 |
| 0800 | 1.14 | 1.12 | 0800 | 1.19 | 1.37 | 0800 | 0.86 | 1.17 | 0800 | 0.72 | 0.73 |
| 0900 | 1.21 | 1.27 | 0900 | 1.34 | 1.35 | 0900 | 1.27 | 1.93 | 0900 | 1.23 | 1.29 |
| 1000 | 1.38 | 1.56 | 1000 | 1.13 | 1.33 | 1000 | 0.88 | 0.87 | 1000 | 1.46 | 1.19 |
| 1100 | 1.19 | 1.03 | 1100 | 0.99 | 1.10 | 1100 | 1.15 | 1.03 | 1100 | 1.03 | 0.89 |
| 1200 | 0.89 | 0.50 | 1200 | 0.96 | 0.88 | 1200 | 1.21 | 1.30 | 1200 | 1.35 | 1.63 |
| 1300 | 0.97 | 1.47 | 1300 | 1.17 | 1.03 | 1300 | 1.49 | 1.17 | 1300 | 2.28 | 2.44 |
| 1400 | 1.37 | 1.29 | 1400 | 1.08 | 1.11 | 1400 | 1.89 | 1.69 | 1400 | 1.26 | 1.27 |
| 1500 | 0.96 | 0.78 | 1500 | 1.18 | 1.00 | 1500 | 1.89 | 1.83 | 1500 | 1.08 | 0.94 |
| 1600 | 0.88 | 1.46 | 1600 | 0.66 | 0.49 | 1600 | 1.86 | 1.82 | 1600 | 0.84 | 0.66 |
| 1700 | 1.13 | 1.31 | 1700 | 0.90 | 1.61 | 1700 | 1.89 | 1.87 | 1700 | 1.14 | 1.21 |
| 1800 | 1.59 | 1.37 | 1800 | 1.54 | 1.40 | 1800 | 1.89 | 1.89 | 1800 | 1.37 | 1.66 |
| 1900 | 1.82 | 1.59 | 1900 | 1.72 | 1.45 | 1900 | 1.76 | 1.83 | 1900 | 1.37 | 1.37 |
| 2000 | 1.47 | 1.64 | 2000 | 1.23 | 0.91 | 2000 | 0.90 | 0.74 | 2000 | 0.64 | 0.29 |
| 2100 | 1.02 | 0.76 | 2100 | 0.50 | 1.04 | 2100 | 0.10 | 0.00 | 2100 | 0.95 | 1.01 |
| 2200 | 0.92 | 0.11 | 2200 | 0.71 | 0.47 | 2200 | 0.17 | 0.45 | 2200 | 1.06 | 1.28 |
| 2300 | 0.45 | 0.65 | 2300 | 0.30 | 0.60 | 2300 | 0.17 | 0.52 | 2300 | 0.91 | 0.66 |

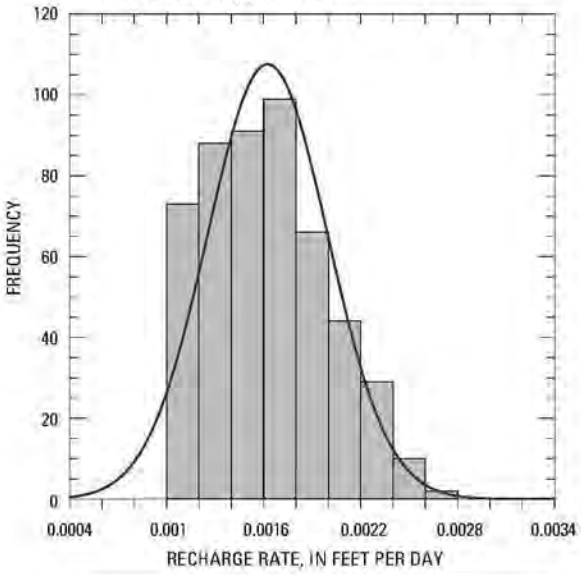
[1]Initial values for demand-pattern factors estimated from water-balance analysis derived from information and data contained in a water-conservation analysis conducted by EGG, Inc. (1999)

[2]Demand-pattern factor modified to 1.80 for calibrated model

[3]Demand-pattern factor modified to 0.15 for calibrated model

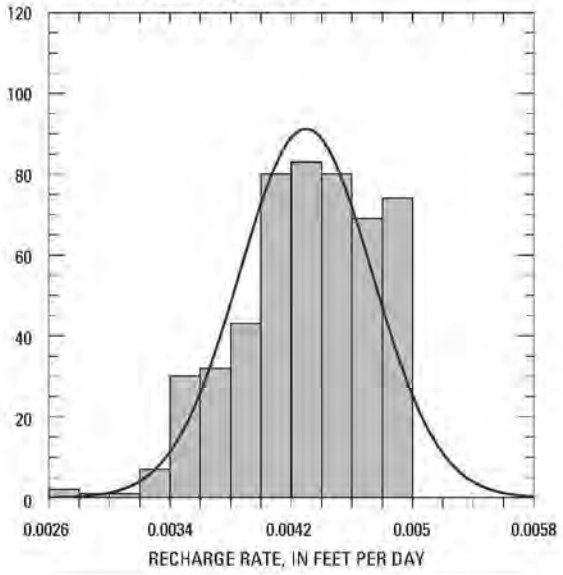
**Appendix I3.** Probability density functions for uncertain model input parameters (variants) derived using pseudo-random number generators.

**Infiltration ($I_R$): Dry year–1968**



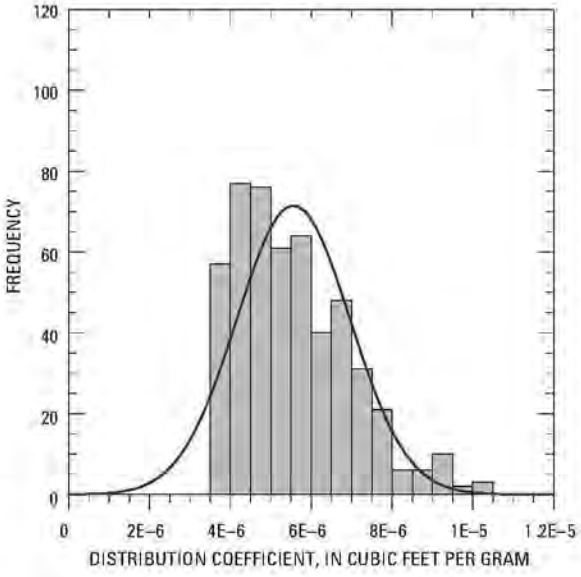

| STATISTICS | Theoretical | Monte Carlo simulation |
|---|---|---|
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 0.001 |
| Maximum | + Infinity | 0.005 |
| Mean | 0.0015 | 0.0016 |
| Mode | 0.0015 | #N/A |
| Median | 0.0015 | 0.0016 |
| Standard deviation | 0.0005 | 0.0004 |

**Infiltration ($I_R$): Wet year–1974**



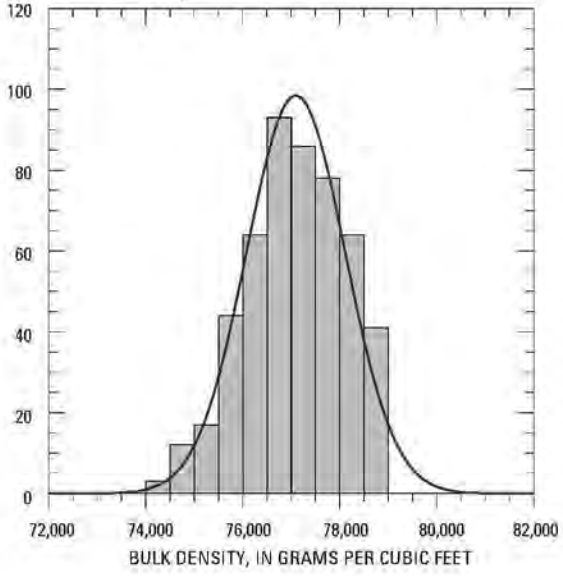

| STATISTICS | Theoretical | Monte Carlo simulation |
|---|---|---|
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 0.001 |
| Maximum | + Infinity | 0.005 |
| Mean | 0.0044 | 0.0043 |
| Mode | 0.0044 | #N/A |
| Median | 0.0044 | 0.0043 |
| Standard deviation | 0.0005 | 0.0004 |

**Distribution coefficient ($K_d$)**




| STATISTICS | Theoretical | Monte Carlo simulation |
|---|---|---|
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 3.5315E-06 |
| Maximum | + Infinity | 2.6839E-06 |
| Mean | 5E-06 | 5.5550E-06 |
| Mode | 5E-06 | #N/A |
| Median | 5E-06 | 5.3030E-06 |
| Standard deviation | 1.7657E-06 | 1.3876E-06 |

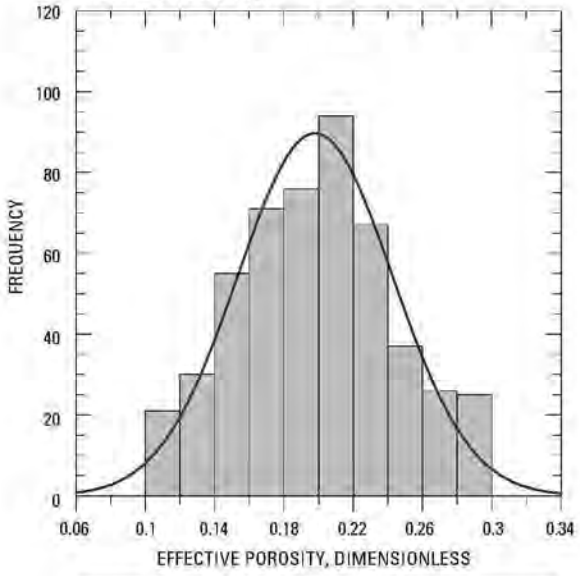
**Bulk density ($\rho_b$)**




| STATISTICS | Theoretical | Monte Carlo simulation |
|---|---|---|
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 69,943 |
| Maximum | + Infinity | 79,004 |
| Mean | 77,112 | 77,097 |
| Mode | 77,112 | 77,512 |
| Median | 77,112 | 77,104 |
| Standard deviation | 1,100 | 1,009 |

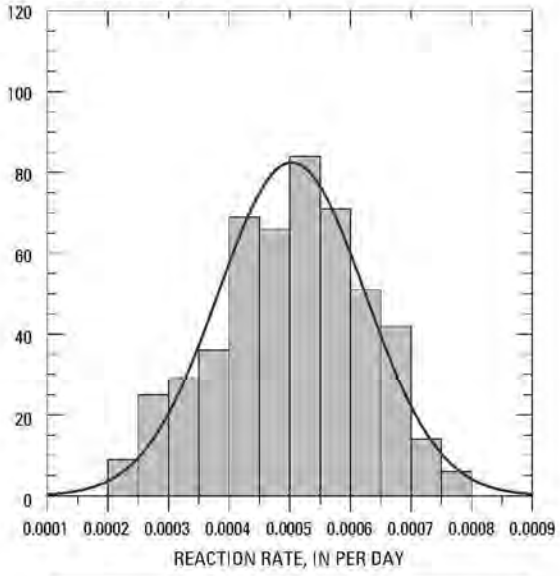
**Appendix I3.** Probability density functions for uncertain model input parameters (variants) derived using pseudo-random number generators.—Continued

**Effective porosity ($n_E$)**



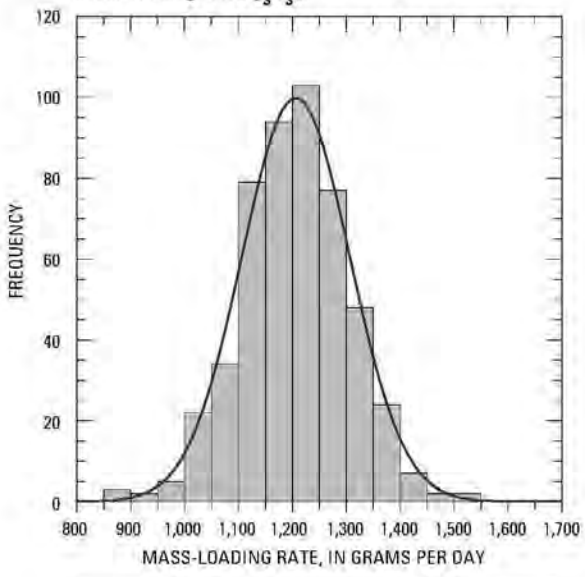

| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 0.1 |
| Maximum | + Infinity | 0.3 |
| Mean | 0.2 | 0.1980 |
| Mode | 0.2 | #N/A |
| Median | 0.2 | 0.1992 |
| Standard deviation | 0.05 | 0.0444 |

**Reaction rate ($r$)**



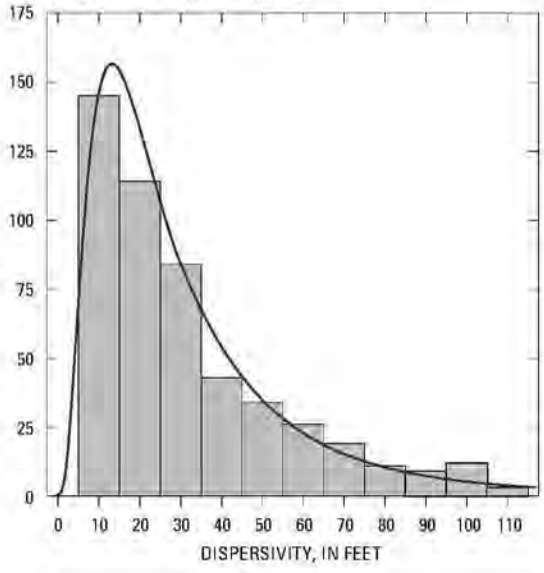

| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 2.3000E-04 |
| Maximum | + Infinity | 7.7000E-04 |
| Mean | 5E-04 | 5.0309E-04 |
| Mode | 5E-04 | #N/A |
| Median | 5E-04 | 5.1309E-04 |
| Standard deviation | 1.35E-04 | 1.2059E-04 |

**Mass-loading rate ($q_s C_s$)**




| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Normal | Normal |
| Number of realizations | Not applicable | 500 |
| Minimum | –Infinity | 200 |
| Maximum | +Infinity | 2,200 |
| Mean | 1,200 | 1,206.3168 |
| Mode | 1,200 | 1,190.2700 |
| Median | 1,200 | 1,207.9450 |
| Standard deviation | 100 | 98.3915 |

**Longitudinal dispersivity ($\alpha_L$)**




| STATISTICS | | |
|---|---|---|
| | Theoretical | Monte Carlo simulation |
| Distribution | Lognormal | Lognormal |
| Number of realizations | Not applicable | 500 |
| Minimum | 0 | 5 |
| Maximum | + Infinity | 125 |
| Mean | 34.56 | 31.3200 |
| Mode | 13.08 | #N/A |
| Median | 25 | 23.8500 |
| Standard deviation | 32.98 | 23.5900 |

**Appendix I4.** Methods for deriving probabilities of occurrence using simulated tetrachloroethylene (PCE) concentrations in finished drinking water, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina. [*P*, probability; Z, evaluated value in the standard normal distribution; $\infty$, infinity]

Appendix I4 presents two methods for determining the probability of occurrence of a specified concentration. In these methods, Monte Carlo simulation results for stress period 337, January 1979, are used for example calculations. For this stress period, the mean ($\mu$) and standard deviation ($\sigma$) for 510 Monte Carlo realizations are 113 and 22.6 µg/L, respectively. The concentration of interest, 100 µg/L, occurs in the interval (or bin) between 96 and 105 µg/L, shown in the histogram representing Monte Carlo simulation results for January 1979 (Figure I27*c*).

## A. Integration of the probability density function

1. The probability density function for the normal distribution is defined by the following formula:

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \tag{I4.1}$$

where:

Y is the value of the probability density function,
$\sigma$ is the standard deviation of simulated concentrations,
$x$ is the selected simulated concentration, and
$\mu$ is the mean of simulated concentrations.

2. Obtain the mean ($\mu$ = 113 µg/L) and standard deviation ($\sigma$ = 22.6 µg/L) for the January 1979 Monte Carlo simulation results. That is, the mean and standard deviation for the 510 concentration values for stress period 337, representing January 1979.

3. Using Equation I4.1 and substituting the values for the mean and standard deviation described in step 2 above, the probability density function for this set of simulations can be written as:

$$Y(x) = \frac{1}{22.6\sqrt{2\pi}} e^{-\frac{(x-113)^2}{2(22.6)^2}} \tag{I4.2}$$

4. Then the probability of occurrence for the interval of 96–105 µg/L is obtained using the following integral:

$$P(96 \le x \le 105) = \int_{96}^{105} \frac{1}{22.6\sqrt{2\pi}} e^{-\frac{(x-113)^2}{2(22.6)^2}} dx \tag{I4.3}$$

5. This integral can be solved analytically or approximated numerically for this case.[1] Using the trapezoidal Riemann sum rule we can obtain the probability of occurrence. Figure I4.1 shows the procedure used to determine the area under the curve that represents probability.

$$Y(96) = \frac{1}{22.6\sqrt{2\pi}} e^{-\frac{(96-113)^2}{2(22.6)^2}} = 0.013303 \text{ L/µg} \tag{I4.4}$$

$$Y(105) = \frac{1}{22.6\sqrt{2\pi}} e^{-\frac{(105-113)^2}{2(22.6)^2}} = 0.016580 \text{ L/µg} \tag{I4.5}$$

[1]Numerical methods are advantageous for integrals that are difficult to evaluate or cannot be solved analytically.

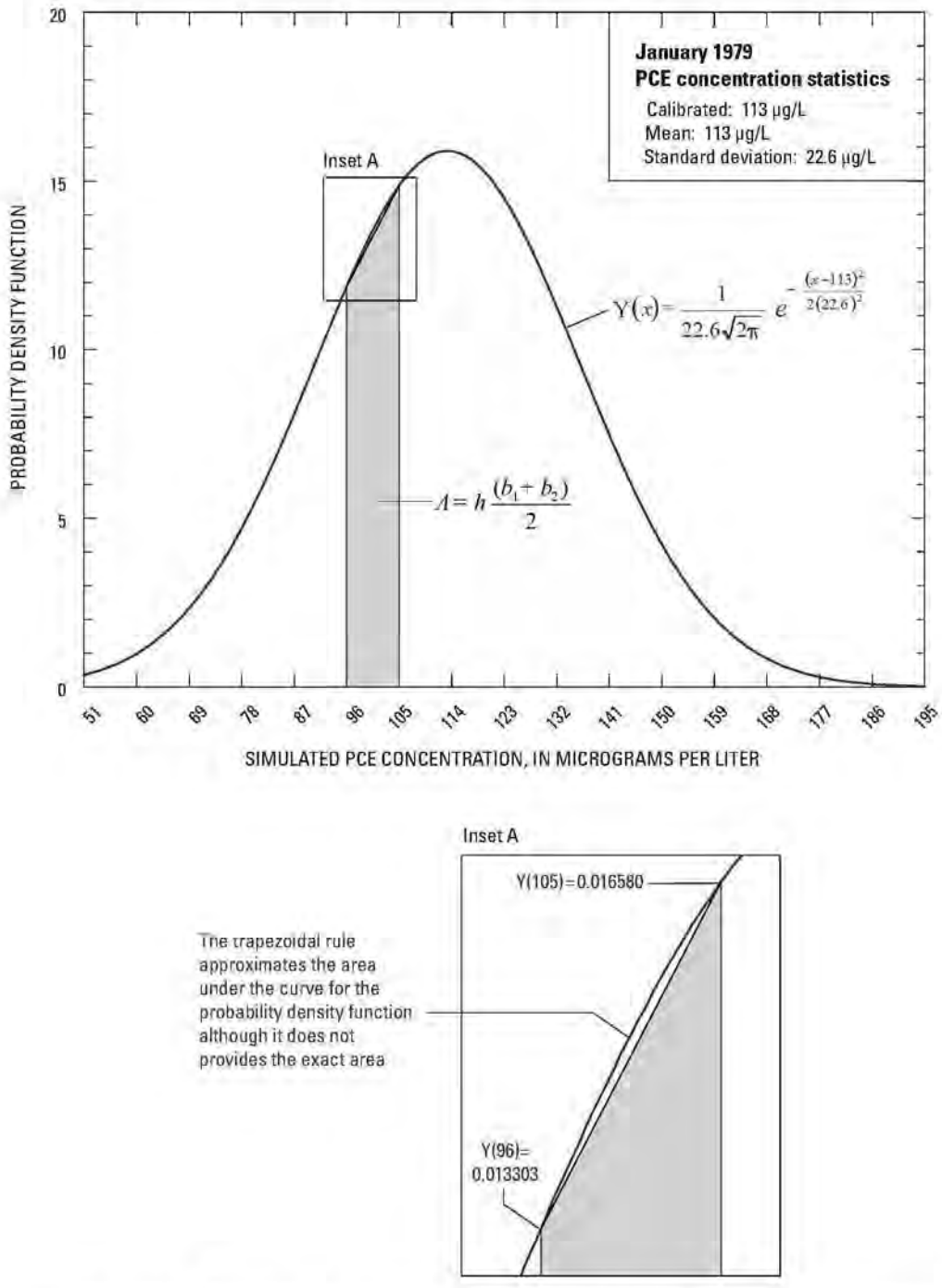



**Figure I4.1.** Probability of occurrence of tetrachloroethylene (PCE) contamination in finished water at the water treatment plant derived from the integration of the probability density function, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Using the area formula for a trapezoid,

$$A = h\frac{(b_1 + b_2)}{2}, \tag{I4.6}$$

where,

$A$ is the area under the curve or probability of occurrence,
$h$ is the height of the trapezoid (9 µg/L [105 µg/L – 96 µg/L]), and
$b_1, b_2$ are the bases of the trapezoid (0.013303 L/µg and 0.016580 L/µg, respectively).

Therefore, the probability of occurrence for concentrations between 96–105 µg/L is approximated as:

$$\mathrm{A} = 9\mu g/L\frac{(0.013303 + 0.0165850\,\mathrm{L}/\mu g)}{2} = 0.134496 = 13.45\% \tag{I4.7}$$

**B. Table of the standard normal distribution**

Another approach that can be used to obtain the probability of occurrence is by using the standard normal distribution table (Table I4.1). The following procedure, described in Haan (1977), summarizes the use of the standard normal table:

1. To use the standard normal distribution,[2] transform selected simulated concentration values as follows (using the simulated mean of µ = 113 µg/L and standard deviation of σ = 22.6 µg/L):

$$x = 96\mu g/L, \text{transforms to: } Z = \frac{x-\mu}{\sigma} = \frac{96-113}{22.6} = -0.7522 \tag{I4.8}$$

$$x = 105\mu g/L, \text{transforms to: } Z = \frac{x-\mu}{\sigma} = \frac{105-113}{22.6} = -0.3540 \tag{I4.9}$$

The standard normal distribution is symmetric about a mean = 0. Tables with negative values (such as those using Equations I4.8 and I4.9) usually are not published because all values can be obtained by using one side of the graph and complementary table values, as discussed below.

2. Obtain the probability from $-\infty$ to $Z$ from the standard normal probability table (Table I4.1). In Figure I4.2 a section of Table I4.1 is shown, specific to this example:

$$P(x \le 96) = P(Z \le -0.7522) \tag{I4.10}$$

$$= 1 - P(Z \le 0.7522) = 1 - 0.7734 = 0.2266$$

This value represents the shaded area under the curve from $-\infty$ to 96 µg/L or the probability that the concentration will be less than or equal to 96 µg/L.

$$P(x \le 105) = P(Z \le -0.3540) \tag{I4.11}$$

$$= 1 - P(Z \le 0.3540) = 1 - 0.6368 = 0.3632$$

This value represents the shaded area under the curve from $-\infty$ to 105 µg/L or the probability that the concentration will be less than or equal to 105 µg/L.

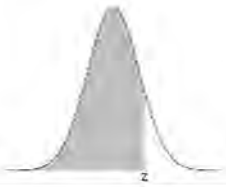
3. The probability of occurrence is obtained by subtracting the two areas such that:

$$P(96 \le x \le 105) = P(x \le 105) - P(x \le 96) \tag{I4.12}$$

$$= 0.3632 - 0.2266 = 0.1366 = 13.66\% \tag{I4.13}$$

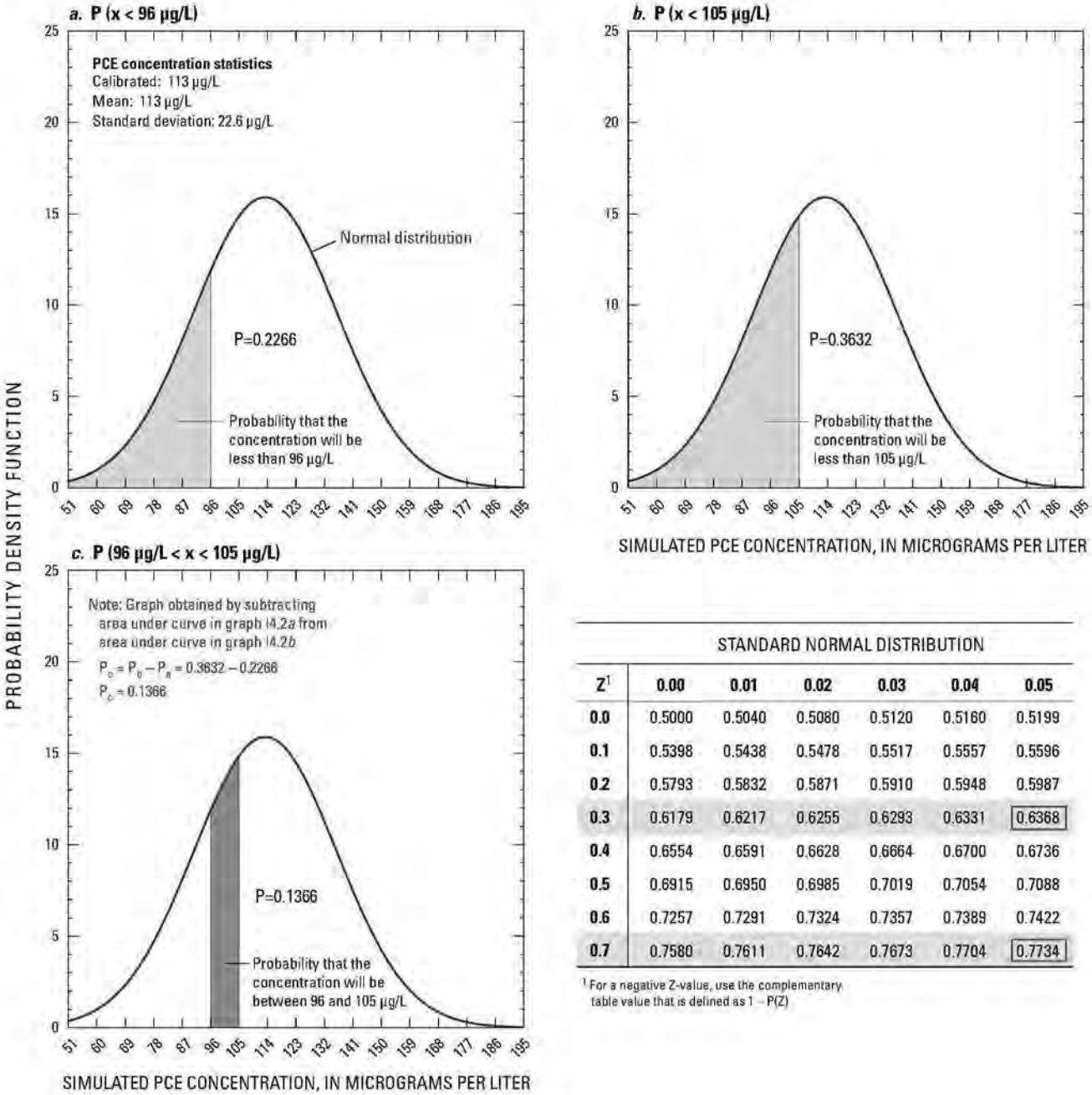
[2]A standard normal distribution has a mean of 0 and a standard deviation of 1.

**Table I4.1.** Standard normal distribution, probability content from $-\infty$ to Z.




| Z[1] | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **0.0** | 0.5000 | 0.5040 | 0.5080 | 0.5120 | 0.5160 | 0.5199 | 0.5239 | 0.5279 | 0.5319 | 0.5359 |
| **0.1** | 0.5398 | 0.5438 | 0.5478 | 0.5517 | 0.5557 | 0.5596 | 0.5636 | 0.5675 | 0.5714 | 0.5753 |
| **0.2** | 0.5793 | 0.5832 | 0.5871 | 0.5910 | 0.5948 | 0.5987 | 0.6026 | 0.6064 | 0.6103 | 0.6141 |
| **0.3** | 0.6179 | 0.6217 | 0.6255 | 0.6293 | 0.6331 | 0.6368 | 0.6406 | 0.6443 | 0.6480 | 0.6517 |
| **0.4** | 0.6554 | 0.6591 | 0.6628 | 0.6664 | 0.6700 | 0.6736 | 0.6772 | 0.6808 | 0.6844 | 0.6879 |
| **0.5** | 0.6915 | 0.6950 | 0.6985 | 0.7019 | 0.7054 | 0.7088 | 0.7123 | 0.7157 | 0.7190 | 0.7224 |
| **0.6** | 0.7257 | 0.7291 | 0.7324 | 0.7357 | 0.7389 | 0.7422 | 0.7454 | 0.7486 | 0.7517 | 0.7549 |
| **0.7** | 0.7580 | 0.7611 | 0.7642 | 0.7673 | 0.7704 | 0.7734 | 0.7764 | 0.7794 | 0.7823 | 0.7852 |
| **0.8** | 0.7881 | 0.7910 | 0.7939 | 0.7967 | 0.7995 | 0.8023 | 0.8051 | 0.8078 | 0.8106 | 0.8133 |
| **0.9** | 0.8159 | 0.8186 | 0.8212 | 0.8238 | 0.8264 | 0.8289 | 0.8315 | 0.8340 | 0.8365 | 0.8389 |
| **1.0** | 0.8413 | 0.8438 | 0.8461 | 0.8485 | 0.8508 | 0.8531 | 0.8554 | 0.8577 | 0.8599 | 0.8621 |
| **1.1** | 0.8643 | 0.8665 | 0.8686 | 0.8708 | 0.8729 | 0.8749 | 0.8770 | 0.8790 | 0.8810 | 0.8830 |
| **1.2** | 0.8849 | 0.8869 | 0.8888 | 0.8907 | 0.8925 | 0.8944 | 0.8962 | 0.8980 | 0.8997 | 0.9015 |
| **1.3** | 0.9032 | 0.9049 | 0.9066 | 0.9082 | 0.9099 | 0.9115 | 0.9131 | 0.9147 | 0.9162 | 0.9177 |
| **1.4** | 0.9192 | 0.9207 | 0.9222 | 0.9236 | 0.9251 | 0.9265 | 0.9279 | 0.9292 | 0.9306 | 0.9319 |
| **1.5** | 0.9332 | 0.9345 | 0.9357 | 0.9370 | 0.9382 | 0.9394 | 0.9406 | 0.9418 | 0.9429 | 0.9441 |
| **1.6** | 0.9452 | 0.9463 | 0.9474 | 0.9484 | 0.9495 | 0.9505 | 0.9515 | 0.9525 | 0.9535 | 0.9545 |
| **1.7** | 0.9554 | 0.9564 | 0.9573 | 0.9582 | 0.9591 | 0.9599 | 0.9608 | 0.9616 | 0.9625 | 0.9633 |
| **1.8** | 0.9641 | 0.9649 | 0.9656 | 0.9664 | 0.9671 | 0.9678 | 0.9686 | 0.9693 | 0.9699 | 0.9706 |
| **1.9** | 0.9713 | 0.9719 | 0.9726 | 0.9732 | 0.9738 | 0.9744 | 0.9750 | 0.9756 | 0.9761 | 0.9767 |
| **2.0** | 0.9772 | 0.9778 | 0.9783 | 0.9788 | 0.9793 | 0.9798 | 0.9803 | 0.9808 | 0.9812 | 0.9817 |
| **2.1** | 0.9821 | 0.9826 | 0.9830 | 0.9834 | 0.9838 | 0.9842 | 0.9846 | 0.9850 | 0.9854 | 0.9857 |
| **2.2** | 0.9861 | 0.9864 | 0.9868 | 0.9871 | 0.9875 | 0.9878 | 0.9881 | 0.9884 | 0.9887 | 0.9890 |
| **2.3** | 0.9893 | 0.9896 | 0.9898 | 0.9901 | 0.9904 | 0.9906 | 0.9909 | 0.9911 | 0.9913 | 0.9916 |
| **2.4** | 0.9918 | 0.9920 | 0.9922 | 0.9925 | 0.9927 | 0.9929 | 0.9931 | 0.9932 | 0.9934 | 0.9936 |
| **2.5** | 0.9938 | 0.9940 | 0.9941 | 0.9943 | 0.9945 | 0.9946 | 0.9948 | 0.9949 | 0.9951 | 0.9952 |
| **2.6** | 0.9953 | 0.9955 | 0.9956 | 0.9957 | 0.9959 | 0.9960 | 0.9961 | 0.9962 | 0.9963 | 0.9964 |
| **2.7** | 0.9965 | 0.9966 | 0.9967 | 0.9968 | 0.9969 | 0.9970 | 0.9971 | 0.9972 | 0.9973 | 0.9974 |
| **2.8** | 0.9974 | 0.9975 | 0.9976 | 0.9977 | 0.9977 | 0.9978 | 0.9979 | 0.9979 | 0.9980 | 0.9981 |
| **2.9** | 0.9981 | 0.9982 | 0.9982 | 0.9983 | 0.9984 | 0.9984 | 0.9985 | 0.9985 | 0.9986 | 0.9986 |
| **3.0** | 0.9987 | 0.9987 | 0.9987 | 0.9988 | 0.9988 | 0.9989 | 0.9989 | 0.9989 | 0.9990 | 0.9990 |

[1]For a negative Z-value, use the complementary table value that is defined as 1 – P(Z)




STANDARD NORMAL DISTRIBUTION

| Z[1] | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 |
|---|---|---|---|---|---|---|
| 0.0 | 0.5000 | 0.5040 | 0.5080 | 0.5120 | 0.5160 | 0.5199 |
| 0.1 | 0.5398 | 0.5438 | 0.5478 | 0.5517 | 0.5557 | 0.5596 |
| 0.2 | 0.5793 | 0.5832 | 0.5871 | 0.5910 | 0.5948 | 0.5987 |
| 0.3 | 0.6179 | 0.6217 | 0.6255 | 0.6293 | 0.6331 | 0.6368 |
| 0.4 | 0.6554 | 0.6591 | 0.6628 | 0.6664 | 0.6700 | 0.6736 |
| 0.5 | 0.6915 | 0.6950 | 0.6985 | 0.7019 | 0.7054 | 0.7088 |
| 0.6 | 0.7257 | 0.7291 | 0.7324 | 0.7357 | 0.7389 | 0.7422 |
| 0.7 | 0.7580 | 0.7611 | 0.7642 | 0.7673 | 0.7704 | 0.7734 |

[1] For a negative Z-value, use the complementary table value that is defined as 1 − P(Z)

**Figure I4.2.** Probability of occurrence of tetrachloroethylene (PCE) contamination in finished water at the water treatment plant derived from the table of the standard normal distribution, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 1-12 | Jan–Dec 1951 | WTP not operating | | | | | | |
| 13 | Jan 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 14 | Feb 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 15 | Mar 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 16 | Apr 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 17 | May 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 18 | June 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 19 | July 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 20 | Aug 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 21 | Sept 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 22 | Oct 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 23 | Nov 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 24 | Dec 1952 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 25 | Jan 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 26 | Feb 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 27 | Mar 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 28 | Apr 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 29 | May 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 30 | June 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 31 | July 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 32 | Aug 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 33 | Sept 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 34 | Oct 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 35 | Nov 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 36 | Dec 1953 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 37 | Jan 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 38 | Feb 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 39 | Mar 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 40 | Apr 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 41 | May 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 42 | June 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 43 | July 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 44 | Aug 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 45 | Sept 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 46 | Oct 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 47 | Nov 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 48 | Dec 1954 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 49 | Jan 1955 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 50 | Feb 1955 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 51 | Mar 1955 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 52 | Apr 1955 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 |
| 53 | May 1955 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 |
| 54 | June 1955 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 |
| 55 | July 1955 | 0.01 | 0.00 | 0.01 | 0.02 | 0.00 | 0.01 | 0.02 |
| 56 | Aug 1955 | 0.01 | 0.00 | 0.01 | 0.03 | 0.00 | 0.01 | 0.02 |
| 57 | Sept 1955 | 0.02 | 0.00 | 0.01 | 0.04 | 0.00 | 0.01 | 0.03 |
| 58 | Oct 1955 | 0.03 | 0.01 | 0.02 | 0.05 | 0.01 | 0.02 | 0.04 |
| 59 | Nov 1955 | 0.04 | 0.01 | 0.03 | 0.07 | 0.01 | 0.03 | 0.07 |
| 60 | Dec 1955 | 0.06 | 0.01 | 0.04 | 0.09 | 0.01 | 0.03 | 0.09 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 61 | Jan 1956 | 0.08 | 0.02 | 0.05 | 0.12 | 0.02 | 0.04 | 0.12 |
| 62 | Feb 1956 | 0.10 | 0.02 | 0.07 | 0.16 | 0.02 | 0.06 | 0.15 |
| 63 | Mar 1956 | 0.13 | 0.03 | 0.09 | 0.21 | 0.03 | 0.08 | 0.18 |
| 64 | Apr 1956 | 0.17 | 0.04 | 0.12 | 0.26 | 0.04 | 0.10 | 0.24 |
| 65 | May 1956 | 0.23 | 0.05 | 0.15 | 0.33 | 0.05 | 0.12 | 0.29 |
| 66 | June 1956 | 0.29 | 0.07 | 0.20 | 0.42 | 0.06 | 0.15 | 0.34 |
| 67 | July 1956 | 0.36 | 0.09 | 0.25 | 0.52 | 0.08 | 0.18 | 0.41 |
| 68 | Aug 1956 | 0.46 | 0.12 | 0.31 | 0.65 | 0.10 | 0.23 | 0.51 |
| 69 | Sept 1956 | 0.57 | 0.15 | 0.38 | 0.79 | 0.13 | 0.29 | 0.65 |
| 70 | Oct 1956 | 0.70 | 0.18 | 0.47 | 0.96 | 0.16 | 0.35 | 0.78 |
| 71 | Nov 1956 | 0.85 | 0.23 | 0.57 | 1.16 | 0.22 | 0.47 | 1.03 |
| 72 | Dec 1956 | 1.04 | 0.28 | 0.69 | 1.38 | 0.24 | 0.54 | 1.14 |
| 73 | Jan 1957 | 1.25 | 0.35 | 0.83 | 1.63 | 0.31 | 0.63 | 1.38 |
| 74 | Feb 1957 | 1.47 | 0.41 | 0.97 | 1.89 | 0.37 | 0.77 | 1.69 |
| 75 | Mar 1957 | 1.74 | 0.49 | 1.16 | 2.21 | 0.43 | 0.88 | 1.84 |
| 76 | Apr 1957 | 2.04 | 0.59 | 1.36 | 2.57 | 0.53 | 1.09 | 2.08 |
| 77 | May 1957 | 2.39 | 0.70 | 1.59 | 2.97 | 0.60 | 1.20 | 2.40 |
| 78 | June 1957 | 2.77 | 0.83 | 1.84 | 3.40 | 0.64 | 1.31 | 2.51 |
| 79 | July 1957 | 3.21 | 0.98 | 2.12 | 3.87 | 0.74 | 1.50 | 3.08 |
| 80 | Aug 1957 | 3.69 | 1.15 | 2.45 | 4.42 | 0.87 | 1.73 | 3.38 |
| 81 | Sept 1957 | 4.21 | 1.33 | 2.80 | 4.99 | 1.07 | 2.11 | 3.83 |
| 82 | Oct 1957 | 4.79 | 1.54 | 3.20 | 5.64 | 1.20 | 2.31 | 4.48 |
| 83 | Nov 1957 | 5.41 | 1.77 | 3.61 | 6.32 | 1.46 | 2.95 | 5.33 |
| 84 | Dec 1957 | 6.10 | 2.02 | 4.08 | 7.07 | 1.61 | 3.08 | 5.81 |
| 85 | Jan 1958 | 6.86 | 2.29 | 4.60 | 7.87 | 1.81 | 3.43 | 6.42 |
| 86 | Feb 1958 | 7.60 | 2.57 | 5.11 | 8.67 | 2.04 | 3.97 | 7.10 |
| 87 | Mar 1958 | 8.47 | 2.88 | 5.71 | 9.58 | 2.36 | 4.36 | 7.74 |
| 88 | Apr 1958 | 9.37 | 3.22 | 6.33 | 10.56 | 2.68 | 5.04 | 8.73 |
| 89 | May 1958 | 10.37 | 3.61 | 7.02 | 11.61 | 2.99 | 5.37 | 9.15 |
| 90 | June 1958 | 11.39 | 4.00 | 7.73 | 12.67 | 2.98 | 5.43 | 9.32 |
| 91 | July 1958 | 12.91 | 4.59 | 8.78 | 14.26 | 4.03 | 6.88 | 11.46 |
| 92 | Aug 1958 | 14.12 | 5.09 | 9.61 | 15.49 | 4.55 | 7.67 | 12.57 |
| 93 | Sept 1958 | 15.35 | 5.62 | 10.47 | 16.74 | 4.62 | 8.07 | 13.12 |
| 94 | Oct 1958 | 16.69 | 6.19 | 11.39 | 18.13 | 5.24 | 8.98 | 14.89 |
| 95 | Nov 1958 | 18.03 | 6.79 | 12.32 | 19.54 | 5.71 | 9.88 | 16.33 |
| 96 | Dec 1958 | 19.49 | 7.45 | 13.33 | 21.07 | 6.32 | 10.83 | 17.27 |
| 97 | Jan 1959 | 20.97 | 8.11 | 14.36 | 22.62 | 6.84 | 11.56 | 18.53 |
| 98 | Feb 1959 | 22.35 | 8.77 | 15.34 | 23.97 | 7.74 | 12.87 | 20.40 |
| 99 | Mar 1959 | 23.92 | 9.53 | 16.47 | 25.59 | 7.80 | 13.07 | 20.81 |
| 100 | Apr 1959 | 25.49 | 10.24 | 17.59 | 27.22 | 8.26 | 14.30 | 23.52 |
| 101 | May 1959 | 27.15 | 11.08 | 18.81 | 29.01 | 8.82 | 15.02 | 23.60 |
| 102 | June 1959 | 28.81 | 11.94 | 20.01 | 30.78 | 10.46 | 16.86 | 25.74 |
| 103 | July 1959 | 30.56 | 12.79 | 21.37 | 32.69 | 11.14 | 17.71 | 27.35 |
| 104 | Aug 1959 | 32.36 | 13.70 | 22.77 | 34.63 | 12.06 | 18.88 | 28.65 |
| 105 | Sept 1959 | 34.14 | 14.62 | 24.11 | 36.56 | 12.39 | 19.29 | 28.82 |
| 106 | Oct 1959 | 36.01 | 15.60 | 25.59 | 38.60 | 13.35 | 20.99 | 31.36 |
| 107 | Nov 1959 | 37.85 | 16.60 | 27.04 | 40.57 | 13.30 | 22.66 | 35.03 |
| 108 | Dec 1959 | 39.78 | 17.68 | 28.50 | 42.59 | 14.48 | 23.99 | 36.02 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 109 | Jan 1960 | 41.86 | 18.82 | 30.15 | 44.74 | 15.99 | 24.99 | 38.89 |
| 110 | Feb 1960 | 43.85 | 19.92 | 31.62 | 46.80 | 16.98 | 27.00 | 41.00 |
| 111 | Mar 1960 | 46.03 | 21.13 | 33.16 | 49.07 | 17.85 | 26.94 | 41.01 |
| 112 | Apr 1960 | 48.15 | 22.35 | 34.81 | 51.31 | 18.45 | 29.03 | 43.84 |
| 113 | May 1960 | 50.37 | 23.59 | 36.60 | 53.65 | 19.84 | 30.13 | 44.48 |
| 114 | June 1960 | 52.51 | 24.80 | 38.35 | 55.92 | 22.20 | 33.22 | 47.21 |
| 115 | July 1960 | 54.74 | 26.08 | 40.12 | 58.27 | 23.30 | 34.55 | 50.18 |
| 116 | Aug 1960 | 56.96 | 27.37 | 42.13 | 60.60 | 24.49 | 36.32 | 51.82 |
| 117 | Sept 1960 | 59.09 | 28.64 | 43.80 | 62.82 | 24.27 | 35.66 | 51.64 |
| 118 | Oct 1960 | 61.30 | 29.98 | 45.51 | 65.09 | 26.27 | 38.51 | 55.86 |
| 119 | Nov 1960 | 63.42 | 31.31 | 47.25 | 67.22 | 26.43 | 40.46 | 59.79 |
| 120 | Dec 1960 | 65.61 | 32.81 | 48.96 | 69.64 | 26.91 | 43.02 | 60.66 |
| 121 | Jan 1961 | 67.69 | 34.22 | 50.74 | 71.88 | 28.21 | 43.30 | 63.65 |
| 122 | Feb 1961 | 69.54 | 35.52 | 52.42 | 73.96 | 30.97 | 45.69 | 70.43 |
| 123 | Mar 1961 | 71.56 | 36.93 | 54.16 | 76.28 | 31.47 | 45.72 | 66.14 |
| 124 | Apr 1961 | 73.49 | 38.31 | 55.82 | 78.51 | 32.33 | 47.92 | 70.86 |
| 125 | May 1961 | 75.49 | 39.76 | 57.54 | 80.74 | 32.37 | 49.12 | 70.32 |
| 126 | June 1961 | 77.39 | 41.04 | 59.14 | 82.99 | 38.28 | 53.02 | 73.49 |
| 127 | July 1961 | 79.36 | 42.45 | 60.87 | 84.92 | 36.88 | 54.13 | 75.55 |
| 128 | Aug 1961 | 81.32 | 43.86 | 62.61 | 86.79 | 38.78 | 56.07 | 77.30 |
| 129 | Sept 1961 | 83.19 | 45.25 | 64.23 | 88.82 | 38.62 | 54.74 | 76.56 |
| 130 | Oct 1961 | 85.11 | 46.69 | 65.85 | 90.84 | 40.37 | 58.11 | 80.91 |
| 131 | Nov 1961 | 86.95 | 48.10 | 67.44 | 92.75 | 39.55 | 59.92 | 87.09 |
| 132 | Dec 1961 | 88.84 | 49.61 | 69.03 | 94.71 | 42.20 | 62.63 | 86.40 |
| 133 | Jan 1962 | 60.88 | 34.23 | 47.47 | 64.96 | 27.60 | 42.46 | 62.20 |
| 134 | Feb 1962 | 62.10 | 35.17 | 48.52 | 66.43 | 30.36 | 45.91 | 68.03 |
| 135 | Mar 1962 | 62.94 | 35.84 | 49.35 | 67.26 | 31.00 | 45.13 | 66.06 |
| 136 | Apr 1962 | 63.59 | 36.33 | 50.10 | 68.07 | 32.57 | 48.08 | 68.30 |
| 137 | May 1962 | 64.17 | 36.80 | 50.73 | 68.98 | 31.10 | 46.57 | 66.06 |
| 138 | June 1962 | 64.70 | 37.21 | 51.33 | 69.81 | 29.45 | 43.47 | 61.90 |
| 139 | July 1962 | 65.23 | 37.65 | 51.82 | 70.45 | 28.63 | 44.36 | 62.01 |
| 140 | Aug 1962 | 65.74 | 38.07 | 52.41 | 71.23 | 29.87 | 45.14 | 64.88 |
| 141 | Sept 1962 | 66.22 | 38.47 | 52.91 | 71.97 | 32.00 | 47.51 | 67.91 |
| 142 | Oct 1962 | 66.71 | 38.89 | 53.53 | 72.74 | 30.29 | 47.30 | 68.59 |
| 143 | Nov 1962 | 67.18 | 39.30 | 54.16 | 73.38 | 35.13 | 53.53 | 77.51 |
| 144 | Dec 1962 | 67.65 | 39.72 | 54.77 | 74.05 | 33.21 | 50.53 | 75.06 |
| 145 | Jan 1963 | 68.06 | 40.19 | 55.24 | 74.67 | 32.41 | 49.74 | 74.10 |
| 146 | Feb 1963 | 68.39 | 40.63 | 55.56 | 75.17 | 34.46 | 52.70 | 77.58 |
| 147 | Mar 1963 | 68.73 | 41.15 | 56.03 | 75.76 | 35.61 | 52.41 | 73.73 |
| 148 | Apr 1963 | 69.03 | 41.66 | 56.47 | 76.32 | 36.91 | 55.39 | 79.81 |
| 149 | May 1963 | 69.33 | 42.03 | 56.98 | 77.17 | 34.47 | 53.02 | 77.36 |
| 150 | June 1963 | 69.62 | 42.25 | 57.46 | 77.94 | 34.18 | 49.23 | 70.00 |
| 151 | July 1963 | 69.90 | 42.45 | 57.98 | 78.48 | 32.75 | 49.62 | 71.03 |
| 152 | Aug 1963 | 70.17 | 42.67 | 58.43 | 79.00 | 34.06 | 51.05 | 73.06 |
| 153 | Sept 1963 | 70.43 | 42.87 | 58.82 | 79.47 | 36.62 | 52.90 | 76.53 |
| 154 | Oct 1963 | 70.69 | 43.17 | 59.15 | 79.90 | 36.26 | 52.47 | 77.15 |
| 155 | Nov 1963 | 70.93 | 43.60 | 59.49 | 80.31 | 38.46 | 59.09 | 84.58 |
| 156 | Dec 1963 | 71.17 | 43.90 | 59.88 | 80.88 | 36.71 | 56.06 | 80.60 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 157 | Jan 1964 | 71.40 | 44.18 | 60.32 | 81.34 | 35.81 | 55.22 | 80.71 |
| 158 | Feb 1964 | 63.77 | 39.66 | 54.00 | 72.84 | 37.51 | 58.47 | 83.80 |
| 159 | Mar 1964 | 63.95 | 39.92 | 54.36 | 73.38 | 37.37 | 57.84 | 81.58 |
| 160 | Apr 1964 | 64.08 | 40.09 | 54.68 | 73.85 | 40.30 | 60.39 | 85.06 |
| 161 | May 1964 | 64.19 | 40.31 | 54.98 | 74.28 | 39.56 | 57.23 | 84.15 |
| 162 | June 1964 | 64.27 | 40.51 | 55.23 | 74.64 | 37.14 | 53.54 | 75.21 |
| 163 | July 1964 | 64.34 | 40.61 | 55.45 | 74.98 | 35.59 | 54.24 | 76.87 |
| 164 | Aug 1964 | 64.39 | 40.68 | 55.64 | 75.27 | 37.29 | 55.12 | 77.08 |
| 165 | Sept 1964 | 64.43 | 40.75 | 55.82 | 75.62 | 39.55 | 57.96 | 80.84 |
| 166 | Oct 1964 | 64.47 | 40.81 | 56.00 | 75.94 | 38.57 | 56.64 | 78.51 |
| 167 | Nov 1964 | 64.49 | 40.88 | 56.18 | 76.19 | 42.49 | 63.10 | 91.13 |
| 168 | Dec 1964 | 64.50 | 40.96 | 56.36 | 76.45 | 39.06 | 59.01 | 88.36 |
| 169 | Jan 1965 | 64.50 | 41.10 | 56.58 | 76.70 | 37.87 | 59.05 | 88.52 |
| 170 | Feb 1965 | 64.49 | 41.12 | 56.70 | 76.94 | 39.46 | 61.35 | 94.71 |
| 171 | Mar 1965 | 64.47 | 41.14 | 56.78 | 77.17 | 41.20 | 60.99 | 89.98 |
| 172 | Apr 1965 | 64.45 | 41.16 | 56.92 | 77.24 | 42.66 | 64.07 | 93.10 |
| 173 | May 1965 | 64.42 | 41.20 | 57.06 | 77.13 | 41.03 | 61.17 | 87.07 |
| 174 | June 1965 | 64.38 | 41.23 | 57.20 | 77.34 | 36.64 | 56.23 | 81.33 |
| 175 | July 1965 | 64.33 | 41.26 | 57.22 | 77.80 | 38.15 | 57.32 | 81.83 |
| 176 | Aug 1965 | 64.27 | 41.14 | 57.22 | 77.91 | 38.93 | 57.04 | 84.04 |
| 177 | Sept 1965 | 64.20 | 41.03 | 57.22 | 77.92 | 41.40 | 60.36 | 84.29 |
| 178 | Oct 1965 | 64.13 | 40.92 | 57.30 | 78.03 | 38.84 | 59.61 | 87.79 |
| 179 | Nov 1965 | 64.05 | 40.85 | 57.34 | 78.10 | 44.47 | 66.00 | 95.45 |
| 180 | Dec 1965 | 63.97 | 40.78 | 57.39 | 78.10 | 39.95 | 61.88 | 91.31 |
| 181 | Jan 1966 | 63.88 | 40.81 | 57.48 | 78.26 | 39.34 | 61.61 | 91.59 |
| 182 | Feb 1966 | 63.79 | 40.88 | 57.54 | 78.38 | 42.06 | 64.63 | 99.81 |
| 183 | Mar 1966 | 63.68 | 41.01 | 57.62 | 78.45 | 41.44 | 63.87 | 94.47 |
| 184 | Apr 1966 | 63.57 | 41.20 | 57.61 | 78.33 | 43.72 | 66.91 | 97.21 |
| 185 | May 1966 | 63.46 | 41.28 | 57.64 | 78.43 | 42.05 | 64.21 | 91.37 |
| 186 | June 1966 | 63.34 | 41.40 | 57.70 | 78.44 | 38.28 | 58.86 | 86.56 |
| 187 | July 1966 | 63.21 | 41.54 | 57.70 | 78.65 | 39.70 | 58.20 | 87.29 |
| 188 | Aug 1966 | 63.08 | 41.69 | 57.74 | 78.94 | 39.57 | 60.11 | 87.73 |
| 189 | Sept 1966 | 62.94 | 41.79 | 57.79 | 78.91 | 41.82 | 62.94 | 91.60 |
| 190 | Oct 1966 | 62.80 | 41.73 | 57.82 | 78.87 | 40.67 | 60.35 | 90.52 |
| 191 | Nov 1966 | 62.65 | 41.67 | 57.78 | 78.78 | 44.43 | 68.76 | 99.82 |
| 192 | Dec 1966 | 62.50 | 41.60 | 57.82 | 78.70 | 40.92 | 63.19 | 97.26 |
| 193 | Jan 1967 | 62.25 | 41.42 | 57.70 | 78.67 | 40.95 | 62.45 | 96.88 |
| 194 | Feb 1967 | 61.99 | 41.20 | 57.61 | 78.56 | 41.00 | 66.51 | 98.39 |
| 195 | Mar 1967 | 61.67 | 40.98 | 57.36 | 78.37 | 43.47 | 64.42 | 95.01 |
| 196 | Apr 1967 | 61.35 | 40.74 | 57.12 | 78.11 | 44.75 | 66.63 | 97.65 |
| 197 | May 1967 | 61.02 | 40.52 | 56.84 | 77.78 | 42.71 | 64.23 | 95.11 |
| 198 | June 1967 | 60.69 | 40.22 | 56.65 | 77.54 | 38.89 | 58.53 | 86.55 |
| 199 | July 1967 | 60.37 | 40.03 | 56.43 | 77.45 | 38.46 | 59.64 | 87.57 |
| 200 | Aug 1967 | 60.05 | 39.87 | 56.26 | 77.39 | 39.01 | 59.72 | 89.18 |
| 201 | Sept 1967 | 59.74 | 39.69 | 56.04 | 77.26 | 40.93 | 61.91 | 90.19 |
| 202 | Oct 1967 | 59.43 | 39.49 | 55.86 | 77.12 | 40.30 | 60.56 | 90.27 |
| 203 | Nov 1967 | 59.13 | 39.31 | 55.71 | 76.98 | 44.01 | 68.01 | 99.90 |
| 204 | Dec 1967 | 58.83 | 39.12 | 55.50 | 76.83 | 41.94 | 63.60 | 97.99 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 205 | Jan 1968 | 58.41 | 38.91 | 55.32 | 76.43 | 40.60 | 63.04 | 98.22 |
| 206 | Feb 1968 | 57.95 | 38.69 | 55.12 | 75.94 | 39.51 | 63.91 | 98.67 |
| 207 | Mar 1968 | 57.43 | 38.44 | 54.74 | 75.51 | 41.62 | 63.54 | 94.21 |
| 208 | Apr 1968 | 56.94 | 38.22 | 54.56 | 75.12 | 42.61 | 65.79 | 99.98 |
| 209 | May 1968 | 56.45 | 37.99 | 54.20 | 74.61 | 39.39 | 62.35 | 92.79 |
| 210 | June 1968 | 55.98 | 37.72 | 53.86 | 74.13 | 37.49 | 57.23 | 84.15 |
| 211 | July 1968 | 55.49 | 37.46 | 53.50 | 73.63 | 37.51 | 56.92 | 83.56 |
| 212 | Aug 1968 | 55.02 | 37.31 | 53.27 | 73.27 | 37.52 | 58.08 | 84.83 |
| 213 | Sept 1968 | 54.58 | 37.16 | 53.00 | 73.05 | 40.06 | 60.24 | 89.84 |
| 214 | Oct 1968 | 54.13 | 36.94 | 52.72 | 72.83 | 37.61 | 59.46 | 87.96 |
| 215 | Nov 1968 | 53.71 | 36.71 | 52.49 | 72.61 | 42.84 | 64.11 | 96.77 |
| 216 | Dec 1968 | 53.28 | 36.45 | 52.16 | 72.34 | 39.36 | 60.93 | 93.74 |
| 217 | Jan 1969 | 53.07 | 36.40 | 52.03 | 72.40 | 37.42 | 60.60 | 90.38 |
| 218 | Feb 1969 | 52.97 | 36.41 | 52.07 | 72.32 | 38.68 | 63.83 | 100.33 |
| 219 | Mar 1969 | 52.94 | 36.41 | 52.21 | 72.23 | 40.85 | 62.20 | 90.15 |
| 220 | Apr 1969 | 52.93 | 36.50 | 52.33 | 72.58 | 41.71 | 63.74 | 95.37 |
| 221 | May 1969 | 52.93 | 36.55 | 52.41 | 72.94 | 40.51 | 60.54 | 94.64 |
| 222 | June 1969 | 52.92 | 36.59 | 52.49 | 73.24 | 37.99 | 56.86 | 82.85 |
| 223 | July 1969 | 52.90 | 36.61 | 52.54 | 73.52 | 35.02 | 57.32 | 85.75 |
| 224 | Aug 1969 | 52.86 | 36.63 | 52.71 | 73.77 | 36.90 | 57.85 | 85.34 |
| 225 | Sept 1969 | 52.81 | 36.64 | 52.74 | 73.98 | 39.74 | 59.97 | 89.19 |
| 226 | Oct 1969 | 52.75 | 36.64 | 52.75 | 74.13 | 37.64 | 59.44 | 92.22 |
| 227 | Nov 1969 | 55.19 | 38.34 | 55.24 | 77.72 | 36.74 | 55.89 | 84.87 |
| 228 | Dec 1969 | 55.19 | 38.30 | 55.23 | 77.70 | 32.94 | 51.96 | 81.13 |
| 229 | Jan 1970 | 55.01 | 38.10 | 55.14 | 77.54 | 32.78 | 50.97 | 81.62 |
| 230 | Feb 1970 | 54.79 | 37.97 | 55.03 | 77.34 | 33.13 | 52.80 | 83.08 |
| 231 | Mar 1970 | 54.49 | 37.71 | 54.76 | 77.08 | 32.85 | 52.72 | 79.35 |
| 232 | Apr 1970 | 54.20 | 37.46 | 54.48 | 76.72 | 34.85 | 54.22 | 82.26 |
| 233 | May 1970 | 53.90 | 37.21 | 54.17 | 76.27 | 33.91 | 51.26 | 78.11 |
| 234 | June 1970 | 53.61 | 37.01 | 53.91 | 75.89 | 29.54 | 47.08 | 71.71 |
| 235 | July 1970 | 53.32 | 36.82 | 53.59 | 75.68 | 28.77 | 46.80 | 72.48 |
| 236 | Aug 1970 | 53.04 | 36.64 | 53.32 | 75.44 | 29.60 | 47.37 | 70.90 |
| 237 | Sept 1970 | 52.78 | 36.47 | 53.06 | 75.25 | 31.55 | 49.00 | 74.82 |
| 238 | Oct 1970 | 52.53 | 36.31 | 52.78 | 75.02 | 30.14 | 48.10 | 73.55 |
| 239 | Nov 1970 | 52.29 | 36.19 | 52.67 | 74.93 | 32.50 | 53.01 | 81.51 |
| 240 | Dec 1970 | 52.05 | 36.05 | 52.54 | 74.88 | 32.47 | 48.94 | 76.35 |
| 241 | Jan 1971 | 51.96 | 35.96 | 52.53 | 75.02 | 30.00 | 48.86 | 77.29 |
| 242 | Feb 1971 | 51.93 | 35.90 | 52.50 | 75.19 | 32.51 | 50.78 | 80.73 |
| 243 | Mar 1971 | 51.95 | 35.87 | 52.60 | 75.42 | 32.25 | 49.82 | 78.27 |
| 244 | Apr 1971 | 51.99 | 35.86 | 52.73 | 75.65 | 32.74 | 52.65 | 81.01 |
| 245 | May 1971 | 52.03 | 35.86 | 52.88 | 75.88 | 30.15 | 49.32 | 76.96 |
| 246 | June 1971 | 52.08 | 35.85 | 52.86 | 76.11 | 29.02 | 45.87 | 72.87 |
| 247 | July 1971 | 52.12 | 35.92 | 52.88 | 76.35 | 29.03 | 45.64 | 72.37 |
| 248 | Aug 1971 | 52.16 | 35.93 | 52.97 | 76.52 | 29.30 | 46.61 | 71.75 |
| 249 | Sept 1971 | 52.20 | 35.93 | 53.07 | 76.72 | 30.33 | 48.38 | 74.56 |
| 250 | Oct 1971 | 52.23 | 35.95 | 53.13 | 76.91 | 29.27 | 46.98 | 73.25 |
| 251 | Nov 1971 | 52.26 | 35.98 | 53.25 | 77.05 | 32.40 | 52.55 | 82.47 |
| 252 | Dec 1971 | 52.29 | 35.91 | 53.28 | 77.28 | 30.91 | 49.57 | 76.35 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 253 | Jan 1972 | 49.34 | 33.93 | 50.30 | 73.12 | 29.17 | 48.14 | 77.82 |
| 254 | Feb 1972 | 49.01 | 33.72 | 50.06 | 72.93 | 30.19 | 50.33 | 81.13 |
| 255 | Mar 1972 | 48.68 | 33.47 | 49.71 | 72.72 | 31.69 | 48.44 | 75.80 |
| 256 | Apr 1972 | 48.40 | 33.25 | 49.54 | 72.47 | 30.79 | 50.77 | 79.48 |
| 257 | May 1972 | 48.14 | 33.10 | 49.27 | 72.26 | 30.44 | 48.53 | 73.97 |
| 258 | June 1972 | 47.90 | 32.98 | 49.08 | 72.17 | 27.68 | 44.98 | 68.87 |
| 259 | July 1972 | 47.67 | 32.85 | 48.97 | 72.02 | 27.13 | 43.58 | 66.62 |
| 260 | Aug 1972 | 47.45 | 32.72 | 48.78 | 71.78 | 26.91 | 43.63 | 68.46 |
| 261 | Sept 1972 | 47.25 | 32.60 | 48.69 | 71.47 | 28.10 | 46.38 | 72.80 |
| 262 | Oct 1972 | 47.05 | 32.49 | 48.58 | 71.34 | 28.15 | 44.90 | 70.07 |
| 263 | Nov 1972 | 46.87 | 32.41 | 48.43 | 71.26 | 30.68 | 49.80 | 78.83 |
| 264 | Dec 1972 | 46.69 | 32.29 | 48.21 | 71.16 | 28.36 | 46.21 | 76.56 |
| 265 | Jan 1973 | 54.28 | 37.52 | 56.04 | 82.79 | 27.54 | 44.70 | 72.51 |
| 266 | Feb 1973 | 54.19 | 37.39 | 55.96 | 82.69 | 29.05 | 47.31 | 78.50 |
| 267 | Mar 1973 | 53.98 | 37.15 | 55.78 | 82.35 | 28.09 | 46.20 | 73.11 |
| 268 | Apr 1973 | 53.76 | 36.91 | 55.44 | 81.94 | 28.95 | 46.73 | 77.52 |
| 269 | May 1973 | 53.52 | 36.68 | 55.24 | 81.51 | 26.12 | 45.17 | 70.36 |
| 270 | June 1973 | 53.30 | 36.46 | 55.22 | 81.10 | 25.61 | 40.75 | 66.70 |
| 271 | July 1973 | 53.08 | 36.24 | 55.12 | 80.74 | 25.25 | 40.82 | 63.84 |
| 272 | Aug 1973 | 52.87 | 36.03 | 54.99 | 80.59 | 25.02 | 41.47 | 64.39 |
| 273 | Sept 1973 | 52.68 | 35.84 | 54.88 | 80.46 | 26.43 | 43.33 | 68.68 |
| 274 | Oct 1973 | 52.51 | 35.66 | 54.87 | 80.34 | 26.17 | 41.28 | 65.28 |
| 275 | Nov 1973 | 52.35 | 35.49 | 54.80 | 80.25 | 27.77 | 45.41 | 72.92 |
| 276 | Dec 1973 | 52.20 | 35.33 | 54.72 | 80.17 | 25.66 | 42.21 | 68.89 |
| 277 | Jan 1974 | 52.43 | 35.41 | 54.97 | 80.49 | 25.72 | 42.62 | 69.65 |
| 278 | Feb 1974 | 52.82 | 35.59 | 55.42 | 80.98 | 26.19 | 43.80 | 72.53 |
| 279 | Mar 1974 | 53.39 | 35.86 | 55.92 | 81.66 | 25.08 | 42.86 | 68.49 |
| 280 | Apr 1974 | 53.99 | 36.16 | 56.60 | 82.41 | 28.14 | 45.59 | 71.28 |
| 281 | May 1974 | 54.63 | 36.49 | 57.21 | 83.20 | 25.84 | 42.70 | 72.49 |
| 282 | June 1974 | 55.25 | 36.80 | 57.69 | 84.15 | 25.00 | 40.00 | 64.50 |
| 283 | July 1974 | 55.90 | 37.13 | 58.15 | 85.07 | 24.17 | 40.57 | 65.57 |
| 284 | Aug 1974 | 56.53 | 37.50 | 58.85 | 85.98 | 24.29 | 40.75 | 65.98 |
| 285 | Sept 1974 | 57.10 | 37.85 | 59.43 | 86.86 | 27.22 | 43.16 | 69.98 |
| 286 | Oct 1974 | 57.70 | 38.22 | 60.00 | 87.74 | 25.22 | 42.68 | 67.27 |
| 287 | Nov 1974 | 58.30 | 38.56 | 60.59 | 88.58 | 28.99 | 47.52 | 76.53 |
| 288 | Dec 1974 | 58.92 | 38.98 | 61.11 | 89.45 | 25.07 | 44.15 | 72.46 |
| 289 | Jan 1975 | 61.00 | 40.30 | 63.17 | 92.62 | 27.61 | 45.83 | 75.73 |
| 290 | Feb 1975 | 61.24 | 40.39 | 63.33 | 92.97 | 28.46 | 48.17 | 80.43 |
| 291 | Mar 1975 | 61.41 | 40.51 | 63.43 | 93.20 | 28.98 | 46.39 | 77.50 |
| 292 | Apr 1975 | 61.57 | 40.61 | 63.45 | 93.38 | 29.37 | 48.59 | 82.56 |
| 293 | May 1975 | 61.72 | 40.78 | 63.62 | 93.32 | 28.00 | 46.55 | 76.49 |
| 294 | June 1975 | 61.88 | 40.92 | 63.77 | 93.48 | 24.95 | 42.93 | 67.44 |
| 295 | July 1975 | 62.05 | 41.05 | 64.04 | 93.91 | 25.59 | 42.20 | 68.93 |
| 296 | Aug 1975 | 62.25 | 41.13 | 64.22 | 94.27 | 26.21 | 42.72 | 68.78 |
| 297 | Sept 1975 | 62.46 | 41.20 | 64.36 | 94.54 | 25.88 | 44.92 | 73.09 |
| 298 | Oct 1975 | 62.69 | 41.18 | 64.65 | 94.84 | 26.24 | 43.56 | 70.58 |
| 299 | Nov 1975 | 62.92 | 41.12 | 64.91 | 95.15 | 27.40 | 49.02 | 80.06 |
| 300 | Dec 1975 | 63.18 | 41.12 | 65.11 | 95.44 | 26.23 | 45.41 | 76.07 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 301 | Jan 1976 | 73.96 | 48.06 | 76.13 | 111.62 | 27.44 | 47.37 | 78.75 |
| 302 | Feb 1976 | 74.94 | 48.64 | 77.01 | 112.96 | 28.08 | 50.08 | 82.73 |
| 303 | Mar 1976 | 75.97 | 49.28 | 77.88 | 114.29 | 30.00 | 49.48 | 77.65 |
| 304 | Apr 1976 | 76.97 | 49.90 | 78.87 | 115.66 | 29.89 | 51.83 | 83.45 |
| 305 | May 1976 | 78.00 | 50.66 | 79.94 | 117.25 | 28.96 | 49.32 | 81.75 |
| 306 | June 1976 | 79.02 | 51.42 | 80.86 | 118.78 | 27.37 | 44.69 | 74.98 |
| 307 | July 1976 | 80.07 | 52.20 | 81.82 | 120.35 | 28.29 | 45.16 | 75.62 |
| 308 | Aug 1976 | 81.13 | 52.86 | 82.70 | 121.82 | 27.95 | 46.57 | 76.48 |
| 309 | Sept 1976 | 82.17 | 53.51 | 83.71 | 123.46 | 29.17 | 49.14 | 79.62 |
| 310 | Oct 1976 | 83.25 | 54.25 | 84.81 | 124.74 | 28.92 | 48.10 | 80.30 |
| 311 | Nov 1976 | 84.31 | 55.09 | 85.76 | 126.00 | 31.09 | 53.61 | 90.47 |
| 312 | Dec 1976 | 85.41 | 55.90 | 86.67 | 127.61 | 28.21 | 50.51 | 82.95 |
| 313 | Jan 1977 | 86.61 | 56.70 | 87.66 | 129.36 | 28.88 | 49.71 | 81.57 |
| 314 | Feb 1977 | 87.70 | 57.45 | 88.70 | 131.09 | 30.18 | 52.13 | 85.43 |
| 315 | Mar 1977 | 88.91 | 58.14 | 89.80 | 133.02 | 29.18 | 51.65 | 83.61 |
| 316 | Apr 1977 | 90.10 | 58.86 | 90.90 | 134.30 | 32.23 | 54.40 | 88.91 |
| 317 | May 1977 | 91.32 | 59.61 | 91.86 | 135.48 | 30.43 | 50.86 | 86.19 |
| 318 | June 1977 | 92.53 | 60.38 | 93.08 | 136.61 | 28.97 | 47.43 | 78.24 |
| 319 | July 1977 | 93.75 | 61.24 | 94.29 | 137.80 | 29.03 | 47.45 | 77.48 |
| 320 | Aug 1977 | 94.99 | 62.11 | 95.48 | 139.43 | 28.20 | 48.28 | 81.51 |
| 321 | Sept 1977 | 96.20 | 62.97 | 96.44 | 140.89 | 30.24 | 50.29 | 85.19 |
| 322 | Oct 1977 | 97.42 | 63.86 | 97.49 | 142.51 | 28.33 | 51.14 | 82.53 |
| 323 | Nov 1977 | 98.62 | 64.58 | 98.62 | 144.08 | 32.33 | 56.02 | 92.86 |
| 324 | Dec 1977 | 99.84 | 65.31 | 99.65 | 145.59 | 29.86 | 53.22 | 90.47 |
| 325 | Jan 1978 | 101.18 | 66.16 | 101.09 | 147.13 | 44.02 | 75.70 | 120.92 |
| 326 | Feb 1978 | 102.77 | 67.25 | 102.62 | 148.91 | 39.93 | 67.26 | 112.31 |
| 327 | Mar 1978 | 103.04 | 67.39 | 103.04 | 149.08 | 52.50 | 84.64 | 133.87 |
| 328 | Apr 1978 | 104.31 | 68.24 | 104.52 | 150.32 | 46.79 | 76.94 | 126.94 |
| 329 | May 1978 | 105.19 | 68.81 | 105.34 | 151.12 | 50.49 | 85.95 | 136.76 |
| 330 | June 1978 | 106.88 | 70.00 | 107.10 | 153.19 | 42.45 | 73.13 | 119.19 |
| 331 | July 1978 | 107.95 | 70.77 | 108.05 | 154.56 | 45.08 | 75.24 | 121.43 |
| 332 | Aug 1978 | 108.69 | 71.12 | 108.58 | 155.63 | 48.54 | 80.46 | 135.92 |
| 333 | Sept 1978 | 109.61 | 71.68 | 109.40 | 156.91 | 48.81 | 83.51 | 139.85 |
| 334 | Oct 1978 | 111.18 | 72.89 | 110.78 | 158.60 | 44.55 | 75.04 | 121.83 |
| 335 | Nov 1978 | 111.08 | 72.99 | 110.76 | 158.33 | 59.23 | 100.40 | 162.58 |
| 336 | Dec 1978 | 111.93 | 73.52 | 111.71 | 159.48 | 58.45 | 100.01 | 162.64 |
| 337 | Jan 1979 | 113.14 | 74.30 | 112.93 | 161.01 | 57.81 | 95.20 | 164.77 |
| 338 | Feb 1979 | 114.05 | 74.80 | 113.75 | 162.04 | 58.23 | 99.50 | 166.62 |
| 339 | Mar 1979 | 114.98 | 75.32 | 114.60 | 163.14 | 59.21 | 101.26 | 162.26 |
| 340 | Apr 1979 | 115.82 | 76.01 | 115.14 | 164.14 | 64.03 | 105.77 | 169.77 |
| 341 | May 1979 | 116.68 | 76.83 | 115.85 | 165.22 | 60.49 | 104.49 | 166.33 |
| 342 | June 1979 | 117.47 | 77.56 | 116.62 | 166.12 | 57.29 | 95.08 | 158.63 |
| 343 | July 1979 | 118.29 | 78.22 | 117.32 | 166.52 | 60.76 | 97.83 | 159.43 |
| 344 | Aug 1979 | 119.08 | 78.87 | 117.95 | 167.11 | 60.40 | 101.30 | 162.28 |
| 345 | Sept 1979 | 119.83 | 79.50 | 118.62 | 167.82 | 67.04 | 105.09 | 167.67 |
| 346 | Oct 1979 | 120.59 | 80.14 | 119.49 | 168.59 | 63.07 | 104.48 | 172.01 |
| 347 | Nov 1979 | 121.31 | 80.74 | 120.12 | 169.34 | 74.24 | 119.14 | 191.45 |
| 348 | Dec 1979 | 122.04 | 81.35 | 120.77 | 170.09 | 68.90 | 113.89 | 186.42 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 349 | Jan 1980 | 123.28 | 82.20 | 122.09 | 171.34 | 61.30 | 101.54 | 159.81 |
| 350 | Feb 1980 | 122.98 | 81.93 | 121.80 | 171.45 | 77.70 | 131.23 | 206.13 |
| 351 | Mar 1980 | 124.03 | 82.63 | 122.99 | 172.63 | 67.73 | 114.94 | 183.21 |
| 352 | Apr 1980 | 123.90 | 82.42 | 123.27 | 172.41 | 86.02 | 143.61 | 229.05 |
| 353 | May 1980 | 124.69 | 82.89 | 123.73 | 173.81 | 85.23 | 138.95 | 220.28 |
| 354 | June 1980 | 125.83 | 83.92 | 124.67 | 175.54 | 80.14 | 128.55 | 203.28 |
| 355 | July 1980 | 0.72 | 0.10 | 0.43 | 1.67 | 0.06 | 0.32 | 1.22 |
| 356 | Aug 1980 | 0.75 | 0.11 | 0.45 | 1.73 | 0.07 | 0.34 | 1.28 |
| 357 | Sept 1980 | 121.36 | 80.64 | 120.61 | 170.25 | 74.54 | 128.20 | 195.86 |
| 358 | Oct 1980 | 121.72 | 80.95 | 121.00 | 170.55 | 82.88 | 137.09 | 215.09 |
| 359 | Nov 1980 | 122.14 | 81.32 | 121.73 | 171.07 | 89.83 | 145.35 | 231.15 |
| 360 | Dec 1980 | 122.95 | 81.96 | 122.56 | 171.97 | 87.97 | 143.51 | 226.80 |
| 361 | Jan 1981 | 114.05 | 76.20 | 113.83 | 159.33 | 81.35 | 131.65 | 210.19 |
| 362 | Feb 1981 | 114.39 | 76.42 | 114.22 | 159.76 | 71.73 | 120.32 | 185.47 |
| 363 | Mar 1981 | 115.60 | 77.32 | 115.10 | 161.62 | 65.38 | 104.23 | 164.75 |
| 364 | Apr 1981 | 116.55 | 78.07 | 116.07 | 163.34 | 61.89 | 101.55 | 158.35 |
| 365 | May 1981 | 117.30 | 78.64 | 116.91 | 164.52 | 63.14 | 99.62 | 156.29 |
| 366 | June 1981 | 118.36 | 79.53 | 117.92 | 165.37 | 54.95 | 86.73 | 140.98 |
| 367 | July 1981 | 133.29 | 89.77 | 132.96 | 186.08 | 58.22 | 92.47 | 142.21 |
| 368 | Aug 1981 | 134.31 | 90.57 | 133.94 | 187.73 | 59.68 | 95.47 | 151.17 |
| 369 | Sept 1981 | 120.72 | 81.40 | 120.32 | 168.91 | 58.90 | 98.56 | 150.82 |
| 370 | Oct 1981 | 121.04 | 81.71 | 120.86 | 169.57 | 61.42 | 99.80 | 157.59 |
| 371 | Nov 1981 | 121.41 | 82.04 | 121.17 | 170.30 | 60.76 | 101.36 | 158.08 |
| 372 | Dec 1981 | 121.81 | 82.41 | 121.56 | 171.08 | 63.30 | 102.27 | 160.36 |
| 373 | Jan 1982 | 103.95 | 70.61 | 103.86 | 145.41 | 55.35 | 91.05 | 141.55 |
| 374 | Feb 1982 | 105.86 | 71.96 | 105.76 | 147.68 | 56.60 | 92.63 | 140.40 |
| 375 | Mar 1982 | 107.52 | 73.05 | 107.51 | 149.67 | 59.57 | 93.91 | 147.10 |
| 376 | Apr 1982 | 108.83 | 74.01 | 108.79 | 151.25 | 58.43 | 97.00 | 147.50 |
| 377 | May 1982 | 148.50 | 101.45 | 147.91 | 206.23 | 66.65 | 107.89 | 166.05 |
| 378 | June 1982 | 110.78 | 75.70 | 110.41 | 153.60 | 61.01 | 99.03 | 151.27 |
| 379 | July 1982 | 111.98 | 76.77 | 111.69 | 154.90 | 62.24 | 97.91 | 154.37 |
| 380 | Aug 1982 | 113.07 | 77.74 | 112.66 | 156.03 | 63.70 | 99.09 | 152.90 |
| 381 | Sept 1982 | 114.04 | 78.49 | 113.60 | 157.00 | 65.21 | 100.91 | 153.98 |
| 382 | Oct 1982 | 114.60 | 79.03 | 114.14 | 157.69 | 67.41 | 108.99 | 165.07 |
| 383 | Nov 1982 | 113.87 | 78.41 | 113.67 | 157.37 | 88.82 | 142.12 | 223.75 |
| 384 | Dec 1982 | 115.16 | 79.21 | 114.95 | 158.89 | 79.98 | 128.05 | 193.75 |
| 385 | Jan 1983 | 1.25 | 0.25 | 0.75 | 2.48 | 0.17 | 0.61 | 1.90 |
| 386 | Feb 1983 | 1.29 | 0.27 | 0.78 | 2.56 | 0.18 | 0.63 | 1.94 |
| 387 | Mar 1983 | 111.76 | 77.09 | 112.19 | 156.29 | 78.57 | 123.82 | 194.41 |
| 388 | Apr 1983 | 112.66 | 77.92 | 112.99 | 157.31 | 74.18 | 119.77 | 182.63 |
| 389 | May 1983 | 113.97 | 79.21 | 114.10 | 158.82 | 70.85 | 117.76 | 174.86 |
| 390 | June 1983 | 106.10 | 74.18 | 106.03 | 147.67 | 68.30 | 103.53 | 162.13 |
| 391 | July 1983 | 116.70 | 81.48 | 116.62 | 162.17 | 66.41 | 108.10 | 166.88 |
| 392 | Aug 1983 | 117.72 | 82.09 | 117.54 | 163.39 | 67.97 | 107.12 | 161.29 |
| 393 | Sept 1983 | 117.83 | 82.03 | 117.63 | 163.40 | 76.74 | 120.27 | 183.16 |
| 394 | Oct 1983 | 117.97 | 82.03 | 117.88 | 163.53 | 84.95 | 133.04 | 207.24 |
| 395 | Nov 1983 | 118.63 | 82.60 | 118.70 | 164.81 | 89.04 | 142.71 | 224.56 |
| 396 | Dec 1983 | 120.78 | 84.23 | 120.74 | 167.35 | 72.65 | 113.38 | 171.38 |

**Appendix I5.** Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.—Continued

[PCE, tetrachloroethylene; µg/L, microgram per liter; $P_{2.5}$, Monte Carlo simulation results for the 2.5 percentile; $P_{50}$, Monte Carlo simulation results for the 50 percentile; $P_{97.5}$, Monte Carlo simulation results for the 97.5 percentile; WTP, water treatment plant; Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Dec, December]

| Stress period | Month and year | Calibrated PCE concentration, in µg/L[1] | Range of concentrations derived from Monte Carlo simulations[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Monte Carlo simulation (Scenario 1)[3] | | | Monte Carlo simulation (Scenario 2)[4] | | |
| | | | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L | $P_{2.5}$, in µg/L | $P_{50}$, in µg/L | $P_{97.5}$, in µg/L |
| 397 | Jan 1984 | 132.87 | 92.63 | 133.27 | 185.03 | 103.04 | 159.84 | 247.01 |
| 398 | Feb 1984 | 180.39 | 126.52 | 180.97 | 249.43 | 94.25 | 150.35 | 230.69 |
| 399 | Mar 1984 | 183.02 | 128.61 | 183.55 | 252.50 | 99.38 | 159.70 | 240.42 |
| 400 | Apr 1984 | 151.46 | 106.37 | 151.54 | 208.97 | 97.90 | 155.71 | 236.45 |
| 401 | May 1984 | 153.42 | 107.63 | 153.20 | 211.58 | 92.85 | 146.63 | 220.85 |
| 402 | June 1984 | 182.13 | 127.45 | 181.99 | 250.57 | 94.11 | 152.75 | 228.36 |
| 403 | July 1984 | 156.39 | 109.41 | 156.40 | 214.58 | 101.95 | 160.97 | 234.39 |
| 404 | Aug 1984 | 170.47 | 106.73 | 158.25 | 238.65 | 108.76 | 168.54 | 261.54 |
| 405 | Sept 1984 | 181.22 | 113.28 | 168.51 | 253.93 | 117.53 | 184.30 | 295.64 |
| 406 | Oct 1984 | 173.73 | 108.42 | 161.84 | 245.02 | 120.12 | 182.33 | 281.84 |
| 407 | Nov 1984 | 173.77 | 108.41 | 161.92 | 245.70 | 124.18 | 187.60 | 287.36 |
| 408 | Dec 1984 | 173.18 | 107.82 | 161.69 | 246.06 | 127.85 | 193.50 | 301.23 |
| 409 | Jan 1985 | 176.12 | 109.98 | 164.71 | 251.48 | 122.98 | 187.00 | 293.19 |
| 410 | Feb 1985 | 3.64 | 1.13 | 2.67 | 6.57 | 0.47 | 1.41 | 3.74 |
| 411 | Mar 1985 | 8.71 | 3.21 | 6.58 | 14.79 | 8.83 | 20.01 | 41.59 |
| 412 | Apr 1985 | 8.09 | 2.99 | 6.16 | 13.70 | 9.00 | 20.41 | 42.30 |
| 413 | May 1985 | 4.76 | 1.50 | 3.46 | 8.36 | 0.58 | 1.68 | 4.47 |
| 414 | June 1985 | 5.14 | 1.65 | 3.80 | 9.21 | 0.64 | 1.81 | 4.78 |
| 415 | July 1985 | 5.54 | 1.80 | 4.12 | 10.04 | 0.69 | 1.96 | 5.12 |
| 416 | Aug 1985 | 6.01 | 1.98 | 4.50 | 10.97 | 0.76 | 2.14 | 5.56 |
| 417 | Sept 1985 | 6.50 | 2.19 | 4.88 | 11.89 | 0.83 | 2.30 | 6.03 |
| 418 | Oct 1985 | 7.06 | 2.43 | 5.33 | 12.88 | 0.92 | 2.53 | 6.53 |
| 419 | Nov 1985 | 7.64 | 2.68 | 5.78 | 13.90 | 1.02 | 2.76 | 7.07 |
| 420 | Dec 1985 | 8.27 | 2.93 | 6.32 | 14.99 | 1.13 | 3.00 | 7.59 |
| 421 | Jan 1986 | 8.85 | 3.18 | 6.82 | 15.87 | 1.24 | 3.22 | 8.14 |
| 422 | Feb 1986 | 9.42 | 3.45 | 7.30 | 16.67 | 1.35 | 3.46 | 8.69 |
| 423 | Mar 1986 | 12.14 | 4.55 | 9.43 | 21.18 | 1.85 | 4.67 | 11.50 |
| 424 | Apr 1986 | 10.83 | 4.09 | 8.44 | 18.71 | 1.64 | 4.08 | 9.90 |
| 425 | May 1986 | 11.56 | 4.42 | 9.06 | 19.63 | 1.79 | 4.41 | 10.49 |
| 426 | June 1986 | 12.28 | 4.77 | 9.70 | 20.59 | 1.94 | 4.76 | 11.08 |
| 427 | July 1986 | 13.06 | 5.14 | 10.35 | 21.75 | 2.11 | 5.12 | 11.77 |
| 428 | Aug 1986 | 13.84 | 5.54 | 11.01 | 23.04 | 2.29 | 5.51 | 12.50 |
| 429 | Sept 1986 | 14.61 | 5.90 | 11.70 | 24.30 | 2.49 | 5.89 | 13.19 |
| 430 | Oct 1986 | 15.42 | 6.28 | 12.41 | 25.59 | 2.71 | 6.33 | 13.94 |
| 431 | Nov 1986 | 16.21 | 6.66 | 13.11 | 26.70 | 2.93 | 6.73 | 14.77 |
| 432 | Dec 1986 | 17.03 | 7.06 | 13.77 | 27.86 | 3.17 | 7.20 | 15.65 |
| 433 | Jan 1987 | 17.85 | 7.47 | 14.46 | 29.04 | 3.41 | 7.66 | 16.46 |
| 434 | Feb 1987 | 18.49 | 7.82 | 15.02 | 29.91 | 3.62 | 8.04 | 17.16 |
| 435 | Mar 1987 | WTP closed | | | | | | |

[1]Results from Faye (2008) and reported in Maslia et al. (2007, Appendix A2)

[2]$P_{97.5}$ and $P_{2.5}$ represent the upper and lower bound, respectively, of 95 percent of Monte Carlo simulations; for a Gaussian (normal) distribution, the median ($P_{50}$) should equal the mean value

[3]Scenario 1 Monte Carlo simulation is for pumping uncertainty excluded

[4]Scenario 2 Monte Carlo simulation is for pumping uncertainty included

ATSDR

Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—Chapter I: Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water

# EXHIBIT 5

**Rebuttal to Reports of Dr. Alex Spiliotopoulos and Dr. Remy J.-C. Hennet**

**Leonard F. Konikow**

**January 13, 2025**

**Qualifications:**

I received a PhD in Geosciences from Penn State University in 1973, specializing in hydrogeology and groundwater modeling. I worked as a research hydrologist for the U.S. Geological Survey for about 42 years, and was the Editor-in-Chief of *Groundwater* journal for four years (2020-2023). At the USGS, I was mostly involved in the development, documentation, and application of groundwater flow models and groundwater solute-transport models. I was elected to the National Academy of Engineering in 2015. I am a Fellow of the American Geophysical Union and the Geological Society of America, which also presented me with their Meinzer Award for publications that have significantly advanced the science of hydrogeology. I have served on several Expert Peer Review Panels during my career, including those for ATSDR's Camp Lejeune groundwater modeling studies in 2005 and in 2009.

My curriculum vitae is included with this report as **Attachment A**, and a list of the publications I authored in the previous 10 years is included as **Attachment B**. I am being compensated at an hourly rate of $400 for my work on this litigation. I have not testified at a deposition or trial in the last 4 years.

**Introduction:**

ATSDR prepared reports describing models developed to simulate groundwater flow and contaminant transport at two areas of Camp Lejeune, North Carolina: Tarawa Terrace (TT) and Hadnot Point/Holcomb Boulevard (HPHB). Their use of the models was innovative in the sense that instead of a typical use of a groundwater model to predict future behavior, they used the model to "predict" how the system evolved in the past (before concentration observations were made) from a known state (an initial condition), in which no contaminants were present, to a contaminated aquifer with a mapped distribution in the early to mid-1980s when contamination was observed at a number of locations (wells, soil samples, and water treatment plants). ATSDR's use of groundwater models to reconstruct trends during a historical gap in concentration measurements is a legitimate and not unprecedented application of groundwater models. In fact, there are other publications in which doing this is documented and considered to be a normal and necessary part of the model calibration process, as discussed in more detail below. Modeling is the best and most logical approach for providing this information.

The ATSDR modeling work was reviewed and commented on by Dr. Alex Spiliotopoulos and Dr. Remy J.C. Hennet. In turn, I was asked to review the reports prepared by Dr. Spiliotopoulos and Dr. Hennet. This report presents my response, comments, and concerns about the technical content of Dr. Spiliotopoulos' and Dr. Hennet's reports. A list of the materials I have considered in rendering my opinions will be provided within seven days.

My opinions expressed in this rebuttal report are based on my review of the reports of Dr. Spiliotopoulos, Dr. Hennet, Mr. Maslia (Oct. 2024), Dr. Aral (Oct. 2024) and Jones & Davis (Oct. 2024), the ATSDR published reports, published literature, documents produced in this litigation, my work on the Camp Lejeune Expert Peer Review Panels, and my experience and expertise in the fields of hydrogeology

and groundwater modeling. I hold these opinions to a reasonable degree of scientific certainty. I reserve the right to supplement and/or amend my opinions in this matter as necessary if additional documents or information are made available for my review.

Background comments about groundwater modeling related to DOJ Expert Reports

This section responds to the opinions of Drs. Spiliotopoulos and Hennet regarding the methodology used by ATSDR to reconstruct groundwater contamination, including their assertions that this methodology is novel, speculative and unfounded, and their repeated claims that this methodology cannot be used where there is limited to no historical data. (*E.g*., Spiliotopoulos Report, pages 25-30).

A numerical computer model of groundwater flow and/or transport is a simplified representation of a complex reality. A model uses averages, approximations, and assumptions to simulate groundwater behavior and to reproduce its properties and characteristics. Because of uncertainty in defining aquifer properties and boundary conditions, groundwater models must be calibrated. Field observations of aquifer responses (such as changes in water levels for flow models and changes in concentration for transport models) are compared to corresponding model-calculated values. The objective of this calibration procedure is to minimize differences between the observed data and calculated values. The minimization is accomplished by adjusting parameter values within their ranges of uncertainty until a best fit is achieved.

Anderson and Woessner (1992) present a dichotomy of prevailing opinions about mathematical models:
1. "Models are worthless because they require too many data and therefore are too expensive to assemble and run. Furthermore, they can never be proved to be correct and suffer from a lack of scientific certainty."
2. "Models are essential in performing complex analyses and in making informed predictions."
They go on to conclude that "Although groundwater models are time-consuming to design and therefore expensive in terms of labor time, it is also true that use of a groundwater model is the best way to make an informed analysis or prediction about the consequences of a proposed action. … For these reasons, the bias of this book is, of course, toward opinion #2."

Groundwater contamination became widely recognized as a serious and pervasive problem in the 1980s. It is common that the existence of a groundwater contamination problem in a particular area would not be recognized until that contamination has migrated far enough and long enough that it affected a water-supply well or a surface water source. Then a monitoring program might be initiated. But this might not happen for several years to a few decades after the contaminant had entered the aquifer. Therefore, it is common that early-time data on concentrations are simply not available, as is the case at Camp Lejeune. Groundwater modeling is a widely recognized and accepted approach to understanding and managing these contamination problems. Models must be (and have been) calibrated in the absence of early time concentration data, as ATSDR has done. Other representative published examples where this has been successfully accomplished include the Rocky Mountain Arsenal, CO (Konikow, 1977) and Lawrence Livermore National Laboratory, CA (Rogers, 1992). In both of these cases, the early time history was reconstructed as part of the model calibration process (it just wasn't called "hindcasting").

In comparing hindcasting to forecasting, there are some similarities and some differences. In both cases, the analyst is using the model to estimate conditions during a time period outside of the calibration

period, and both types of "predictions" have uncertainty associated with them. One difference is that for predictions of future conditions (forecasting), you can come back later and assess the accuracy of those model predictions. With hindcasting, that is not directly possible. Another difference is that with forecasting (predicting), future conditions are somewhat unbounded, so that uncertainty will tend to increase with time beyond the calibration period. With hindcasting, there is often a way to estimate initial or early time conditions, thereby putting a constraint or bound on uncertainty going back in time. While predictive uncertainty exists and must be recognized, hindcasting is an acceptable and reasonable way to use a calibrated model to assess groundwater conditions during a historical period when there were no observations.

"Hindcasting" was accomplished as part of a study of the Rocky Mountain Arsenal (CO) contamination problem, in which I developed and calibrated a groundwater flow and transport model (Konikow, 1977). The RMA began operations in or about 1943. A groundwater contamination problem was recognized in 1954 & 1955. No observations of concentration (chloride in this early case) were made until late 1955 to 1956. The model was developed to simulate the entire history of operation and contamination at RMA, starting in 1943, but no concentration data were available for the first 13 years of operation. Konikow (1977) made and described reasonable assumptions about the initial conditions, source locations, and source loading—but of course there was uncertainty associated with those estimates (as described by Konikow and Thompson, [1984]). The RMA model was calibrated using measurements made at four distinct times including 1956, 1961, 1969 and 1972. Work was documented and published in a 1977 USGS Water-Supply Paper (https://pubs.usgs.gov/wsp/2044/report.pdf), which received wide distribution. The RMA site became one of the first sites to fall under the Installation Restoration Program. Another example of reconstructing the early history of contamination migration was published by Rogers (1992) in *Groundwater* journal about their model calibration at the Lawrence Livermore National Laboratory site in California. In both of these earlier studies, the historical reconstruction wasn't called "hindcasting," but was considered a scientifically valid component of the model development and application.

Numerical simulation models of groundwater flow and transport processes in porous media are probably the most valuable single tool available to help analysts understand subsurface systems, integrate available data, evaluate conceptual models, and predict responses of groundwater systems to various stresses (such as pumping from wells and leakage or loading of contaminants into the subsurface environment). Groundwater flow models typically estimate the head distribution (equivalent to water levels, water table elevation, or potentiometric surface) in an aquifer system and how the head may change over time in response to changes in well locations or pumping rates. Groundwater transport models (solute transport or contaminant transport for dissolved chemicals) calculate how the concentration of a particular dissolved chemical will vary from place to place and over time. Groundwater systems are three-dimensional in nature, and their properties vary both horizontally and with depth. Therefore, groundwater models must typically be three-dimensional in nature. There is a large record in the published peer-reviewed literature of cases describing the development and application of models for complex real groundwater problems.

Contaminant transport in the subsurface is strongly influenced by the groundwater flow field. Thus, contaminant-transport modeling for a specific site requires a reasonably reliable groundwater flow model. If the contaminant is nonreactive or mildly reactive, the groundwater velocity (based on hydraulic

gradients and effective porosity) is the primary control on advective and dispersive contaminant migration.

Comments about the distribution coefficient ($K_d$) and the retardation coefficient ($R_f$)

This section provides background information in support of my responses later in this report to Opinion 3 of Dr. Spiliotopoulos and Opinion 11 of Dr. Hennet regarding the methodology ATSDR used to calculate the retardation factor.

If a contaminant undergoes chemical reactions during the transport process, its net movement relative to the flow of groundwater may be slowed down. Such effects can be (and often are) represented in a simplified manner as a retardation process. Two parameters that are used to simulate retardation are discussed frequently in the comments by Dr. Spiliotopoulos. The contaminant transport conceptual model is that the migration of a contaminant may be slower than the average velocity of the groundwater in which it is dissolved because of adsorption to material in the aquifer. The net effect of this process is described by a so-called "retardation factor" ($R_f$), which is calculated as:

$$R_f = 1 + (\rho_b K_d)/\theta$$

where $R_f$ = retardation factor; $\rho_b$ = bulk density; $K_d$ = distribution coefficient; and $\theta$ = porosity.

The model calculates $R_f$ on the basis of the three parameter values on the right side of the above equation, all of which can vary in space and will include uncertainty in their estimated values. If $\rho_b$ is estimated too high by 25% and $K_d$ is too low by 25%, then the errors in those two estimates cancel each other out (i.e., they are compensating errors), and the net estimated value of $R_f$ used in the model will be the same as if those two parameters were estimated precisely to their "true" values.

In general, the use of a distribution coefficient ($K_d$) as a component of a retardation factor in contaminant transport modeling in groundwater systems is a common modeling approach in simulating contaminant transport in aquifers, but one whose rigorous scientific basis is debatable. The $K_d$ approach assumes that sorption of the PCE is instantaneous, reversible, and follows a linear equilibrium isotherm, and that "the solid matrix has an infinite sorption capacity" (Zhang & Bennett, 2002, p. 81). But in transport through complex heterogeneous porous media, the actual behavior of PCE would not match these idealized assumptions. Nevertheless, it is a simplifying assumption that can be useful in light of the uncertainties about the contaminant's distribution and reactive behavior. In effect, it represents an engineering approximation, which is why using a model calibration process to arrive at an approximate average value is an acceptable, reasonable, and common approach. Thus, Drs. Spiliotopoulos and Hennet's concern about precisely and accurately defining a value for $K_d$ is misplaced because the theoretical underpinnings for this parameter are not rigorous. That is, conceptual uncertainty in its application must always be recognized, and this conceptual uncertainty carries forward to the use of a conceptually simple retardation factor in the transport equation. This theoretical uncertainty, however, does not preclude the use of these two parameters ($K_d$ and $R_f$) for characterizing the average transport behavior of a contaminant such as PCE in flowing groundwater.

Zheng & Bennett (2002) describe some limitations in modeling sorption processes. They note that there are significant computational difficulties inherent in coupling advective-dispersive transport with

chemical reactions (p. 79). They further note (p. 79-80) that "… field problems always involve uncertainty as to the nature of the controlling reactions, and as to the quantities and properties of the reacting substances. As a result, the biogeochemical processes represented in field-scale transport models at the present time are largely limited to reactions of the simplest kind, based on highly idealized representations of the effects of more complex reactions."

Kret et al. (2015) studied a Quaternary sandy aquifer to estimate sorption coefficients for PCE fate and transport modeling. They estimated $K_d$ from both batch and column experiments and concluded that reasonable values for $R_f$ for PCE are typically between 1.1 and 3.6.

Rogers (1992) developed a groundwater transport model for the Lawrence Livermore National Laboratory (LLNL) site in California, which includes "several hundred feet of complexly interbedded, unconsolidated alluvial sediments" with an upper boundary represented by an unconfined water table condition. Their calibration and history matching resulted in reasonable matches for $R_f$ values between 1.0 and 3.0, with their conclusion that "a spatially averaged retardation factor of approximately 3 is recommended…"

Model Documentation:

To facilitate assessment of the scientific credibility and scientific defensibility of a groundwater model, the model study should be well documented. Reilly and Harbaugh (2004) state: "Because models are embodiments of scientific hypotheses, a clear and complete documentation of the model development is required for individuals to understand the hypotheses, to understand the methods used to represent the actual system with a mathematical counterpart, and to determine if the model is sufficiently accurate for the objectives of the investigation. … The appropriate level of documentation will vary depending on the study objectives and the complexity of the simulations."

Reilly and Harbaugh (2004) list ten topics that should be addressed in reports documenting model studies. These are:

1. Describe the purpose of the study and the role that simulation plays in addressing that purpose.
2. Describe the hydrologic system under investigation.
3. Describe the mathematical methods used and their appropriateness to the problem being solved.
4. Describe the hydrogeologic character of the boundary conditions used in the simulation of the system.
5. If the method of simulation involves discretizing the system (finite-difference and finite-element methods for example), describe and justify the discretized network used.
6. Describe the aquifer system properties that are modeled.
7. Describe all the stresses modeled such as pumpage, evapotranspiration from groundwater, recharge from infiltration, river stage changes, leakage from other aquifers, and source concentrations in transport models.
8. For transient models, describe the initial conditions that are used in the simulations.
9. If a model is calibrated, present the calibration criteria, procedure, and results.
10. Discuss the limitations of the model's representation of the actual system and the impact those limitations have on the results and conclusions presented in the report.

The documentation for the ATSDR model studies at Tarawa Terrace and HPHB study areas are detailed, comprehensive, and clear, and meet or exceed these guidelines, as evidenced by the series of model documentation reports that include 11 separate book chapters for Tarawa Terrace and 4 separate book chapters and 8 supplemental volumes for HPHB. Careful review of this comprehensive documentation indicates that ATSDR used scientifically acceptable tools and followed correct scientific methodology in performing its historical reconstruction, in contrast to the assertions of Dr. Spiliotopoulos and Dr. Hennet.

**Review Comments on Dr. Spiliotopoulos' Opinions:**

**Opinion 1**: Dr. Spiliotopoulos states "Due to the absence of sufficient historically observed data and site-specific parameters, the results of these calculations [in the ATSDR models] are highly uncertain and cannot be used for determining dose reconstructions at the level of detail that ATSDR presented in their analyses." I would counter that although early time data are lacking, there are still a lot of data and historical observations available, as documented in the several ATSDR reports on the investigations. Dr. Spiliotopoulos fails to specify how much data would be "sufficient". In any groundwater modeling study, there are never "enough" data and there is always uncertainty in the final model results. This is normal and expected. In this case, there were enough data to calibrate groundwater flow and transport models, and the data deficiencies were not so great as to prevent a historical reconstruction. In fact, a reasonable historical reconstruction was indeed accomplished, so it was possible. The historical reconstruction recognized the existence of uncertainty and assessed its impact on the results.

Dr. Spiliotopoulos refers to Section 4 of his report as his support for this opinion. Following are comments about his discussion in Section 4 of his report.

In the introduction to Section 4 (p. 27, para. 2), Dr. Spiliotopoulos overstates the lack of data for the Camp Lejeune groundwater system. He says that without site-specific data and a lack of observations, a model "can even be considered speculative and unfounded." That might be true if there were no site-specific data and no observations. But that is simply not true for these models. There are certainly site-specific data available on subsurface properties, as well as observations of heads, boundary conditions, and chemical concentrations for some time periods. These are all described in detail in the numerous reports published by ATSDR. There is no basis for applying the characterization of "speculative and unfounded" to the ATSDR models of TT and HPHB. Even for predictive periods, the system behavior simulated in the model still obeys the laws of physics and hydraulic principles, and contaminants will move in directions predictable by the hydraulic gradient, as calculated with the flow model.

In para. 3 (p. 27), he states that "'predictions' refer to model output, regardless of whether its results are used for hindcasting or forecasting …" I agree with this statement. However, in the next paragraph he discusses "When historical data are not available…" But whether the model predictions are used for forecasting or hindcasting, if it's truly a prediction, then there will be no measurements available (except later for a forecasting prediction). But at the time of model development, observation data for heads and concentrations will only be available during the calibration period. Implying that the lack of data during a predictive period is a problem is misleading. (If data were available during a historical period of interest,

hindcasting would not be needed—it would just be used as part of the observed data set for the calibration period.)

In para. 2 (p. 29), Dr. Spiliotopoulos states that Dr. Clement (in Clement's 2011 publication) "indicated that ATSDR's analysis implied almost exact knowledge of past conditions." I disagree. I find that ATSDR is clear that uncertainty exists about the conditions during the historical reconstruction period, as well as during the calibration period, and the results include assessments of uncertainty. If Dr. Clement inferred that ATSDR believed they had an exact knowledge of past conditions, then that is Dr. Clement's mistake. In the same paragraph on p. 29, Dr. Spiliotopoulos quotes Dr. Clement's comments about the uncertainty analysis. Although the quote starts with Dr. Clement saying that "the results appear to be reasonable …", he ends the quote with an apparent criticism by saying: "The figure also shows that closer to the initial starting point the confidence band is almost 100%, implying that our knowledge of initial conditions, initial source loadings, and initial stresses is almost exact." Although it may be counterintuitive, as I discuss in my Introduction, I actually do have high confidence in the assumption that there were no (or negligible) contaminants in the groundwater from ABC Cleaners prior to Jan. 1953, and probably very little for at least several months after that. Thus, at some point the confidence band should get narrower going backwards in time towards the starting date of the simulation.

In his Summary of Opinion 1 (p. 30), Dr. Spiliotopoulos says "these models were largely not constructed using site-specific data …" I strongly disagree. The geometry and boundary conditions of the model and its hydrogeologic framework are derived from hydrogeologic and geophysical studies of the subsurface aquifer system at the Camp Lejeune and adjacent areas, as documented in USGS reports and in several of the ATSDR reports. This type of information provides a critical and necessary foundation for the models. The potentiometric and water table maps also provide important information for the construction and calibration of the models. Dr. Spiliotopoulos also states in this summary that the models were not "calibrated to observed data for the first 30 years of simulation." Of course, because those concentration data did not exist. That is the reason these models were built—to estimate those concentrations in a state-of-the-art way that is consistent with principles of groundwater flow and transport processes. The models did not generate arbitrary or random numbers. The results are based on the physics of groundwater flow and contaminant transport, and the results appear reasonable and realistic, and the existence of error bands or uncertainty ranges around the estimates is expected and openly acknowledged.

**Opinion 2**: Dr. Spiliotopoulos says that ATSDR used "parameters and assumptions that are incorrect or not representative of site conditions …" Parameter values for groundwater models are never known precisely and accurately. That is an unfortunate fact of life in groundwater modeling. The parameter estimation process (essentially, the model calibration exercise) is conducted to adjust parameter values within a range of reasonable values to yield a best fit between model simulation results and the limited observation data available. This naturally allows and/or creates compensating errors in the input data for the model. Dr. Spiliotopoulos says this results in conservative estimates of estimated monthly contaminant concentrations. It is not clear what is meant by "conservative" or why that is not a good trait. He also says the results are biased high. His main argument for that opinion seems to be that early (in time) results often lie above the mid-point of the uncertainty bands. The uncertainty bands reflect a zone within which results are expected 95% of the time; if results mostly fall within the uncertainty

bounds, they should be considered acceptable. He cites sections 4.1.1 and 4.1.2 of his report for support of this Opinion.

On p. 31 (Section 4.1, 4th para.) Dr. Spiliotopoulos states "ATSDR's calibrated model sits at the top of the uncertainty range, … This demonstrates that the calibrated model was biased high." But it does not prove ATSDR's model is wrong. The results are within the uncertainty bounds and true values are expected to lie somewhere within the uncertainty bands. Furthermore, best estimates of concentrations do not have to lie at the center of the error band. A model may become insensitive to certain parameters used to create the error bounds at their upper or lower limits, and the response of the model to some parameter variations is not linear.

In para. 7 on p. 31, Dr. Spiliotopoulos quotes the NRC (2009) report where it says "Reporting precise values based on model predictions gives the misleading impression that the exposure of the former residents and workers at Tarawa Terrace during specific periods can be accurately defined." Would he prefer imprecise values? NRC gives no examples of where the ATSDR-reported values are too precise or are prone to misinterpretation in light of the pervasive discussions of model uncertainty provided by ATSDR in its reports. Furthermore, Dr. Spiliotopoulos fails to cite the first sentence of that same paragraph, where the NRC report states "The committee concluded that ATSDR applied scientifically rigorous approaches to address the complex groundwater-contamination scenario at Tarawa Terrace." [emphasis added.]

For Section 4.1.1 (p. 32), Dr. Spiliotopoulos uses the heading "Available data are limited to non-existent", but the first statement after that notes that there were 36 aquifer tests at TT to estimate aquifer properties. This is actually a lot of data, especially considering that aquifer tests are time-consuming and expensive to run. Data for TT are certainly *not* non-existent. I am sure many groundwater models have been developed for areas where there were less than 36 aquifer tests available.

In his summary of Opinion 2 (p. 33), Dr. Spiliotopoulos references his Fig. 5, which includes a reproduction of ATSDR's Fig. F16 about TT results, and goes on to say that ATSDR's work resulted in "biased high estimates." I reproduce that part of Dr. Spiliotopoulos' Fig. 5 (Fig. F16) here because it actually illustrates the opposite. It shows 5 measured PCE concentrations in samples from well TT-26 collected within weeks of each other in early 1985. Over this relatively short time span, the concentrations varied greatly (bracketed between a high of 1,580 ug/L on 01/16/1985 to a low of 3.8 ug/L on 02/12/1985)—a rate of change that cannot be replicated in a model using monthly time steps. Most importantly, the plot shows that the model results fell almost exactly at the midpoint of the range of observed values (about 800 ug/L)—countering the claim of the model being biased high.

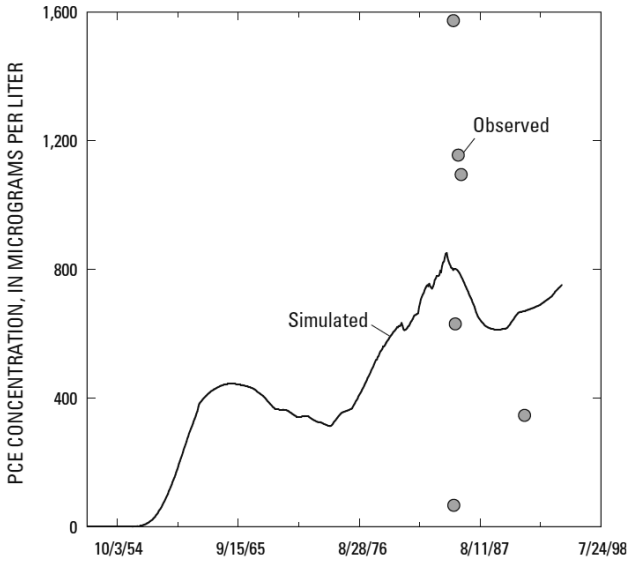



**Figure F16.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1952–December 1994 (see Figure F6 for location).

Section 4.1.2, p.34, 1st para.: Dr. Spiliotopoulos quotes TT Chapter C (p. C38) saying that "… simulation results are unqualified for the years 1951-1977, …" This is a statement of recognition by ATSDR that there is a paucity of water-level measurements during that early time period. This is also part of ATSDR's consistent messaging that uncertainty exists, and is greater for some time periods than for other time periods. However, it does not disqualify or "unqualify" the model itself, as even during that same time period, other calibration controls and constraints exist in terms of boundary conditions and stresses. Specifically, the adjacent surface water systems represent hydrologic boundaries with known average elevations that change very little over periods of decades. Average monthly recharge can also be estimated based on precipitation and other climatic data that are available. Given such constraints, there is a limited range over which the simulated heads can vary, and that range is not unqualified or unconstrained.

In Section 4.1.2, p.34-36, Dr. Spiliotopoulos cites ATSDR (TT, Chapter F) as noting that 53% of comparisons of simulated to observed concentrations violated ATSDR's calibration target. But many of these samples were collected on the same day or within a short time of other samples (Figure 6 (Table F13), p. 35), so giving equal weight to each comparison is not statistically reasonable. These temporally closely spaced samples are not truly independent samples. Alternatively, I would say a fair comparison should be made on the basis of the quality of the agreement between simulated and observed concentrations at the 11 separate sampling (well) locations. This gives equal weight to every sampling location. Of these, 8 can be deemed "accurate" (including two that have some low and some high samples, so accurate on average), one is high but within the target range, one is slightly high, and one is consistently high (TT-23). On this basis, 73% of the sampling wells show reasonably and acceptably accurate simulation results. Also see my related discussion of calibration targets below (for Section 3.3).

On p. 36, para. 4, in his summary of Opinion 2, Dr. Spiliotopoulos states that the "model calibration did not rely on observed data prior to 1984." Yes, no contaminant concentration data were available then, and that is why ATSDR needed a deterministic groundwater simulation model to estimate how the contaminants were distributed in the aquifer during that time period.

**Opinion 3**: This Opinion notes that the calibrated model for TT was built using different parameter values and assumptions than the HPHB model. Dr. Spiliotopoulos cites sections 4.1.2.2, 4.1.2.3, and 4.2.3.2 of his report for support. In general, I note that these two study areas do not overlap. Although they are adjacent, and one would expect similar characteristics, having differences is not surprising and certainly the two independent calibrations can yield different values for the various parameters in the models. The models were also developed and calibrated at different times (TT being the earlier model) and improved calibration (parameter estimation) software was applied in developing the latter (HPHB) model.

Dr. Spiliotopoulos (Section 4.1.2.2.1, p. 37) indicates that an error was made in calculating the bulk density ($\rho_b$) for the TT system. Using an average value for total porosity of about 35%, he calculated that $\rho_b$ should be lower, stating that "In the Hadnot Point model, this error was not repeated." That value was 1.65 g/cm$^3$. He states that "This has a significant impact on the calculation of the retardation factor, resulting in faster (sooner) arrival of PCE at the water-supply wells, …" However, as Dr. Spiliotopoulos himself admits, this significant impact on $R_f$ does not actually occur because the calibration process compensates for an overestimate of $\rho_b$ by estimating a value for $K_d$ that appears to be too low. Recall that neither of these two parameters are used directly in the transport model. Rather, the retardation factor is used to calculate the migration velocity of the contaminant, and this retardation factor depends on the product of $\rho_b$ and $K_d$. The calibration process yields a very reasonable value for $R_f$ for PCE—a value (about 2.9) that is very consistent with values in other field studies reported in the literature (e.g., Rogers, 1992; Kret et al., 2015). In Section 4.1.2.3, Dr. Spiliotopoulos has a whole paragraph describing the erroneous consequences "if ATSDR had used a retardation factor of 6.44." But ATSDR did *not* use a $R_f$ = 6.44, so this argument is irrelevant. In summary, the two specific possible errors cited by Dr. Spiliotopoulos for $\rho_b$ and $K_d$ largely offset each other, and have a minimal or negligible impact on the final results, as documented by ATSDR (CLJA_WATERMODELING_01-0000075468; ATSDR_WATERMODELING_01-0000887324).

Dr. Spiliotopoulos (Section 4.1.2.4, p. 39 and elsewhere) and Dr. Hennet (Opinion 11) raise concerns that site-specific data were not used to estimate total organic carbon (TOC) or to calculate $K_d$. TOC is used to estimate $f_{oc}$, which in turn is used together with an estimate of $K_{oc}$ to estimate $K_d$, which in turn is but one factor in the equation used to estimate $R_f$. That is a long string of dependencies. Appendix A of Dr. Spiliotopoulos' report shows that reported values of TOC vary over a range of about four orders of magnitude. That is a huge variation and uncertainty, which is not accounted for. You cannot simply assume that the mean of that distribution of TOC values is the true and correct one to use to estimate $K_d$. Overall, there would be much less uncertainty, greater value, and more clarity in just estimating an average value for $R_f$ as part of the calibration process, which is the methodology ATSDR employed. I believe that this is not optional and that $R_f$ must be estimated during and in accordance with the calibration process. In light of this, it simply would not have mattered if $K_d$ had been preliminarily

estimated by ATSDR using highly variable site-specific measurements of $f_{oc}$/TOC. In the end, the value of $R_f$ = 2.9 calibrated by the ASTDR modeling work is very close to other values reported in the literature for aquifers having similar geologic materials.

Dr. Hennet also criticizes ATSDR for failing to consider available site-specific data for $f_{oc}$ (fraction of organic carbon) to estimate values of $K_d$ (his Opinion 11). Rogers (1992, p. 51) in discussing the $K_d$ parameter says "Numerous researchers have used theoretical methods correlating the organic carbon content (OCC) of the subsurface material and the $K_d$ (Karickhoff, 1984). Others have used the partitioning between octanol and water to predict the $K_d$ (Kenega, 1980). **These methods are not considered appropriate where the OCC is less than approximately 0.1%**." OCC is equivalent to TOC, and 0.1% is equivalent to a fraction or 0.001. Hennet's Expert report lists (Exhibit 3-2, and p. D-11 to D-12) 21 Camp Lejeune samples where $f_{oc}$ is given. The median value is 0.0013, barely above the indicated limit, and 9 samples (43% of the samples) have values <0.001, indicating that the use of $f_{oc}$ to estimate $K_d$ is not appropriate. If ATSDR had used this approach, it would have introduced additional errors and sources of uncertainty.

In his summary of his Opinion 2&3 (p. 38-39), Dr. Spiliotopoulos states (in reference to $\rho_b$ and $K_d$) that "parameter values in the Tarawa Terrace model were different than those used in the Hadnot Point model, even though both models simulated similar hydrogeologic conditions." This is not a problem, and it would be more surprising if they had applied identical values. The areas have similar conditions, not exactly the same conditions. Hydraulic conductivity measurements show notable differences between the two areas, reflecting local differences in aquifer material properties. These differences also cause differences in the factors contributing to the $R_f$. There is nothing wrong or unexpected about this. $R_f$ was estimated in the calibration process, and the HPHB calibration used a different (and supposedly better) automated parameter estimation software package, which was not used in the TT calibration. So of course some differences will result. If they had applied the same parameter estimation software to both sites, it still would most likely result in different values for the average $R_f$ in the two different areas. But the differences are small and inconsequential.

In a summary of his Opinion 3 (p. 39), Dr. Spiliotopoulos states that "these incorrect assumptions resulted in faster plume migration in the aquifer and estimated monthly concentrations that were conservative and biased-high." However, this would only be the case if the errors in the two parameters were considered separately and alone. But the model does not respond to these values separately. It responds to their net effect on the retardation factor, which was calibrated to a very reasonable value consistent with other peer-reviewed studies. The errors were compensatory and that compensation was built into the critical $R_f$ value by the calibration process, as would be expected from a calibration process for a groundwater model.

**Opinion 4**: Dr. Spiliotopoulos says that use of "parameter values based on site-specific data … in Tarawa Terrace would result in substantially lower estimated monthly concentrations. Furthermore, the model uncertainty range would also be lower." Dr. Spiliotopoulos cites his Section 4.1.2.5 as support.

On p. 39, Dr. Spiliotopoulos argues that site-specific data for calculating $K_d$ would result in a higher $K_d$ value. Again, the model calibration process adjusted values of $K_d$, one component of the retardation

factor, so that the value of $R_f$ was as reasonable and accurate as possible for maintaining consistency with the available observed concentrations. Furthermore, in calculating $K_d$, Dr. Spiliotopoulos used a porosity value of 20%, which was the effective porosity used in the transport model. However, in calculating $\rho_b$, the other component of $R_f$, Dr. Spiliotopoulos used a porosity value of about 35%--a value representing the total porosity measured in two soil samples (p. 37). Using two different values for porosity in the same equation is inherently wrong, creating an inconsistency of 75%, and is done with no explanation.

In section 4.1.2.5, Dr. Spiliotopoulos develops a "revised" model using a late start date and a different $K_d$ value. He presents his results in comparison to the ATSDR model results in his Figs. 7 and 8. He accentuates the early time differences by plotting results arithmetically rather than logarithmically. But that's a minor point. The proper start date is outside the scope of my opinions. But adjusting the $K_d$ without also adjusting $p_b$ is one-sided. In any case, Dr. Spiliotopoulos' value for $R_f$ in the revised model is 3.48. The value of 2.93 used by ATSDR is only 16% lower than this new value used in Dr. Spiliotopoulos' revised model. This difference is relatively small. Furthermore, as seen in those two figures, the difference between the ATSDR results and Dr. Spiliotopoulos' revised model results are very small after approximately 1970. More importantly, both models are consistent in showing that PCE concentrations are above the MCL for most of the study period—and since Jan. 1, 1960 in both models, at both Well TT-26 and in influent to the TT WTP.

Also noteworthy in Dr. Spiliotopoulos' Fig. 7 is that for both models, there is a peak concentration shortly before 12/84. When $K_d$ is higher and $R_f$ is consequently higher, then one would expect that a peak moving through the groundwater system would be somewhat delayed, yet there is no indication in the results for Dr. Spiliotopoulos' revised model that this peak concentration was delayed at all. Instead, it appears to have arrived at TT-26 at the same time as in the ATSDR model. This demonstrates a lack of sensitivity to the value of $K_d$ in this particular system. It simply did not make a significant difference.

Dr. Spiliotopoulos' only support for his opinion that the uncertainty range would be lower is a concluding statement in his Summary on p. 41, which states, "The uncertainty range for such historical reconstruction would also be lower, as it would be based on slower plume migration and lower concentrations for many years after the start of contaminant releases from the source." However, this is an inference that itself is not supported by analytics. Dr. Spiliotopoulos has not demonstrated that the uncertainty range would be lower. Dr. Spiliotopoulos' results also do not demonstrate significantly slower plume migration (peaks are coincident) or significantly lower concentrations (after 1970 they are almost identical—differing at TT-26 by an average of about 30 or 40 ug/L out of an average concentration of roughly about 500 ug/L—less than 10%).

**Opinion 5**: This opinion states that the ATSDR groundwater model for TT "resulted in biased-high estimates of monthly contaminant concentrations at one of the water-supply wells." The well in question is TT-23. Dr. Spiliotopoulos cites Section 4.1.2.6 of his report in support of this opinion.

Section 4.1.2.6 (p. 42) offers no clear evidence that the discrepancy at this one well (out of many) has a substantial impact on the overall results. Based on ATSDR Table E2, of the nine unique sampling dates for this well, six had an observed level of PCE or TCE above the MCL. Furthermore, with respect to the overall effect on concentrations estimated at the WTPs, it is important to note that TT-23 was

operational for only about 9 months or less, starting in 1984, and had the shortest operational (pumping) period of any of the 16 pumping wells operating in the TT area (see Table H3 in Chapter H of the TT series of reports). When it was pumping, the contribution from this well provided only a small fraction of the total groundwater inflow to the WTP with concentrations far less than well TT-26 (with its modeled concentrations likely being underestimated). Thus, if indeed the estimates for this well were too high (by less than two times), the effect on calculated concentrations in the WTP would be minimal both in magnitude and in duration.

**Opinion 6:** Dr. Spiliotopoulos says that the ATSDR model did not reflect "observed data that indicated absence of contamination in the aquifer." Does he doubt that there was contamination in the aquifer? The presence of contamination in the aquifer is well documented; the absence of contamination in some locations means little overall—only that the contamination was not everywhere. That is normal. The statement and implication that there is no contamination in the aquifer is simply incorrect. The ATSDR reports clearly document observations where the contaminants were not detected (e.g., Table F13), and their analyses reflect that. Support for this opinion is stated to lie in Section 4.1.2.7.

In Section 4.1.2.7, Dr. Spiliotopoulos makes a major point about plotting non-detects, and he criticizes ATSDR for not plotting nondetects. He cites the reason as being that "non-detections listed as zeros are not visible in a logarithmic-scale scatterplot. This is because a logarithmic scale can only show numbers greater than zero." However, nondetects do not mean that the value is zero—only that it is less than the detection limit. In aiming to support his point, Dr. Spiliotopoulos relies on an analysis that is arbitrary, incorrect, and biased. He selects a value of 0.1 ug/L to represent all nondetects. For these samples, the detection limits were between 2 and 10 for most analyses. Helsel and Lee (2006) say: "The most common procedure within environmental chemistry to deal with nondetects continues to be substitution of some fraction of the detection limit. This method is better labeled as "fabrication", as it reports and uses a single value for concentration data where a single value is unknown. Within the field of water chemistry, one-half is the most commonly used fraction, so that 0.5 is used as if it had been measured whenever a <1 (detection limit of 1) occurs." If representing nondetects in a plot is to be done, a reasonable value and common way to represent a nondetect would be halfway between the detection limit and zero. For the Camp Lejeune data with detection limits of 2.0 and 10.0, the plotted position should be either 1.0 or 5.0 respectively (the latter being 50 times greater than the arbitrary value Dr. Spiliotopoulos used—so plotting 0.1 instead of 5.0 is a significantly misleading/biased-low way to present the data). This will make a big difference on his plot (such as his Fig. 18). Note: On this topic, Helsel and Lee (2006) also state: "All such plots [scatterplots using halfway points] are misleading, because unique censored values are unknown. Instead, left-censored data can be plotted as intervals between zero and the detection limit for each observation. In this way, no false statements about where an individual value is located, or that all such observations are at the same value, are made." There may also be other alternatives for plotting nondetects (newer and better, but more complicated). Regardless, Dr. Spiliotopoulos' selection of 0.1 to represent all nondetects is arbitrary, misleading, and wrong. ATSDR's approach of not plotting nondetects avoids the possible perception of "fabrication" and is more defensible than Dr. Spiliotopoulos' approach of assuming all nondetects can be fairly represented by an arbitrary value of 0.1, as shown in his Fig. 9 (p. 43). The discussions of Helsel and Lee (2006) justify the ATSDR's approach for not including nondetects on the data plots because of the risk of appearing to

fabricate data or presenting misleading plots. ATSDR does show nondetects in all tables of measured concentrations.

In para. 1 (p. 45), Dr. Spiliotopoulos notes that the model results indicate a low value of 5.8 ug/L in well TT-54, but the observed value was a nondetect. He states that the calibration "is not supported by the non-detection in the sample collected in February 1985." I would argue that it is indeed supported by that data. The detection limit for that analysis was 10 ug/L (TT Table F2). The halfway point between zero and the detection limit is 5.0, a value that is very close to ATSDR's simulated value, and that close agreement is certainly supportive of the quality of the calibration.

Dr. Spiliotopoulos notes (p. 45) that "Well TT-54 had a reported non-detection in July 1991. However, the ATSDR model indicated an increasing concentration trend at well TT-54, suggesting that the PCE plume continued arriving at that well until that time. This is unlikely to be accurate." However, if one examines the predevelopment and transient potentiometric surfaces (TT Chapters C and F), it is clear that TT-54 is downgradient from the ABC Cleaners, and that a plume evolving from that source while several water-supply wells are operational will likely contribute some contaminants to well TT-54.

Dr. Spiliotopoulos' Summary of Opinion 6 (p. 45) picks two of the wells to generalize that "ATSDR's model overestimated the plume migration extent and rate of migration, which were both conservative and biased-high." This is an overgeneralization that ignores other wells and locations where estimates were very close or were underestimated. The nature of model calibration is that there will be compensating errors and that some simulated values will be too high and others too low. Certainly, the results for the flow model (e.g., Fig. C9) do not support a generalization that the flow model is inaccurate or biased-high.

**Opinion 7:** Dr. Spiliotopoulos states that "the presentation of results of the uncertainty analysis conducted by ATSDR for the Tarawa Terrace model was misleading by showing a narrow uncertainty range around the calibrated model." Support is given in Section 4.1.3.1.

In 4.1.3.1, Dr. Spiliotopoulos' characterization changes from "misleading" to "visually misleading." The stated reason is that "they used a logarithmic scale, which visually compresses the uncertainty range around their calibrated model [results]." However, the use of a logarithmic scale is a valid and common approach in engineering and scientific studies, and is not characterized as being misleading by scientists and engineers. He observes that the plot ranges over six orders of magnitude on the axis for PCE concentration, but the width of the uncertainty bands do not. When values span such a large range, it is normal and standard to use a log plot. Using just an arithmetic scale would effectively hide all the changes in the lower part of the scale.

Dr. Spiliotopoulos states (p. 46, para. 4) that "the difference between the high and low values in Figure 11 [ATSDR's Fig. I29] is not significant enough to justify the use of a logarithmic scale." I disagree because the observed values span more than two orders of magnitude (excluding nondetects) and the simulated values span more than five orders of magnitude. Plotting these using a log scale is reasonable and informative, and is the only way to portray the early time results of the simulation in the same graphic. It is fine to also present these results plotted on an arithmetic scale (Fig. 12), but not sufficient to do so solely. Dr. Spiliotopoulos' concern over the concentration plots is mostly cosmetic.

On p. 48 (para. 1), Dr. Spiliotopoulos criticizes the uncertainty analysis, saying "… the concentrations calculated by the model should be generally in the middle of the uncertainty range … However, the calibrated model-simulated concentrations are almost identical to the upper bound of the uncertainty range in the early years of operation (1957-1963)." However, if one examines his Fig. 12 (p. 48 of his report), it clearly shows that the results are indeed generally in the middle of the uncertainty range. In the few early years it is above the middle, but consistently below the upper bound, as desired. Such a result is within a probabilistic expectation. In those early years the concentrations are the smallest. For example, in 1960 the difference between the upper bound and the middle of the range is only about 10 ug/L, which is a small value on the full scale of PCE values considered. Being "generally near the middle" is not an objective or quantitative rule.

**Opinion 8:** Dr. Spiliotopoulos states that "ATSDR's uncertainty analysis was not bound by historical concentration data, and as a result, focused only on model precision and not accuracy in predicting COC concentrations. ATSDR's uncertainty analysis was presented as though it evaluated the model's accuracy. It did not." Support is stated as being in Section 4.1.3.2.

The criticism is based on the lack of historical data on concentrations prior to 1982 (Section 4.1.3.2, p. 49), and would mean that "the uncertainty analysis would result in precise but not necessarily accurate solutions …" However, once again, the lack of concentration data prior to 1982 is the reason that the model was developed. Data are available afterwards, and initial conditions for the contaminant distribution can be stated with reasonable reliability that the concentrations in the TT area were zero prior to the start of operations at ABC Cleaners. That is an important known concentration condition for the early 1950s. What the model does is estimate how the concentration changed spatially between the time of the start of ABC operations and the time when observations of PCE became available, and it does so in a manner that is consistent with the principles of groundwater flow field and solute transport, with the further recognition that the groundwater flow field has been simulated with acceptable accuracy.

The ATSDR assessed uncertainty using a sophisticated but standard and acceptable statistical approach—using a Monte Carlo simulation method. They carefully documented their approach, which generated 840 realizations. In a Monte Carlo simulation approach, no single realization is expected to be "accurate." Rather, the ensemble of realizations is intended (and expected) to bracket a range of feasible but realistic outcomes. The range of results (generally considering 95% of the outcomes) is a measure of the model's predictive accuracy. The Monte Carlo uncertainty analysis would not be expected to yield a different calibrated model.

In the last paragraph on p. 49, Dr. Spiliotopoulos states that "one of the most critical parameters for determining how fast contaminants will migrate in the aquifer is the retardation factor." I would argue that both the speed and direction of migration is more critically determined by the head distribution (hydraulic gradients, as determined by the groundwater flow model) and the effective porosity. The retardation factor will have no effect on the direction of transport of a contaminant for a given flow field. Furthermore, the results presented by Dr. Spiliotopoulos in his Fig. 7 show that the model results, at least at Well TT-26, are relatively insensitive to a range of uncertainty in the assumed value of $K_d$ and $R_f$.

On p. 50 (para. 3), the Monte Carlo approach used by ATSDR is criticized by Dr. Spiliotopoulos "… because ATSDR implemented a 'probability distribution function' … to describe how values closer to the mean

value of the range are more probable than those away from the mean." I do not see a problem here as this is an option within standard practice for random sampling of parameter values for a MC analysis when information or theory indicates that a parameter has a statistically normal or log-normal distribution. Zheng & Bennett (2002, p. 353) say "The Monte Carlo method is by far the most commonly used method for analysis of uncertainty associated with complex numerical methods." They further state (p. 356) "The heart of the Monte Carlo method is the generation of multiple realizations (or samples) of input parameters that are considered to be random variables. Each random variable is assumed to follow a certain probabilistic model characterized by its probability density function (PDF). The probability distributions commonly used in hydrogeologic studies include *normal*, *lognormal*, *exponential*, *uniform*, *triangular*, *Poisson*, and *beta* distributions." It is worth noting that when this book was published, co-author Bennett was an employee of SSP&A and first author Zheng was a former employee and affiliate of SSP&A.

The plots shown in Fig. 13 are discussed in para. 8 (p. 50, Section 4.1.3.2). Dr. Spiliotopoulos notes that the results of the calibrated model "sits at the upper bound of the retardation-factor uncertainty range." However, that is not true for the majority of the simulation period. It is close to the middle of the range during the period of 1962 through the end (around Dec. 1987). And prior to 1962, it still lies within the uncertainty bounds, which is acceptable and not indicative of bias. As stated earlier, error bounds need not be evenly distributed around the mean because a model can be sensitive to a parameter at either high or low values, but not both.

In the 3rd paragraph on p. 51, Dr. Spiliotopoulos presents the values for the retardation factor with four significant figures. Whether $R_f$ is estimated by adjustments during model calibration or estimated from highly variable and uncertain site-specific data, presenting it with 4 significant figures is an unjustified and meaningless precision.

**Opinion 9:** This continues the previous discussion of the uncertainty analysis and cites the same section (4.1.3.2) as support. Dr. Spiliotopoulos says that the uncertainty analysis for TT "… did not encompass uncertainty bounds representative of site-specific conditions, resulting in biased-high uncertainty range."

It is not clear exactly what is meant by a "biased-high uncertainty range." If it means that the uncertainty range is incorrectly too high, that implies that the model is even more accurate than indicated.

On p. 52 and in Fig. 14, Dr. Spiliotopoulos discusses the results if $R_f$ were 4.3 instead of 2.9. But this value of 4.3 is higher than those presented in published peer-reviewed articles of PCE transport in similar types of aquifer materials (Rogers, 1992, and Kret et al., 2015). Even with Dr. Spiliotopoulos' high value of $R_f$, Fig. 14 shows that after about 1970, the differences at Well TT-26 are small—less than 100 ug/L difference during the final 20 years of the simulation, with Dr. Spiliotopoulos' revised model showing lower concentrations because it includes a larger sorption rate. Again, it is relevant to note that the observed data shown in this figure range from about 3 ug/L to almost 1600 ug/L for samples collected over a relatively short time period in early 1985. The ATSDR model results fall very close to the midpoint at that time—at about 800 ug/L—not indicative of any bias. However, Dr. Spiliotopoulos' revised model with the higher $R_f$ value calculated a PCE concentration of about 700 ug/L at the time when the data are available—lower than the mid-point, which does not provide evidence that the higher value of $R_f$ is more

accurate (actually, it's an indication that it is less accurate). Either way, the computed PCE concentration values are higher than the MCL for all times after 1960, which is a critical point.

The three highest observed values of PCE in well TT-23 were underestimated by the ATSDR model, which counters the claim that the ATSDR model is biased high.

On p. 55, Dr. Spiliotopoulos says that "ATSDR's selection of the retardation factor parameters forced the calibrated model to simulate fastest arrival of PCE at well TT-26 …" This use of the word "forced" appears to unfairly attribute an unscientific and biased motive to the way the model calibration was conducted. First of all, this was not the fastest possible arrival. If they had used a value of $R_f = 2$, the arrival would have been faster than the value they calibrated to. I think a fairer way to characterize the calibration relative to $R_f$ is that they varied the values of $R_f$ and of other parameters and selected parameter values that yielded the best overall fit to the available data. This happened to be a value of 2.9 for $R_f$, which was very consistent with other values reported in the literature for PCE transport in similar types of geologic material.

**Opinion 12:** This opinion focuses on the model post-audit performed by Jones and Davis. The opinion says that the post-audit showed that "ATSDR's dose reconstruction groundwater model for drinking water in Tarawa Terrace used parameters and assumptions that resulted in conservative and biased-high estimates of monthly contaminant concentrations." Support is said to be given in Section 4.1.5.

It is my understanding that Jones and Davis, as well as Maslia, will respond to this opinion in their rebuttal reports. A few general comments about the content of section 4.1.5 follow.

In Section 4.1.5.1 (p. 60, para. 2) Dr. Spiliotopoulos states that "Observed concentrations of zero correspond to non-detections." As mentioned previously, this statement is not accurate in the sense that nondetect values do not necessarily have a value of zero, but their value may be anywhere below the detection limit for that particular analysis. Also, in para. 3 and Fig. 18 (p. 60), Dr. Spiliotopoulos repeats the same error in assuming that a nondetect can be substituted by a value of 0.1 ug/L. This is arbitrary and biasing.

Dr. Spiliotopoulos calculates a mean error for partitioned segments of the data set—separately for points where the observed value is higher and separately for points where the simulated value is higher. This is not a common or standard way to compute a mean error. Based on my experience and expertise, the standard methodology is to compute the mean error for all data.

**Opinion 13:** This opinion also focuses on the model post-audit performed by Jones and Davis, and is closely related to Opinion 12. It suggests what Maslia and Aral should have done with the data of Jones and Davis. Support is again said to be given in Section 4.1.5. It is my understanding that Maslia will respond to this opinion in his rebuttal report, but I have a general comment regarding the absence of data.

On p. 63, Dr. Spiliotopoulos expresses concern that "no data are available to evaluate whether the overall extents of the simulated plume are real." Some data are certainly available. It would be nice if

more data were available. If extensive data were available to map the plume in detail over time, there would be little need for a simulation model. The ATSDR models reliably simulate the groundwater flow field and head distributions so that the transport models can simulate advective and dispersive processes, as modified by chemical reactions and adsorption (as simplified using the retardation factor), to fill in the gaps in the observational database in a way consistent with widely accepted governing principles of groundwater hydraulics and transport phenomena. This is a reasonable and appropriate approach to addressing this issue.

**Opinion 14:** This opinion restates previous ones, but for Hadnot Point, and says that the ATSDR model "was constructed and calibrated using parameters and assumptions that are uncertain or incorrect." Support is said to be given in Sections 4.2.1, 4.2.2, 4.2.3, and 4.2.4.

In general, groundwater systems occur within subsurface geologic frameworks that are complex, heterogeneous, and hidden from view. There are and always will be uncertainty associated with even the best efforts to define the properties and relevant characteristics of these systems. This does not preclude the development of reliably sound numerical models to simulate groundwater flow and transport processes. But model developers must always be aware of, and assess, the existence of uncertainty and the sensitivity of the model results to this uncertainty. ATSDR has indeed accomplished this. For TT, they have produced a 187-page chapter (Chapter I) solely about this task (in addition to many discussions of it throughout the other chapters). For HPHB, there are two sections in Chapter A of their reports focused on these topics.

Dr. Spiliotopoulos states (p. 68, para. 4) that "Unlike the Tarawa Terrace model, ATSDR did not know the precise location of all contamination sources and the magnitude of contamination each source contributed." This is true—there is uncertainty in the source terms (as with all model parameters). But that can be handled and does not preclude the development of a reasonable flow and contaminant transport model. Assumptions had to be made, but they were not "arbitrary" and were clearly and comprehensively documented. He cites the NRC (2009) report, which said "There were multiple sources of pollutants, including an industrial area, … [etc.]" What is certain is that all of these are likely sources of groundwater contamination. Industrial operations in the 1950s, 60s, and 70s were typically not concerned with protecting groundwater quality.

In footnote 235 (p. 68-69), Dr. Spiliotopoulos says, "ATSDR used simulated contaminant concentrations in the influent to the WTP to calculate concentrations in the water delivered to a family housing or other facility, without considering any contaminant losses during treatment." However, unless the treatment process was designed to treat these contaminants, it would have been "arbitrary" and highly uncertain to simply assume that the treatment reduced contaminant concentrations or removed contaminant mass.

p. 69: Dr. Spiliotopoulos cites "evaporative" losses in a treatment plant. However, evaporation is rarely significant in a water treatment plant and direct evidence would be needed to support this hypothetical claim. Contaminant loss due to volatilization during the treatment and distribution process was discussed at the March 28, 2005 expert panel meeting where panelists—including Dr. Pommerenk of AH Environmental— opined that any loss would be minimal (See March 28, 2005 Expert Panel Meeting Transcript at 55:2-57:14, 56:2-57:14).

In para. 3, Dr. Spiliotopoulos says “Based on [his] professional judgment, there was insufficient data to conduct groundwater flow and contaminant transport model calibration and uncertainty analysis.” But in fact, ATSDR did “conduct” it, and clearly documented their calibration and uncertainty analyses. In my professional judgment, they did a good job with the limited data available.

In para. 4 (p. 69), Dr. Spiliotopoulos repeats that “prior to 1982, no water quality data were available …” However, groundwater flow directions can be deduced with typically small uncertainties, and flow rates (velocities) and advective-dispersive transport can be simulated with some additional uncertainty, but these key processes are reasonably well defined. Also, it is highly certain that prior to the start of these industrial and landfill operations, the contaminant concentrations were zero—an important early-time data point.

In para. 7, Dr. Spiliotopoulos quotes NRC (2009) as saying “simpler modeling approaches should be used to assess exposures from the Hadnot Point water system.” While this is easy to say and sounds appealing, they don’t say how to do that or what simple modeling approach would work. How does one know if a model is too simple? What processes should be eliminated in the simpler model? In fact, the way to produce a simpler model is to first develop and calibrate a maximally realistic “complex”, detailed, and comprehensive model that can be then used to assess which processes or factors have little effect on the results and so can be safely eliminated to produce a simpler model. The benefit cited by NRC is faster and more efficient modeling, but that potential benefit is not a major need here, and the use of models that might be too simple is offset by their reduced realism and risk of oversimplification.

On p. 70 (section 4.2.1), Dr. Spiliotopoulos says “available data are limited or non-existent” but in the first bullet point states that “more than 200 aquifer and slug test analyses” exist. This is a lot of data! There are many groundwater models that have been developed and calibrated on the basis of much fewer hydraulic testing at the specific site of interest.

On p. 70, Dr. Spiliotopoulos is also concerned that pumpage data for individual wells were estimated on the basis of “ancillary data.” This is common standard practice in groundwater modeling, as pumpage measurements for wells are often not available or are of questionable quality.

In the last para. (p. 70) Dr. Spiliotopoulos notes that the HP WTP was built in 1942 and during its first 40 years of operation, there were no water quality data for the contaminants of concern. This is unfortunate, but not unexpected; it is rather common for groundwater contamination problems that a chemical that turns out to be problematic at a later date is not monitored prior to that awareness. This is why ATSDR had to use modeling to help reconstruct the historical record as well as possible, using documented quantitative methods. Of course, there will be uncertainty in the results, but they seem reasonable given the information that is available.

p. 71, Fig. 25 (ATSDR Fig. A18): Dr. Spiliotopoulos presents four plots of simulated and observed TCE concentrations at four wells in the HPHB study area. All four plots show that the simulated values were either close to the middle point between observations (HP-602 and HP-608) or below the observed values (HP-634 and HP-601/660). There is no indication here that the model overestimated concentrations (or was biased-high).

In summarizing Opinion 14 (p. 71), Dr. Spiliotopoulos says “Selection of model parameters was based, primarily, on professional judgment.” This is always the case. Data are always limited, and professional

judgment is required to assess how to deal with that paucity of data and how much weight to give the limited number of measurements. A groundwater modeler always wishes they had more data, but the reality is that there are never so much data available so as to avoid using professional judgment.

In Section 4.2.2 (p. 72) the claim is made that ATSDR "made arbitrary assumptions to reconstruct pumping history …" In my opinion, the assumptions were not arbitrary, but rather were well-informed, well-reasoned, and carefully documented. Assumptions had to be made about the pumping history, and they were made, but they were not arbitrary. For example, Dr. Spiliotopoulos notes that "Yearly volumes are available for some years prior to 1980. A trendline was used to estimate raw-water flows for years prior to 1980 when no data exist." This appears to be a sound statistical approach, and the use of a trend line is certainly not arbitrary.

In Section 4.2.2 (p. 72-73) Dr. Spiliotopoulos offers a further criticism that "it was assumed that a well would be operated in the historical period based on a pattern similar to the more recent 'training period,' with further adjustments to account for information on the varying capacity of wells, where available." Dr. Spiliotopoulos' statement actually contradicts his assertion that estimates were arbitrary. Here he describes a reasoned and reasonable approach to estimating a pattern of past water use (well pumpage)—an approach that is not "arbitrary."

In several additional paragraphs on p. 73 (as well as elsewhere), he repeats the claim that pumping rates were based on arbitrary assumptions. ATSDR uses sound statistical methods (such as regression and correlation) to estimate pumpage. This is neither arbitrary nor unreasonable. Similar wells managed by the same operating authority are likely to have been operated in a similar manner. If not, that would be arbitrary. It is unlikely that Dept. of Navy engineers operating the well fields did so in an arbitrary manner. In the early years they just weren't required to maintain as detailed records as would be expected today. Again, ATSDR made reasonable assumptions with the data that they had available.

Near the top of p. 77, Dr. Spiliotopoulos states that model calibration was "improperly influenced" by "erroneous concentrations reported for well HP-634 … while non-detections were ignored." It has not been established nor agreed that erroneous concentrations (actually, one single value) were reported for well HP-634. This is discussed in more detail below in reference to Section 4.2.3.3. Non-detections were not ignored. They are clearly listed and labeled in many tables presented in the ATSDR reports (such as Table A4 in Chapter A of the HPHB report series, and in many other places too).

In Section 4.2.3.1 (p. 77) Dr. Spiliotopoulos claims that "The groundwater flow model has significant limitations in the absence of data for calibration." Although the model has limitations, there is no evidence that the limitations are significant for the purposes that the model was developed. Furthermore, there is not an "absence of data for calibration." In the very next paragraph, Dr. Spiliotopoulos notes that more than 700 water-level measurements were used in calibrating the predevelopment model, which is also the initial conditions for the transient groundwater flow model. Also, there are a lot of data available on the boundary conditions and hydrogeologic framework for the model.

In the 6$^{th}$ paragraph (p. 77), Dr. Spiliotopoulos indicates that the simulation of contaminant transport in the aquifer is inherently uncertain. This is true for all groundwater models. But the uncertainty does not mean that the model is not useful.

In Section 4.2.3.2, p. 78, Dr. Spiliotopoulos notes that ATSDR recognizes that explicit data defining source locations and mass loadings are not available, but then he criticizes ATSDR by saying "these quantities were arbitrarily assigned to the model in order to fit the limited water-quality data available starting in 1982." However, by criticizing ATSDR's methodology, Dr. Spiliotopoulos in effect is criticizing the essence of the model calibration, history matching, and parameter estimation process practiced in groundwater modeling, in which parameter values are adjusted (either manually or automatically) in order to improve the fit (e.g., see Hill and Tiedeman, 2007). Furthermore, the source locations and mass loadings were not "arbitrarily assigned." The general locations of the sources are well-documented, and sources were placed in the vicinity of these documented locations. Consistent with principles of model calibration, the exact placement and strength of these sources were varied within limits until the observed concentrations were reasonably matched by the model. The variation in the exact location, timing, and strength of sources is rarely known, and adjustment of source properties is a commonly-accepted part of calibrating a flow and transport model.

p. 79: Dr. Spiliotopoulos discusses the lack of data to define the source loading terms for the model in the HPHB area. However, there is no doubt that these chemical contaminants (including TCE and PCE) were present in the groundwater at toxic concentrations (above the MCLs) in the HPHB area, and that they were pumped out of the aquifer by several operating water-supply wells.

p. 79: In the summary for Opinion 14, Dr. Spiliotopoulos criticizes the ATSDR for having "assumed constant mass loading of the same magnitude at all sources for more than 40 years", which he characterizes as "highly uncertain, if not impossible." Viewed from a different perspective, what ATSDR did was apply an average rate over the critical time period because there was no basis for differentiating how the loading might have varied over time. In my opinion, this was a reasonable approach. Furthermore, the constant source resulted in a reasonable model calibration, and so there was no reason to incorporate a variable source in the absence of data on transient source characteristics.

**Opinion 15:** In this opinion, Dr. Spiliotopoulos repeats the claim that ATSDR included an erroneous value in its analysis and model calibration (presumably for the 1,300 ug/L value measured in a sample from HP-634). Section 4.2.3.3 is cited for support.

In Section 4.2.3.3, Dr. Spiliotopoulos argues that concentration data for well HP-634 was incorrectly interpreted and that the reported value of 1,300 ug/L on Jan. 16, 1985 "should be considered erroneous" (although he considers other samples from that well that showed non-detects to be valid). I believe that his basis for this conclusion is speculative and unsupported by facts, as discussed below.

On p. 80, Dr. Spiliotopoulos says "it is unlikely that this well [HP-634] was ever contaminated with elevated TCE concentrations," and he and Dr. Remy Hennet argue that the analysis showing a concentration of 1,300 ug/L should be thrown out. Although Dr. Spiliotopoulos and Dr. Hennet claim the well was shut down permanently, documentation suggests that HP-634 was online in January 1985 (see CLJA_CLW00000004559, CLW4546, and CLW1818). However, even if the well was shut down permanently shortly before the date this sample was collected, I strongly disagree with Dr. Spiliotopoulos' argument that "contamination could not have reached that well when it was non-operational." It is plausible and possible that TCE could have reached the well sometime after the previous sample had been collected. As Dr. Spiliotopoulos surely knows, after a pumping well is shut off,

water levels do not instantly recover and the head distribution does not instantly return to a nonpumping configuration and nonpumping hydraulic gradients. During predevelopment (nonpumping steady-state) conditions, flow near HP-634 is predominantly to the west and southwest (see HPHB reports Fig. A19 for 1951, reproduced below). While this well was operational, a cone of depression (a drawdown of water levels) formed around it, lowering the heads and reversing local hydraulic gradients, and enabling the movement of contaminants from nearby areas containing contaminants west of HP-634 to move eastwards towards HP-634 (as also shown for later times in Fig. A19 below). When a well is shut down, the heads take time to recover (recovery is not instantaneous). During the slow recovery period, water and contaminants will continue to move towards the well while the cone of depression is slowly filled in and recovers. This simple normal response of groundwater systems to the cessation of pumping easily explains the presence of contaminants in a sample collected after the pumping was stopped. Note that concentrations of DCE and VC were also unusually high in this same sample, so the TCE value is not an isolated "outlier" (see table C7 in report Chapter C). This progression is seen in the maps for all three layers for the November 1984 maps shown in Fig. A19 below, where the contaminant is shown to have moved very close to HP-634 from its previous location in the industrial area just to the west. If Dr. Spiliotopoulos argues that it is not possible for contaminants to reach HP-634 once its pump ceases operation, then it is contingent on him to provide some evidence that (a) the recovery is so fast that it is irrelevant (i.e., how long would it take for the hydraulic gradients to reverse again and return to a predevelopment condition?), and (b) that the contaminants were so far from HP-634 when it was shut off that it could not have migrated that distance during the recovery time. Without such calculations or evidence, one can conclude that it is indeed possible for contamination to reach that well shortly after it became non-operational. The primary evidence that it did become contaminated is the measurement of 1,300 ug/L in the January 1985 well sample, and I do not see conclusive evidence that that sample analysis should be discarded.

Dr. Hennet argues that this well was not contaminated by TCE because some vials in the shipment were broken (he does not say the samples for this analysis were in broken vials, so the relevancy of other vials being broken is not apparent). I doubt that the lab would or could perform an analysis or report a value on a sample taken from a broken vial. Dr. Hennet says a CCLJ report shows the value as 10 ug/L. However, the lab that did the analysis reported 1,300 ug/L. Hennet and Spiliotopoulos also say that the value of 1,300 is an outlier, so should be discarded. But there are many high-valued "outliers" in the record, and the record shows other instances where the value can change over similar large magnitudes in a very short time (e.g., TT-26 shown in Fig. F16, where the PCE concentration changed from 1,580 to 3.8 ug/L in successive samples collected just 4 weeks apart, mirroring the change in HP-634 from ND to 1,300 ug/L in a similar 4 week timeframe). The reasoning by Dr. Spiliotopoulos and Dr. Hennet to discard this reported value seems entirely speculative. They offer no actual evidence that the analysis or its reporting was erroneous.

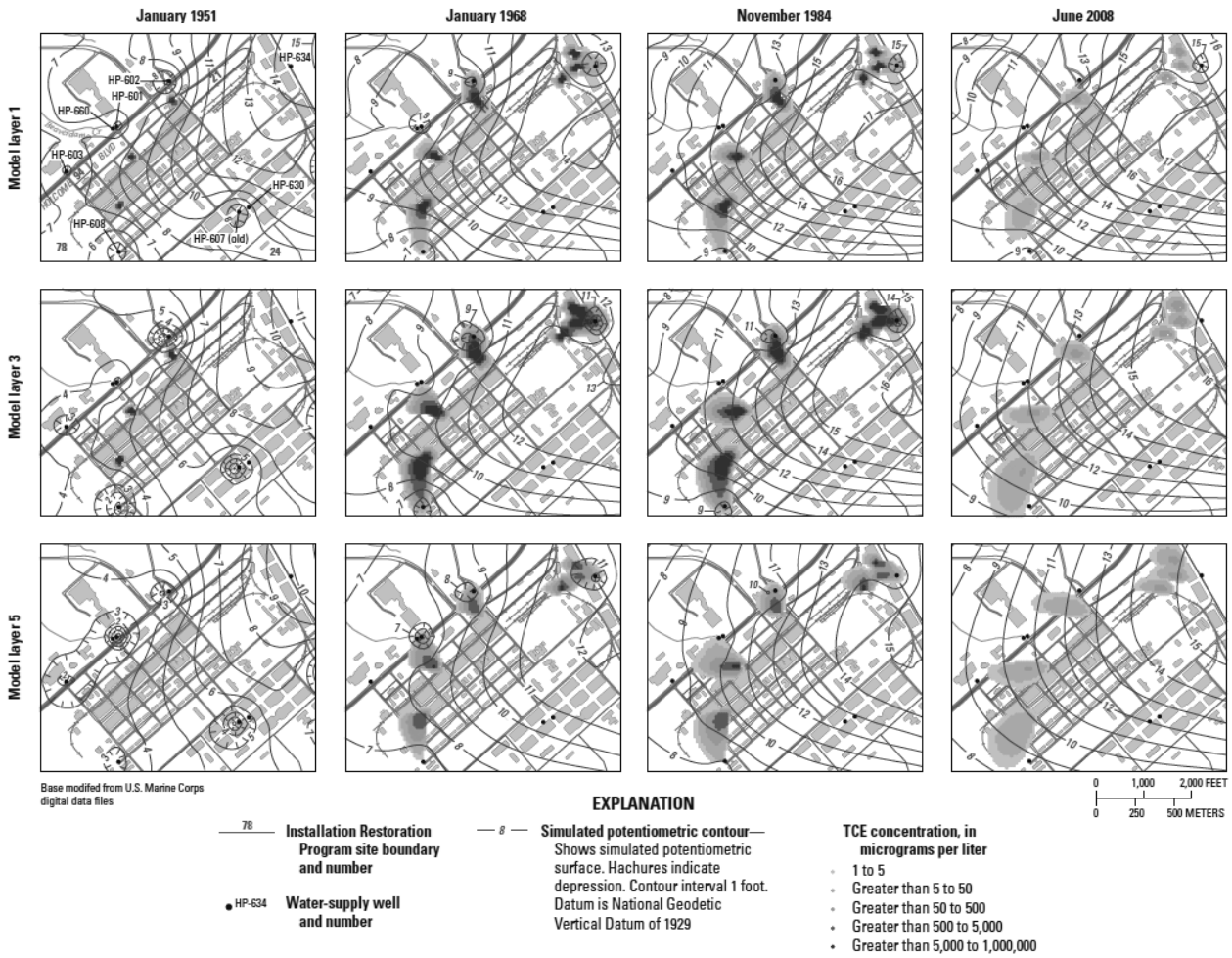



**Figure A19.** Reconstructed (simulated) water levels and distribution of trichloroethylene (TCE) within the Hadnot Point Industrial Area fate and transport model subdomain, model layers 1, 3, and 5, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951, January 1968, November 1984, and June 2008. (See Figure A13 for location and building numbers; see Appendix A4 for more detailed maps and results.)

On p. 81, Dr. Spiliotopoulos presents his Fig. 31 plotting of TCE concentrations in HP-634. However, he purposely does not include the data point with the value of 1,300 in his plot; including it would yield a very different picture, and show a much better match between simulated and observed TCE at the well location. TCE is found to be present in many locations immediately adjacent to HP-634, as seen in Fig. C33 (reproduced below). HP-634 is within the industrial area HPIA in that map (close to its northeastern boundary).

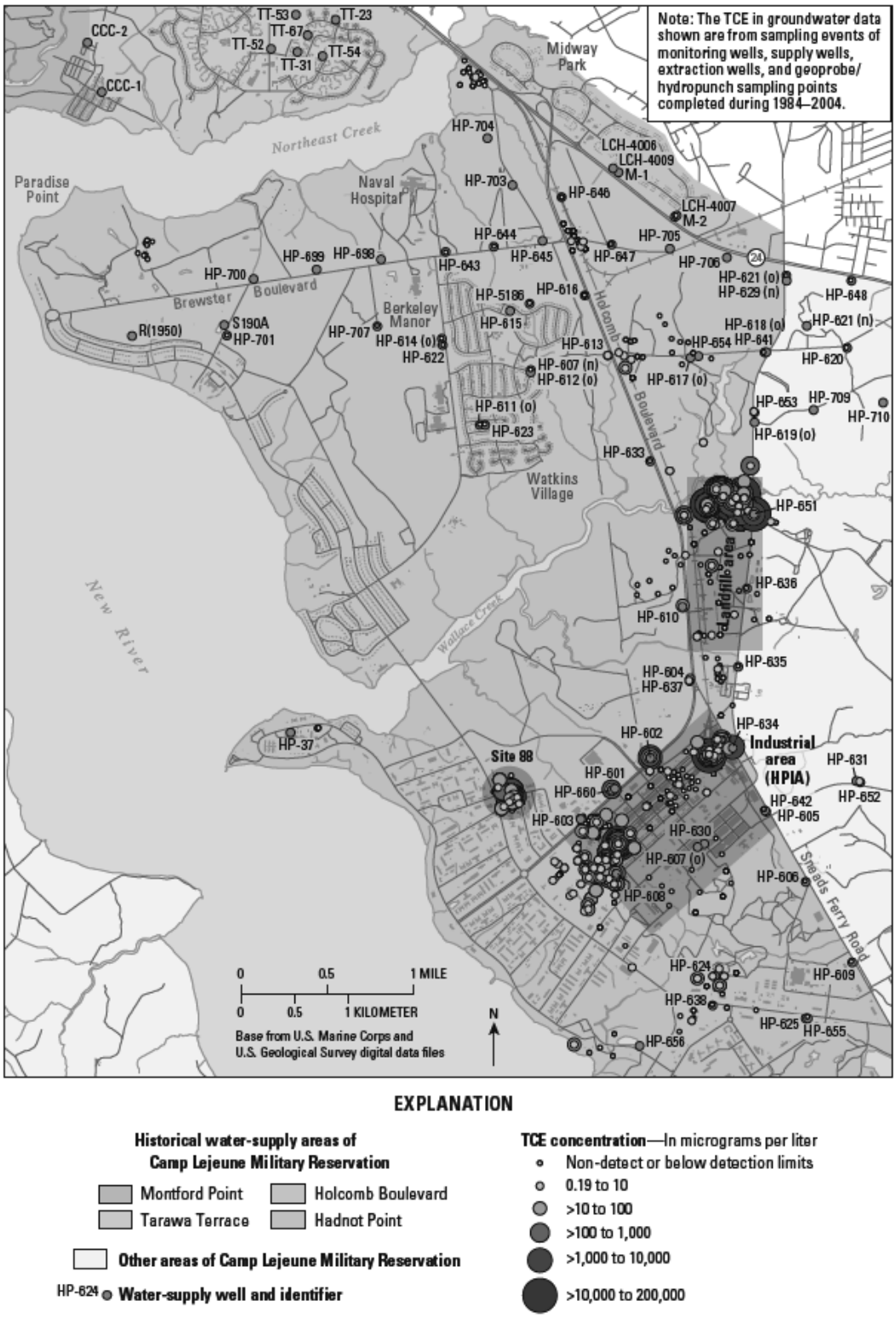



**Figure C33.** Groundwater sample locations for trichloroethylene (TCE) and ranges of TCE concentration in monitor and supply wells within the Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

**Opinion 16:** Dr. Spiliotopoulos argues here that the model for VOC degradation products was based on limited data, and "ATSDR's historical reconstruction prior to December 1984 cannot be verified." He cites section 4.2.4 as support.

In section 4.2.4 (p. 82-83), Dr. Spiliotopoulos states that "As illustrated in Figure 33 [ATSDR Fig. A25], the historical reconstruction prior to 1985 cannot be verified, due to lack of observed data for the period." This is true, and it is the reason why a simulation model was needed and was developed. For the four contaminants shown in Fig. 33, the agreement between simulated values and observed data is excellent in all four plots. This close agreement when observations are available builds confidence in the reliability of the model and its predictions, including for the hindcasting results for times prior to 1985.

In the summary for Opinion 16 (p. 83), Dr. Spiliotopoulos repeats that "… such data were not available prior to December 1984. Therefore, the estimated monthly contaminant concentrations cannot be verified." Again, the whole point was to use a technically sound model, which would be calibrated to available data in and after 1985, to estimate the values during the 15 or so years prior to that calibration period to inform the epidemiological studies. For PCE and TCE, the fit with the LCM model was actually slightly better than with the MT3DMS model, which was not designed to simulate degradation products. The quality of that fit is illustrated in Figure A25.

**Opinion 17:** Dr. Spiliotopoulos says that "the sensitivity analysis for the various contaminant sources in Hadnot Point indicated that the timing of source-release start date is uncertain and, therefore, it is impossible to determine the historical period that contamination was present in groundwater." The conclusion of this sentence does not follow from the precedent. Of course there is uncertainty in the timing of the release. That is well known. But the uncertainty does not make analyses impossible. Also, the uncertainty is not unconstrained. The model helps constrain the reconstructed history as it incorporates the physics of groundwater flow and solute (contaminant) transport. It is *not* impossible "to determine the historical period that contamination was present in groundwater." It can be (and was) estimated, but with the recognition of uncertainty in the model and in the predictions. There are a fair amount of data on the groundwater flow field, which provide the calibration basis for the flow model, and the calibrated flow model has sufficient accuracy and reliability to estimate groundwater velocities and directions. The model basically shows that to simulate the observed increases in concentration at observation points, the timing of the source release becomes more narrowly constrained and its uncertainty is reduced (but not eliminated). The key is that the flow model simulates groundwater flowpaths and velocities with reasonable and acceptable accuracy.

On p. 84, referring to underground storage tanks, Dr. Spiliotopoulos says "The empirical data for UST releases may or may not be applicable to the USTs installed at Camp Lejeune and, therefore, assignment of timing and magnitude for these sources is arbitrary and uncertain." Although uncertainty is clearly recognized, the assignment is not arbitrary. The basis is the EPA data on more than 12,000 leak incidents. Without direct observation to the contrary, why would one think that these USTs would behave much differently than the average failure time for such a large representative sample of documented cases? The approach used is not arbitrary, nor "highly" uncertain, nor an unreasonable assumption.

On p. 85, Dr. Spiliotopoulos goes on to discuss the range of years used in the sensitivity analysis, which spanned ±9 years. The point is not that the starting release date could have been anytime in that 18-year span, but rather to examine how sensitive the results are to such uncertainty. The results shown in Fig. 34 (ATSDR Fig. A37) indicate that at the later times—i.e., during the 18 years of the epidemiological studies—uncertainty in the starting release dates has little effect on estimated TCE concentrations. For the period between about 1950 and 1970, results from each of the various starting dates tend to converge on the same solution after only 3 or 4 years of simulation time.

In the summary for opinion 17 (p. 86), Dr. Spiliotopoulos says "it is not possible to confidently determine the actual period of groundwater contamination …" I would counter that it is possible to do so with some reasonable level of confidence, and ATSDR has done so. Of course there is uncertainty.

**Opinion 18**: Dr. Spiliotopoulos states that "the sensitivity analysis of the dose reconstruction model for HP was based on parameter variability unsupported by data." And that "the results of the sensitivity analysis were incorrectly presented as an uncertainty analysis range." Support is said to be in Section 4.2.5.1.2.

First, I note that there is some overlap and linkage between sensitivity analysis and uncertainty analysis. Anderson & Woessner (in their 1992 book on "Applied Groundwater Modeling") in discussing sensitivity analysis state: "The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions."

On p. 87 (Section 4.2.5.1.2) Dr. Spiliotopoulos argues that the sensitivity analysis used extreme values for parameters. But these "extreme" values were not used for the hindcasting (historical reconstruction), which was done using the calibrated model and calibrated parameter values. The wide range in parameter values was only used to assess model sensitivity and uncertainty, and thereby gain some further understanding of how and why the model is behaving as it does. This is not unusual. It has minimal or negligible effect on the calibrated model.

On p. 89, Dr. Spiliotopoulos argues that the range of parameter values in the sensitivity analysis was too wide. The inference then seems to be that the range of results (shaded areas) shown in Fig. 35 (ATSDR's Fig. A34, shown on p. 90) is too wide and should be narrower (closer to the results for the calibrated model). This doesn't seem like a major problem, as it would imply that the model results may be better defined than indicated otherwise. In looking at sensitivity, ATSDR did not imply that these "extreme" values were realistic or expected. They only illustrated a possible maximum bracketing of results.

In the Summary comments for Opinion 18, Dr. Spiliotopoulos concludes that "ATSDR presented the results of this analysis as indicative of the expected range of reconstructed monthly contaminant concentrations." I don't see where they said or implied this.

**Opinion 19**: Dr. Spiliotopoulos expresses a concern that the Hadnot Point analysis "only partially addressed model uncertainty." Support is included in Section 4.2.5.2.

In Section 4.2.5.2 (p. 91): In the first paragraph Dr. Spiliotopoulos seems to imply that ATSDR's use of Latin Hypercube Sampling was somehow an oversimplified approach. This is a valid and appropriate

method to use in these circumstances. For example, in conducting the Performance Assessment for the radioactive waste repository at the WIPP site in New Mexico, DOE and Sandia National Labs used the LHS approach with their groundwater flow and transport models for the WIPP site, as part of their application for approval to begin operations. This work was carefully reviewed by a National Academy Committee (NRC, 1996) and WIPP was granted approval to begin operations by the U.S. Environmental Protection Agency in the mid-1990s. There is nothing wrong (and a lot right) with the use of this method. EPA approval was granted even though there were no observations at all of concentrations in the aquifer of concern, yet predictions were made for 10,000 years into the future.

Section 4.2.5.2 (p. 91): In indicating that the uncertainty analysis was incomplete, Dr. Spiliotopoulos says (para. 2, p. 91) "ATSDR considered a small number of only 10 uncertainty scenarios." While it is debatable as to whether ten is a "small" number of scenarios to evaluate, it is a reasonable number to consider, and the 10 scenarios encompass a lot of the uncertainty in parameters and boundary conditions. ATSDR accomplished the goal of completing and documenting an uncertainty analysis, although it would have been possible to add additional scenarios to consider. It is highly unlikely, however, that adding more scenarios would lead to a modification of the calibrated model or to a different historical reconstruction.

In the first paragraph on p. 92, Dr. Spiliotopoulos quotes Doherty: "ideally, the value of the prediction should lie somewhere near the center of the uncertainty band." He then states that the ATSDR calibrated model "fails to conform with this rule …" However, this is not anyone's "rule." It is an idealization. Where the calibrated model lies off the center of the uncertainty range of estimates, it may simply be because additional parameters and scenarios need to be incorporated into the Monte Carlo simulations. In statistical testing, it is generally acceptable for a point or sample to fall within a range of two standard deviations of the mean.

In his summary for Opinion 19 (p. 92), Dr. Spiliotopoulos states that "the analysis only partially addressed the model uncertainty." But if more scenarios were considered or if more than 95% of the results were shown, the increased number of scenarios would widen the range and place the calibration results more consistently towards the middle of the range. Most of the time, the calibration is within the range of uncertainty brackets; when not, it is only very slightly above them. Overall, this does not seem to be a major issue. If additional factors were considered, the range would likely be wider and encompass all of the calibrated results. I also see no reason why this would have led to a different set of calibrated parameters.

**Section 4.2.5.3, Concluding Remarks (p. 92)**: Dr. Spiliotopoulos reiterates his concern that there is lack of historical data to constrain the calibration. He quotes an article that says the "model should replicate observed system behavior." This must be taken in a general way because a model is by definition a simplified approximation of a complex real system, and no model can literally replicate a real system and its behavior. He argues that "The ATSDR model results did not meet this requirement." I disagree, and believe that there was a satisfactory representation of observed behavior for both head distributions and concentration distributions. Could it have been better? Sure, if more data had been available. Is it good enough to produce a reasonable hindcast historical reconstruction? I believe the answer is yes. Dr. Spiliotopoulos says "that there is 'no observed system behavior.'" This is simply wrong. There are some water-level data available, and very good agreement between observed and simulated heads (water

levels). This agreement provides confidence in the computed directions and velocities of contaminant migration. There are some observed concentrations. It would be nice if more concentration observations had been made in the past, but they weren't. Where such data are available, the model often provides a very good match to those data. With the goal and implementation of computing monthly averages, there is no way that the model could have replicated the large concentration changes sometimes observed over short time periods and between successive samples. He also states that "ATSDR failed to quantify the uncertainty range reliably." But they did quantify it and document it. They did so reliably. Perhaps it could have been more comprehensive and considered more factors, but that doesn't mean that they didn't "quantify it reliably." Although comprehensive uncertainty analysis is desirable, doing so is not a necessary condition for calibrating a groundwater model.

**Section 4.2.5.3, Concluding Remarks (p. 93)**: Dr. Spiliotopoulos says "If parameter sensitivity and uncertainty can only be evaluated in a qualitative way, …" then the results and conclusions are not "scientifically defensible." The sensitivity and uncertainty analyses were definitely quantitative, and the quote from ATSDR (bottom p. 92) did not say these analyses were ONLY "qualitative". I believe that the model development by ATSDR for both TT and HPHB are scientifically defensible.

**Review Comments on Chapter 3:**

**p. 10, Section 3.1.8 (Concluding Remarks)**: Dr. Spiliotopoulos says "Model calibration is not possible when there are no historical data to match." However, there are historical data available for Camp Lejeune. The ATSDR models were calibrated using comparisons to historical data—both groundwater level observations and some data on solute concentrations in water samples. There are many direct measurements of hydraulic conductivity—a key parameter in simulating groundwater flow and velocity. So the concluding statement above is simply not applicable to the ATSDR model development and calibration.

**p. 12, Section 3.2:** In this paragraph, Dr. Spiliotopoulos concludes by stating "However, the timing and quantification of contaminant releases from that source [ABC Cleaners] are uncertain, due to a lack of historical data." Of course, the timing and quantification of contaminant releases from ABC Cleaners has some associated uncertainty. However, there is knowledge of when they operated, precise information on its location, and there is little doubt that it was a source of contamination. The modeling exercises help reduce the uncertainty about the timing and strength of the contaminant source. It is rare (if ever) that the precise release dates and strengths of a historical contamination source are known. This is a type of uncertainty that is commonly dealt with in model development, and this type of uncertainty does not preclude the development, calibration, and usefulness of a groundwater model.

A related issue of contaminant travel times from ABC Cleaners to well TT-26: (**Hennet's report, p. 5-15 – 5-16 and his Attachment D**): Dr. Hennet estimates a range of values for travel times of PCE between ABC Cleaners and TT-26 that are stated to be "in the 15 to 25 years range", based on three assumed "representative" flow paths, indicating the arrival didn't occur until the 1970s. He presents supporting material and calculations in his Attachment D. Dr. Hennet assumes the horizontal travel distance in the shallow aquifer is either (1) 200 ft in the shallow aquifer and 800 ft in the pumped aquifer, (2) 500 ft in the shallow aquifer and 500 ft in the pumped aquifer, or (3) 800 ft in the shallow aquifer and 200 ft in the pumped aquifer. He further assumes that the hydraulic gradient in the layer 2 confining unit is the same

in all cases (i.e., at three different distances from the pumping well). This is not a reasonable assumption (for example, see TT Figs. C19 & C21). In the pumped aquifer, a cone of depression will form with lowest heads adjacent to the well and higher heads further from the well. In the shallow aquifer, the heads will not change much due to pumping in the deeper aquifer. This drawdown effect is strongest near the well, and results in a greater hydraulic gradient (and faster velocity) across the confining layer closer to the well.

Pumping also results in a steeper horizontal gradient (and faster velocity) closer to the well in model layer 3, and a shallower gradient further from the well. Dr. Hennet's calculations assume the same horizontal velocity in the pumped aquifer regardless of the distance from the pumped well, which is not a valid assumption.

Examining the heads for model layers 1 and 3 as shown in TT Figs. C18 and C19, and looking at a point about halfway between ABC Cleaners and TT-26 and at a point very close to TT-26, the head difference between the two layers (across the confining bed) is about 10' – 9' = 1 ft at the halfway location and about 5' – 2' = 3 ft at a location close to TT-26. Therefore, the hydraulic gradient potentially driving downward flow is about 3 times greater close to the well than it is halfway between the well and the contaminant source. So this large spatial change in vertical hydraulic gradient must be accounted for, and the assumption that it is the same at all locations cannot be supported. Dr. Hennet does not account for the steeper vertical gradient in layer 2 for the path closer to the pumped well, nor does he account for the faster velocity in layer 3 when the travel distance is only 200 ft.

It is more likely that the travel distance in the shallower aquifer for much of the contaminated shallow groundwater would be more than 800 ft and the corresponding travel distance in the pumped aquifer would be less than 200 ft because (1) the vertically downward transport is more likely to occur where the vertical gradient is the strongest in the confining layer, which is closest to the pumping well, (2) the downward velocity would be fastest where the gradient is steeper close to TT-26, and (3) according to Dr. Hennet's calculations, the downward flux is only about 5% of the horizontal flux in the shallow aquifer, so that even if some contaminant leaked downward at further upgradient distances from TT-26, much would remain in the shallow aquifer to migrate to locations closer to, or even adjacent to, TT-26, where downward leakage would be the fastest. Thus, Dr. Hennet's three "representative" flow paths did not include a more critical flow path in which travel in the shallower aquifer is close to 1,000 ft. For this critical flow path, the travel time would be much less than 15 years—on the order of 3.5 to 5 years. For these several reasons, Dr. Hennet's estimates of travel times from ABC to TT-26 are erroneous, misleading, biased-high, and based on unreliable assumptions.

**Well TT-26 pumpage (Hennet's report p. 5-36)**: Dr. Hennet continues in criticizing the pumpage assumptions about well TT-26. He says, "ATSDR assumed that supply well TT-26 was constantly pumping prior to 1980. This is unlikely as supply wells cannot remain in service for decades without shut down periods for repairs and maintenance." Dr. Hennet implies it is unreasonable to assume this, yet offers absolutely no evidence to support his contention. This can be contrasted with ATSDR's study, which (p. 18) states that they have documented pumping records for TT-26 (and other wells) for some time periods and those estimates "are based on documented information detailing periods of maintenance for specific wells." For earlier periods in which there are no explicit pumping records, TT Chapter C (p. C22-C23) describes their estimation approach in detail (and Dr. Hennet does not offer a better way that this could have been done). Furthermore, in general, well maintenance frequently only requires a day to

a few days to complete. If TT-26 had been shut down for only a few days during a few months of every year for servicing, the monthly simulation model would still have to assume it operated for a full month each time, though at a proportionately reduced monthly pumping rate to reflect the actual total monthly withdrawal. It is hard to accept Dr. Hennet's speculative and hypothetical criticism or expect that it would make any difference.

**p. 21-22 (Section 3.3) & p. 29:** Dr. Spiliotopoulos cites Clement's 2011 issue paper (published in Ground Water journal); but these comments don't cite the Author's Reply (by Clement) to the published Comment by Maslia et al. in response to the original article. In his Reply to the Comment, Clement states "The goal of my article was not to review the Camp Lejeune (CLJ) modeling studies. Rather it was to use the CLJ problem as an example to highlight issues related to model complexities and to spark an open debate on when, where, and why we should limit model complexity." Therefore, Clement admits the article did not constitute a detailed technical review of the Camp Lejeune model study, so his 2011 Issue Paper that appeared to criticize it should not be taken as an expert analysis of the model or of its reliability or of the site. The Comment by Maslia et al. provided detailed rebuttals to Clement's concerns.

**p. 21 (Section 3.3):** Also, on p. 21 Dr. Spiliotopoulos states that "Dr. Clement's article echoed the NRC's concerns about the uncertainty in ATSDR's water model related to Tarawa Terrace and recommended a simpler approach for the water model related to Hadnot Point and Holcomb Boulevard to meet policy-oriented goals." Dr. Spiliotopoulos implies that the NRC report is a second independent review of the work. With regards to the groundwater modeling, it is not. Dr. Clement, a civil engineer, was the only groundwater expert on that committee (there were no geologists or hydrogeologists on that NRC Committee), so his concerns don't simply echo those of the NRC committee. Instead, it was likely that he was the source of those comments in the NRC Committee. While the use of "simpler models" might be okay for assessing policy-oriented goals, the simpler models would be subject to even greater uncertainty and lack of physical realism. Furthermore, the goals of historical reconstruction require a detailed and fairly complex modeling approach because the system being modeled is complex, and the use of simple models to meet such technical goals would be neither acceptable nor sufficiently accurate.

Regarding the 2009 NRC report and committee, Dr. Spiliotopoulos states that its primary charge was "to assess the strength of evidence in establishing a link or association between exposure to TCE, PCE, and other drinking-water contaminants and each adverse health effect suspected to be associated with such exposure." Consequently, almost all of the NRC Committee members were experts in medical and health fields. Only one was an expert in groundwater. The Committee had neither the focus, goal, intent, nor multiple experts to assess in depth the ATSDR's groundwater models. They were expected to focus on health effects.

**Section 3.3 and scientific validity of ATSDR's models**: In this section, Dr. Spiliotopoulos refers to statements by Dr. Dan Waddill. Dr. Waddill testified (Aug. 26, 2024, p. 234-235) regarding the ATSDR water modeling that "I do not think their results … were scientifically valid because, you know, science needs to be based on real-world observations and analysis. … and there were just not enough real-world measurements for this to count as a scientifically valid approach." He continues and concludes that the work was not scientifically valid because no concentration data were available in the 1950s-70s, and such observations can no longer be made (obviously). He argues that because of this, the hypothesis cannot be tested, so therefore it is not scientifically valid. I disagree.

I first note that Copi (1961) in discussing science and hypotheses states that "Few propositions in science are *directly* verifiable as true." He later states, "They can, however, be tested *indirectly*." Therefore, I would counter Dr. Waddill's statements by noting that in developing and applying the ATSDR groundwater models, that scientifically valid methods were used, and the models were based on sound hydraulic and physical principles that themselves have been tested and shown to be accurate and reliable approaches to describing and predicting groundwater flow and contaminant transport. The models were also based on many available hydraulic tests measuring hydraulic properties of the subsurface that do not change over time, and hence were data applicable to the site during the 1950s through 1970s. The models are indirectly tested during the calibration process in that available observations are compared to simulated values. This is an indirect type of model testing (or hypothesis testing) in which observations are compared to simulated values. The underlying theories and models have been tested in numerous field studies and are widely recognized as being scientifically valid.

The question should be whether this model for this site was sufficiently well calibrated and representative to perform a hindcasting prediction. I believe it was. I think there are many questions in our universe that are addressed using principles and models of physics that cannot (for all practical purposes) be directly tested in the foreseeable future. That does not render that work to be unscientific or lacking scientific validity. Predictive uses of models, whether forward in time or backwards in time, are widely accepted uses of scientifically valid models, while allowing for the existence and recognition of uncertainty in those predictions. The fact that there is uncertainty does not mean that they are not scientifically valid or scientifically defensible. The fact that one type or time period of observations are not available does not mean that the model is not scientifically valid.

**Section 3.3 and Calibration Targets:** At several places in this section, the issue of "calibration targets" is mentioned along with criticism that some simulated values did not fall within the calibration target. Relevant to this discussion are my comments in the 2009 Expert Panel Report (p. 101), with which I still agree and which I therefore repeat verbatim here:

> "a. **Are there established standards for establishing specific calibration targets? If so, what are they?** Overall, there are no standards and probably should not be any. Such targets are inevitably arbitrary and to some extent meaningless. They tend to distract from the quality of the calibration process and shift focus to the arbitrary goal. It is a "red herring." Not achieving a predetermined calibration target should not disqualify a model, nor does that prove a model is not valuable or useful. Conversely, meeting such a predetermined calibration target does not prove that the model is a good one or that it meets the needs of the particular study or that its calculations and predictions are accurate and/or reliable.
>
> "b. **Should ATSDR establish different calibration targets than for the Tarawa Terrace model?** In my opinion, the use of specific calibration targets should be abandoned. They have no real value in the context of hydrogeology, and can only serve to provide a false or meaningless image of the quality of the developed model. ATSDR only has a limited time to complete the study, and you will do the best job possible within that limited time and budget. Applying a calibration target will not lead to a better model, but it will cause some time to be spent on comparing the results to the target, and perhaps forcing the results to

fall within the target. It would be better to include on-going independent expert peer review during the model development process, as this will have a much higher payoff than calibration targets in terms of improving the quality of the final product."

**Conclusions:**

Groundwater models must be (and have been) calibrated in the absence of early time concentration data, as ATSDR has done. Other representative published examples where this has been successfully accomplished include the Rocky Mountain Arsenal, CO (Konikow, 1977) and Lawrence Livermore National Laboratory, CA (Rogers, 1992). In both of these cases, the early time history was reconstructed as part of the model calibration process (it just wasn't called "hindcasting"). This is a widely accepted procedure among groundwater modelers.

Although Dr. Spiliotopoulos repeatedly questions the accuracy of the ATSDR model and its calibration, I don't see any evidence that it is unacceptably inaccurate. In my opinion, ATSDR followed generally accepted methods that yielded reasonably accurate results for the mean monthly concentration of contaminants. ATSDR's TT Table F13 shows comparisons between observed and simulated concentration values, and most (but not all) are within the calibration target range. The presence of differences is not unexpected and does not indicate the model is unreasonably inaccurate or unscientific. Concentrations for many chemical constituents in groundwater typically show a high variation at local spatial scales and small time scales—much greater variability than presented by hydraulic heads. This is normal, and no groundwater transport model would be expected to reproduce or explain such small-scale variability in concentration.

Dr. Hennet presents a summary opinion on p. 5-36 of his report stating "ATSDR's assumptions are deficient, not verifiable, and at times demonstratively incorrect." I believe, to the contrary, that ATSDR's assumptions are reasonable and clearly documented with their supporting basis clearly described in detail and with recognition of uncertainty. I would argue that his counter examples, such as for bulk density and $K_d$, make little to no difference. Dr. Hennet's own estimates of travel times are clearly deficient and incorrect. Of course, the early time reconstructed concentrations cannot be directly verified. Those data don't exist. That is why the state-of-the-art simulation models were needed. He further states that "ATSDR estimates are not quantitatively reliable as different plausible assumptions would lead to different results." Nonuniqueness of calibrated groundwater models is a well-recognized issue. Different assumptions can lead to different results and different assumptions can also lead to identical results. This is true of every groundwater model ever developed. It does not negate the value or reliability of the model. This is why sensitivity and uncertainty analyses are helpful. Furthermore, it is why we put strong reliance on the expert judgment of those who have studied the particular aquifer system the longest and most in-depth, such as the ATSDR's authors of the modeling reports. Finally, Dr. Hennet says "ATSDR COC concentration estimates are for raw water which is not equivalent to COC concentrations in the distributed water." As I previously stated above, the opinion of experts on the 2005 Expert Review panel was that possible COC losses during water treatment at the Camp Lejeune WTPs would be small to minimal.

In my opinion, ATSDR has done an admirable job in completing a challenging task of using hindcasting with a calibrated model to reconstruct credible concentration distributions in time and space prior to the

availability of data from chemical analyses of groundwater samples in the mid-1980s. In the face of missing historical data, the ATSDR models provide useful input to epidemiological studies. ATSDR clearly and comprehensively documented the model development—providing transparency to their work. There is uncertainty in the calibrated models (as there always is in such models) and in the hindcasted results, and that is clearly recognized and evaluated. The uncertainty is not so large or unexpected as to preclude the use of the model results in the epidemiological studies or for providing monthly mean concentrations for use by health professionals to estimate past exposure of residents on an "as likely as not" or "more likely than not" basis. The methods used were rigorous and scientifically sound.

Dr. Leonard F. Konikow, PhD, NAE

January 13, 2025

**References**


Anderson, M.P. and Woessner, W.W., 1992, Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, San Diego. 381 pp.

Copi, I.M., 1961, Introduction to Logic. [2nd Ed.] Macmillan, New York. 512 pp.

Helsel, D. and Lee, L., 2006, Analysis of Environmental Data with Nondetects: Statistical Methods for Censored Environmental Data. Continuing Education Workshop at the Joint Statistical Meetings, American Statistical Association, Seattle, Washington (Aug. 2006). [Based on the textbook "Nondetects and Data Analysis: Statistics for censored environmental data" By Dennis Helsel, Wiley, 2005.]

Hill, M.C. and Tiedeman, C., 2007, Effective Groundwater Model Calibration, with Analysis of Data, Sensitivities, Predictions, and Uncertainty. Wiley-Interscience, Hoboken, NJ, 455 pp.

Konikow, L.F., 1977, Modeling chloride movement in the alluvial aquifer at the Rocky Mountain Arsenal, Colorado: U.S. Geol. Survey Water-Supply Paper 2044, 43 p.

Konikow, L. F., and Thompson, D.W., 1984, Groundwater contamination and aquifer reclamation at the Rocky Mountain Arsenal, Colorado: *in* Groundwater Contamination, National Academy Press, Washington, D.C., p. 93-103.

Kret, E., Kiecak, A., Malina, G., Nijenhuis, I., and Postawa, A., 2015. Identification of TCE and PCE sorption and biodegradation parameters in a sandy aquifer for fate and transport modelling: batch and column studies. Environ. Sci. Pollut. Res. 22. p. 9877–9888. DOI 10.1007/s11356-015-4156-9.

National Research Council. 1996. *The Waste Isolation Pilot Plant--A Potential Solution for the Disposal of Transuranic Waste*. National Academy Press, Washington, D.C., 169 p.

National Research Council. 2009. *Contaminated Water Supplies at Camp Lejeune: Assessing Potential Health Effects*. Washington, DC: The National Academies Press. ttps://doi.org/10.17226/12618.

Reilly, T.E., and Harbaugh, A.W., 2004, Guidelines for evaluating ground-water flow models: U.S. Geological Survey Scientific Investigations Report 2004-5038, 30 p.

Rogers, L. 1992. History matching to determine the retardation of PCE in ground water. *Groundwater* **30**, no. 1: p. 50–60.

Zheng, C., and Bennett, G.D. 2002, Applied Contaminant Transport Modeling. [2nd Edition] Wiley-Interscience, New York. 621 pp.

# ATTACHMENT A

# *Leonard F. Konikow, PhD, NAE*

## Contact Information

11316 Myrtle Ln, Reston, VA 20191; 703-855-5498 (Cell); email: LFKonikow@gmail.com

## Education

1966 BA, Geology, Hofstra University, Hempstead, New York
1969 MS, Geology, Pennsylvania State University
1973 PhD, Geology, Pennsylvania State University

## Work Experience

2020-2023 Editor-in-Chief, *Groundwater* journal
2013-2023 Emeritus Scientist, Water Mission Area, U.S. Geological Survey
1980–2013 Project Chief, Natl. Research Program, Water Resources Division, U.S. Geological Survey, Research Project "Digital modeling of transport in saturated zone"
1978–1980 Staff Hydrologist, Ground Water Branch, U.S. Geological Survey, Reston, Virginia
1974–1978 Project Chief, Research Project "Solute Transport in Ground Water," U.S. Geological Survey, Central Region, Lakewood, Colorado
1972–1974 Project Chief, Subsurface Waste Investigations, U.S. Geological Survey, Lakewood, Colo.
5/66-7/66 Hydrogeologist assistant, Geraghty & Miller, Inc., Groundwater Consultants, Port Washington, NY.

## Other Experience*

*Instructor and lecturer at:*
Fall 1991 & 1992 Department of Environmental Sciences, University of Virginia
Fall 1997 Department of Geological Sciences, Stanford University

## Professional Societies*

- American Geophysical Union (AGU) (1970–present; elected Fellow, 2001)
- AGU Spring Meeting Program Chairman for Hydrology (1984–1987)
- AGU Groundwater Committee (1977–1986; Chairman, 1980–1982)
- Geological Society of America (GSA) (1974–present; Fellow since 1990)
- Management Board, Hydrogeology Division, GSA (1991–1995); Chair (1993-1994)
- International Association of Hydrogeologists (IAH) (1985–present); IAH Vice President, North America and IAH Executive Council (2009-2012); Chairman of U.S. National Chapter, IAH (2001–2004)
- National Ground Water Association (NGWA), Scientists and Engineers Division (SAE) (1990–present)
- NGWA/SAE—Board of Directors (1996–2000)
- American Institute of Hydrology (Certified Professional Hydrogeologist) (1991–2023)
- Registered Professional Geologist, Pennsylvania (1996–2023)

## Honors and Awards*

- Birdsall Distinguished Lecturer (1985–1986), GSA, Hydrogeology Division
- M. King Hubbert Science Award (1989), Life Member Award (2013) National Ground Water Association
- O.E. Meinzer Award (1997), Distinguished Service Award (2000), GSA, Hydrogeology Division
- C.V. Theis Award (1998), American Institute of Hydrology
- Distinguished Service Award (1999), U.S. Department of Interior
- Elected as Fellow (2001), American Geophysical Union
- President's Award (2001), International Association of Hydrogeologists
- **Elected to National Academy of Engineering (2015)**

## Selected Professional Activities*

- Rocky Mountain Arsenal (Colorado) Technical Review Committee (1975–1977)
- National Research Council, Panel on Groundwater Contamination (1981–1982)
- National Research Council, Committee on Ground-Water Modeling Assessment (1987–1989)
- National Research Council, Waste Isolation Pilot Plant Committee (1989–1997)
- Peer Review Panel, U.S. EPA Environmental Monitoring Systems Lab, Las Vegas, Nevada (1991)
- National Science Foundation, Review Panel for Hydrologic Sciences and interim staff assistant (1992)
- Member of Modeling Project Subcommittee, Science Advisory Board, U.S. EPA (1993)
- Associate Editor, Ground Water Journal (1993–1995); Water Resources Research (1981-1984)
- Adviser to U.S. AID project studying seawater intrusion in Gaza and Morocco (1994–1997)
- National Research Council, Committee on Principles and Operational Strategies for Staged Repository Systems (2001–2002)
- Expert Peer Review Panel for ATSDR to evaluate historical ground-water contamination and water-supply distribution problems at Tarawa Terrace, U.S. Marine Corps Base, Camp Lejeune, NC (March 2005)
- Expert Peer Review Panel for the South Florida Water Management District (SFWMD) to evaluate East Central Florida Transient model (Oct. 2006-Feb. 2007)
- Coastal Sound Science Initiative Technical Advisory Committee for Georgia and S.C. (2008)
- Expert Peer Review Panel for ATSDR to evaluate historical ground-water contamination at Hadnot Point area of the U.S. Marine Corps Base, Camp Lejeune, NC (April, 2009)
- International Scientific Advisory Committee for the National Centre for Groundwater Research & Training of Australia (2009-2014)
- Member of an Independent Review Panel to evaluate the Death Valley Regional Flow System Project for the USGS Nevada Water Science Center (March-July 2014)
- AGI, Geoscience Policy Advisory Comm. (2005-16); Critical Needs Working Group (2015-16)
- Invited lecturer, McCormick Specialized Reporting Institute 2015: Covering Water in a Changing World, University of Florida, College of Journalism & Communications, Gainesville, FL (Nov. 2015)
- Chair, DOE Expert Peer Review Panel for the Rainier Mesa/Shoshone Mountain Flow and Transport Model, Nevada National Security Site (NNSS), Nevada (Oct. 2017-April 2018)
- Member, DOE Expert Peer Review Panel for the Pahute Mesa Flow and Transport Model, NNSS (2022)

## Publications*

Author or coauthor of numerous articles in peer-reviewed journals, government publications, conference proceedings, book chapters, and talks given at professional society meetings (complete detailed list available on request).


Konikow, L.F., and Bredehoeft, J.D., 1974, Modeling flow and chemical-quality changes in an irrigated stream-aquifer system: Water Resources Research, v. 10, no. 3, p. 546-562.

Konikow, L.F., and Bredehoeft, J.D., 1978, Computer model of two-dimensional solute transport and dispersion in ground water: U.S. Geol. Survey Techniques of Water-Resources Investigations, Book 7, Chapter C2, 90 p.

Konikow, L.F., 1986, Predictive accuracy of a ground-water model -- Lessons from a postaudit: Ground Water, v. 24, no. 2, p. 173-184.

Konikow, L.F., and Bredehoeft, J.D., 1992, Ground-water models cannot be validated: Adv. Water Res., v. 15, no. 1, p. 75-83.

Ewing, R.C., Tierney, M.S., Konikow, L.F., and Rechard, R.P., 1999, Performance assessments of nuclear waste repositories: A dialogue on their value and limitations: Risk Analysis, v. 19, no. 5, p. 933-958.

Konikow, L.F., and Kendy, E., 2005, Groundwater depletion: A global problem: Hydrogeol. Jour., v. 13, no. 1, p. 317-320.

Konikow, L.F., 2011, The Secret to Successful Solute-Transport Modeling: Ground Water, v. 49, no. 2, p. 144-159. doi: 10.1111/j.1745-6584.2010.00764.x.

Bredehoeft, J.D., and Konikow, L.F., 2012, Reflections on Our Model Validation Editorial: Ground Water, v. 50, no. 4, p. 495.

Konikow, L.F., and Leake, S.A., 2014, Depletion and Capture: Revisiting "The Source of Water Derived from Wells": Groundwater, v. 52, no. S1, p. 100-111. DOI: 10.1111/gwat.12204.

Konikow, L.F., 2015, Long-term groundwater depletion in the United States: Groundwater, v. 53, no. 1, p. 2-9.

Konikow, L.F. and J.D. Bredehoeft, 2020. Groundwater Resource Development: Effects and Sustainability. The Groundwater Project, Guelph, Ontario, Canada. https://gw-project.org/books/groundwater-resource-development/

# ATTACHMENT B

Jan. 13, 2025

**Leonard F. Konikow**

**Publications During Past 10 Years**


Konikow, L.F., 2015, Long-term groundwater depletion in the United States: Groundwater, v. 53, no. 1, p. 2-9, doi: 10.1111/gwat.12306.

Alley, W.M., and Konikow, L.F., 2015, Bringing GRACE Down to Earth: Groundwater, v. 53, no. 6, p. 826-829, doi: 10.1111/gwat.12379.

Simmons, C.T., Anderson, M.P., Bredehoeft, J.D., Freeze, R.A., Gorelick, S.M., Konikow, L.F., de Marsily, G., Sudicky, E.A., and Voss, C.I., 2015. *Call for an International Strategic Plan for Groundwater*, Aqua 2015 - Hydrogeology: Back to the Future, 42nd International Congress of the International Association of Hydrogeologists, September 13-18, Rome, Italy.

Konikow, L.F., 2020, Passing the Torch. [Editorial] Groundwater, v. 58, no. 1, p. 1-2. doi: 10.1111/gwat.12964.

Marshall, S.K., Cook, P.G., Konikow, L.F., Simmons, C.T., and Dogramaci, S., 2020, Conjoint use of hydraulic head and groundwater age data to detect hydrogeologic barriers. *Hydrogeology Journal,* v. 28, 1003–1019. https://doi.org/10.1007/s10040-019-02095-9

Konikow, L.F. and J.D. Bredehoeft, 2020. Groundwater Resource Development: Effects and Sustainability. The Groundwater Project, Guelph, Ontario, Canada. https://gw-project.org/books/groundwater-resource-development/.

Konikow, L.F., 2021, Science and Politics. [Editorial] Groundwater, v. 59, no. 3, p. 310–311. doi: 10.1111/gwat.13097.

S.K. Marshall, P.G. Cook, C.T. Simmons, L.F. Konikow, and S. Dogramaci. 2022. An Approach to Include Hydrogeologic Barriers With Unknown Geometric Properties in Groundwater Model Inversions. Water Resources Research, 58(7). https://doi.org/10.1029/2021WR031458

Scanlon, B.R., Fakhreddine, S., Rateb, A., I. de Graaf, J. Famiglietti, T. Gleeson, R.Q. Grafton, E. Jobbagy, S. Kebede, S. Kolusu, L.F. Konikow, *et al.* 2023. Global water resources and the role of groundwater in a resilient water future. *Nat. Rev. Earth Environ.* **4**, 87–101. https://doi.org/10.1038/s43017-022-00378-6

L.F. Konikow, E.G. Reichard, and M.J. King, 2023, John D. Bredehoeft (1933-2023)—A Geologist at the Frontiers of Hydrogeology. Groundwater, v. 61, no. 3, p. 446-451. https://doi.org/10.1111/gwat.13313.

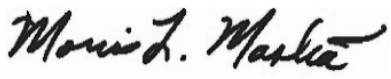
Konikow, L.F., 2023, Peer Review: Again. [Editorial] Groundwater, v. 61, no. 3, p. 289-290. doi: 10.1111/gwat.13312.

# EXHIBIT 6

# Rebuttal Response to:

# Reports of Alexandros Spiliotopoulos, Remy J.-C. Hennet & Jay Brigham

**Prepared by:**



**Morris L. Maslia**

**M. L. Maslia Consulting Engineer**
**Registered Professional Engineer, GA #PE012689**

**3360 Norfolk Chase Drive, Peachtree Corners, GA 30092**
**Mobile: +1 (404) 431-0035 — Email:** H2OBoy54@gmail.com
https://www.linkedin.com/in/mlmaslia/

# Table of Contents

## List of Figures



## List of Tables

## Glossary of Abbreviations and Acronyms

Definitions of terms and abbreviations used throughout this report are listed below.

### A

**AS** Alexander Spiliotopoulos, Ph.D., DOJ Expert

**ATSDR** Agency for Toxic Substances and Disease Registry; codified under CERCLA, section 104(i), 42 U.S.C. §9604(i); https://atsdr.cdc.gov

### B

**BTEX** Benzene, toluene, ethylbenzene, and xylenes

**Bz** Benzene

### C

**CERCLA** The Comprehensive Environmental Response, Compensation, and Liability Act of 1980, also known as Superfund

**CLW** Camp Lejeune Water document

**COC** Contaminant or chemical of concern

### D

**DCE** 1,1-dichloroethylene or 1,1-dichloroethene

**1,2-tDCE** *trans*-1,2-dichloroethylene or *trans*-1,2-dichloroethene

**DON** Department of the Navy

### E

**EDRP** Exposure-Dose Reconstruction Program developed by ATSDR in 1993

**EPA** U.S. Environmental Protection Agency, https://www.epa.gov, also see USEPA

### F

**ft** Foot or feet

**$ft^3/d$** Cubic foot per day

### G

**Ga. Tech** Georgia Institute of Technology, Atlanta, Georgia

**g** Grams

**gpm** Gallons per minute

## H

**HB** Holcomb Boulevard

**HBWTP** Holcomb Boulevard water treatment plant

**HP** Hadnot Point

**HPFF** Hadnot Point fuel farm

**HPIA** Hadnot Point Industrial Area

**HPLF** Hadnot Point landfill

**HPWTP** Hadnot Point water treatment plant

## I

## J

**JB** Jay L. Bringham, Ph.D., DOJ Expert

## L

**LCM** Linear control model; a model based on linear control theory methodology developed to reconstruct historical contaminant concentrations in water-supply wells

**LHS** Latin hypercube sampling

## M

**MODFLOW** A family of three-dimensional groundwater-flow models, developed by the U.S. Geological Survey, https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs

**MT3DMS** Three-dimensional mass transport, multispecies model developed on behalf of the U.S. Army Engineer Research and Development Center. MT3DMS-5.3 (Zheng and Wang 1999) is the specific version of MT3DMS code used for the Hadnot Point–Holcomb Boulevard study area analyses

**MCL** Maximum contaminant level

**µg/L** micrograms per liter; 1 part per billion

**Model calibration** The process of adjusting model input parameter values until reasonable agreement is achieved between model-predicted outputs or behavior and field observations

## N

**ND** non-detect

**NRC** National Research Council

## P

**PCE** Tetrachloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK®

**PDF** Probability density function

## R

**RH** Remmy J.-C. Hennet, Ph.D., DOJ Expert

**ROD** Record of Decision

## S

**SCADA** Supervisory control and data acquisition

## T

**TCE** 1,1,2-trichloroethene, or 1,1,2-trichloroethylene, or trichloroethylene

**TechFlowMP** A three-dimensional multispecies, multiphase mass transport model developed by the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, Atlanta, Georgia

**TT** Tarawa Terrace

**TTWTP** Tarawa Terrace water treatment plant

## U

**USMC** U.S. Marine Corps

**USMCB** U.S. Marine Corp Base

**UST** Underground storage tank

## V

**VC** Vinyl chloride

**VOC** Volatile organic compound

## W

**WDS** Water-distribution system

**WTP** Water treatment plant

# 1.0 Introduction

I am Morris L. Maslia, P.E., a licensed Professional Engineer in the State of Georgia and a consulting engineer retained by the Camp Lejeune Plaintiffs' attorneys. On December 10, 2024, I was provided with electronic copies of the Expert Reports of Alexandros Spiliotopoulos (**AS**), Remy J.-C. Hennet (**RH**), and Jay L. Brigham (**JB**), who have been retained by the U. S. Department of Justice (DOJ). Their Expert Reports evaluate and review the Agency for Toxic Substances and Disease Registry's (ATSDR) water-modeling analyses and historical reconstruction conducted at U.S. Marine Corps Base (USMCB) Camp Lejeune, North Carolina, for the Tarawa Terrace (TT), Hadnot Point (HP), and Holcomb Boulevard (HB) water treatment plants (WTP), water-distribution systems (WDS), and associated service areas.

## Purpose of Report

The purpose of this rebuttal report is to respond to certain positions as set out by the DOJ Expert Reports (authored by AS, RH, and JB), dated December 9, 2024 (Spiliotopoulos 2024, Hennet 2024, Brigham 2024). My responses are grouped by major topical areas discussed and presented in the DOJ Expert Reports and listed below (Section 4.0 of this report). This report is organized as follows:

- **Section 1.0:** Introduction
- **Section 2.0:** Purpose of Rebuttal Report
- **Section 3.0:** Agreed Upon Concepts and Facts
- **Section 4.0:** Response to Department of Justice (DOJ) Expert Reports
    - **Section 4.1:** Start Dates for Sources of Contamination
    - **Section 4.2:** Water-Supply Well Operations
    - **Section 4.3:** Volatilization of VOCs During Water Treatment Process
    - **Section 4.4:** Derivation and Computation of Sorption Parameter Values
    - **Section 4.5:** Model Calibration and Uncertainty Analysis
    - **Section 4.6:** Post-Audit of the ATSDR Tarawa Terrace Models
    - **Section 4.7:** Graphing and Visualization of Data and Model Results
    - **Section 4.8:** Non-Degraded and Degraded PCE Historical Reconstructions
    - **Section 4.9:** Additional Topics
- **Section 5.0:** Summary and Conclusions
- **Section 6.0:** References
- **Appendices A:** Volatilization Issues: Excerpts from ATSDR's Expert Panel Meetings, March 28, 2005 and April 30, 2009

# 3.0 Agreed Upon Concepts and Facts

Prior to providing responses to DOJ Expert Reports (Spiliotopoulos 2024, Hennet 2024, Brigham 2024), I set forth several fundamental concepts that are accepted as scientifically valid approaches and facts that can be agreed upon. These are listed below.

1. The Agency for Toxic Substances and Disease Registry (ATSDR) is a federal, non-regulatory public health agency codified in the Comprehensive Environmental Response, Compensation & Liability Act (CERCLA) of 1980, also known as Superfund (CERCLA 1980); 42 U.S.C. §9604(i).

2. ATSDR, overseen by the U.S. Department of Health and Human Services, is the lead federal public health agency for determining, preventing, and mitigating the human health effects of exposure to hazardous substances. It does this by responding to environmental health emergencies, investigating emerging environmental health threats, conducting research on health impacts of hazardous waste sites (public health assessments, epidemiological studies, and toxicological profiles), and building capabilities and providing actionable guidance to state and local health partners.

3. When data are limited or unavailable, ATSDR conducts exposure-dose reconstruction studies, which can include the use of environmental data, models (air, soil, water, and pharmacokinetic) or biomarkers to estimate and quantify environmental concentrations and exposures to toxic substances.

4. Historical reconstruction is an analysis and diagnostic method used to examine historical characteristics of groundwater flow, contaminant fate and transport, water-distribution systems, air dispersion, and exposure to contaminants (chemical and radiological) when data are limited or unavailable. It is an accepted method of analysis having been applied since the 1930s and described in many peer-reviewed publications (*e.g.*, Costas et al. 2002, Grayman et al. 2004, Konikow and Thompson 1984), Maslia ad Aral 2004, NRC 199), Rodenbeck and Masli,1998, Rogers 1996, Samhel et al. 2010).

5. The mathematical, analytical, and numerical models (e.g., groundwater flow, contaminant fate and transport, and water-distribution system) used by ATSDR are accepted tools and practices among engineers, researchers, and scientists. These models approximate the physics of groundwater flow and contaminant fate and transport, which do not depend on professional judgment. The uncertainty in these models can be reasonably bounded and quantified to provide useful results of chemical exposure (EPA 1998).

6. The rationale and justification for using the historical reconstruction process, including models, at Camp Lejeune is precisely because historical data were limited and not available to ATSDR. As such, the models play an important role in providing insight, information, and quantitative estimates of environmental and exposure concentrations when data are missing, insufficient, or unavailable (Konikow and Thompson 1984, Maslia and Aral 2004).

## 4.0 Response to Department of Justice (DOJ) Expert Reports

In this section, I present rebuttal responses to DOJ Expert Reports by topical subject matter. The opinions in this report are based on my review of the DOJ Expert Reports, published literature, data

and documents made available to me while consulting on this case (e.g., Plaintiffs' and DOJ's Expert Reports) and my work and analysis during my work on the Camp Lejeune studies as an employee of ATSDR. I have reviewed and am relying upon the rebuttal expert reports of Dr. Leonard F. Konikow, Dr. Norman Jones/Mr. R. Jeffrey Davis, and Dr. David R. Sabatini. I hold the opinions expressed in this report to a reasonable degree of scientific and engineering certainty. I will produce a list of all materials I considered in reaching these opinions within seven days of service of this report. Many of the materials, documents, and data are also listed in the publicly available ATSDR reports on Tarawa Terrace (Maslia et al. 2007) and Hadnot Point-Holcomb Boulevard (Maslia et al. 2013, Appendix A2).

## 4.1 Start Dates for Sources of Contamination

### *4.1.1 ABC One-Hour Cleaners*

The ATSDR Tarawa Terrace (TT) fate and transport modeling analysis applied a 1,200 gram/day (g/d) tetrachloroethylene (PCE) mass loading rate as the contaminant source at ABC One-Hour Cleaners. ATSDR used a contaminant (source) release date of January 1953. DOJ Experts (AS, RH, and JB) posit that July 1954 is a more appropriate start date for releases of PCE at ABC One-Hour Cleaners (Spiliotopoulos 2024, Section 4.1.2.1; Hennet 2024, Opinion 3; Brigham 2024, Section IV.B). ATSDR relied upon the deposition (sworn testimony) of Victor Melts (owner of ABC One-Hour Cleaners) who testified on April 12, 2001 that he started ABC One-Hour Cleaners in 1953 and that he operated the company in the same location since 1953 (Melts 2001, p.6–7)[1]. Additionally, in remedial investigation reports of the ABC One-Hour Cleaners site by Roy F. Weston, Inc. (1992, 1994)[2] a specific date for start of operations is not provided; rather, these documents indicate that ABC One-Hour Cleaners is a North Carolina corporation registered with the Secretary of State as of March 4, 1958. The U.S. Environmental Protection Agency's (EPA) Record of Decision (ROD) for the ABC One-Hour Cleaners Site (Section 2.1 Facility Operations and History) [3] also does not provide a specific date for start of operations—it also indicates that ABC One-Hour Cleaners is a North Carolina corporation registered with the Secretary of State as of March 4, 1958. Without documented information and data as to the specific date for start of operations at ABC One-Hour Cleaners, ATSDR relied upon the sworn testimony of Victor Melts (Melts 2001, p. 6-7).

To test the effect of varying the start date for operations at ABC One-Hour Cleaners on reconstructed PCE concentrations, Plaintiffs' experts conducted a sensitivity analysis using the calibrated (and published) ATSDR Tarawa Terrace MODFLOW and MT3DMS input files (Maslia et al., 2007, provided on DVD). The sensitivity analysis consists of applying the following start date of operations (source release dates) at ABC One-Hour Cleaners:

- January 1953 (ATSDR calibrated model start date used in Faye 2008)
- January 1954 (+1 year from calibrated model start date)
- July 1954 (+1.5 years from calibrated model start date posited by DOJ Experts AS, RH, and JB)

[1] CLJA document 00897_PLG_0000067569 – 00897_PLG_0000067570.
[2] CLJA_WATERMODELING_09-0000083841; CLJA_WATERMODELING_09-0000084255.
[3] CLJA_EPA01-0000383135 – CLJA_EPA01-0000383136.

- January 1955 (+2 years from the calibrated model start date)

Results of varying the start dates of operations at ABC One-Hour Cleaners (source release date) are shown in Figures 4.1A and 4.1B for reconstructed PCE concentrations at water-supply well TT-26 and the Tarawa Terrace water treatment plant (TTWTP), respectively. These results show that the calibrated TT modeled PCE concentrations are insensitive to these variations in source release date throughout much of the exposure period since these variations make a negligible difference in PCE concentrations from the calibrated reconstructed concentrations for the duration of the epidemiological study (1968-1985)[4], as listed in Table 4.1. Additionally, the dates that the maximum contaminant level (MCL) for PCE of 5 ug/L is exceeded at water-supply well TT-26 and at the TTWTP, the duration of exceedance (in months), and the maximum reconstructed concentrations are listed in Table 4.2. Note the negligible changes from the calibrated ATSDR model results due to the variable start dates (Maslia et al. 2007; Faye 2008). Based on this sensitivity analysis, I conclude that the ATSDR calibrated models for reconstructing PCE concentrations are not sensitive to the start date of operations (source release date) at ABC One-Hour Cleaners. I stand by the ATSDR start of operations at ABC One-Hour Cleaners of January 1953, as documented in the sworn testimony of Victor Melts (2001) and applied by Faye (2008) as a more reliable start date.[5]

[4] Reconstructed concentrations are shown for the start of the epidemiological study of January 1968 and the last in-service date of TT-26.

[5] The evidence for ABC One-Hour Cleaners opening in 1954 as presented by Dr. Jay Brigham is circumstantial. Advertisements are subject to a lag in publication so that they may come out well after things have changed on the ground. Similarly, grand openings often occur well after a business has opened, when operations are more fully established. The sworn testimony of Mr. Melts is more reliable than the information provided by Dr. Brigham.

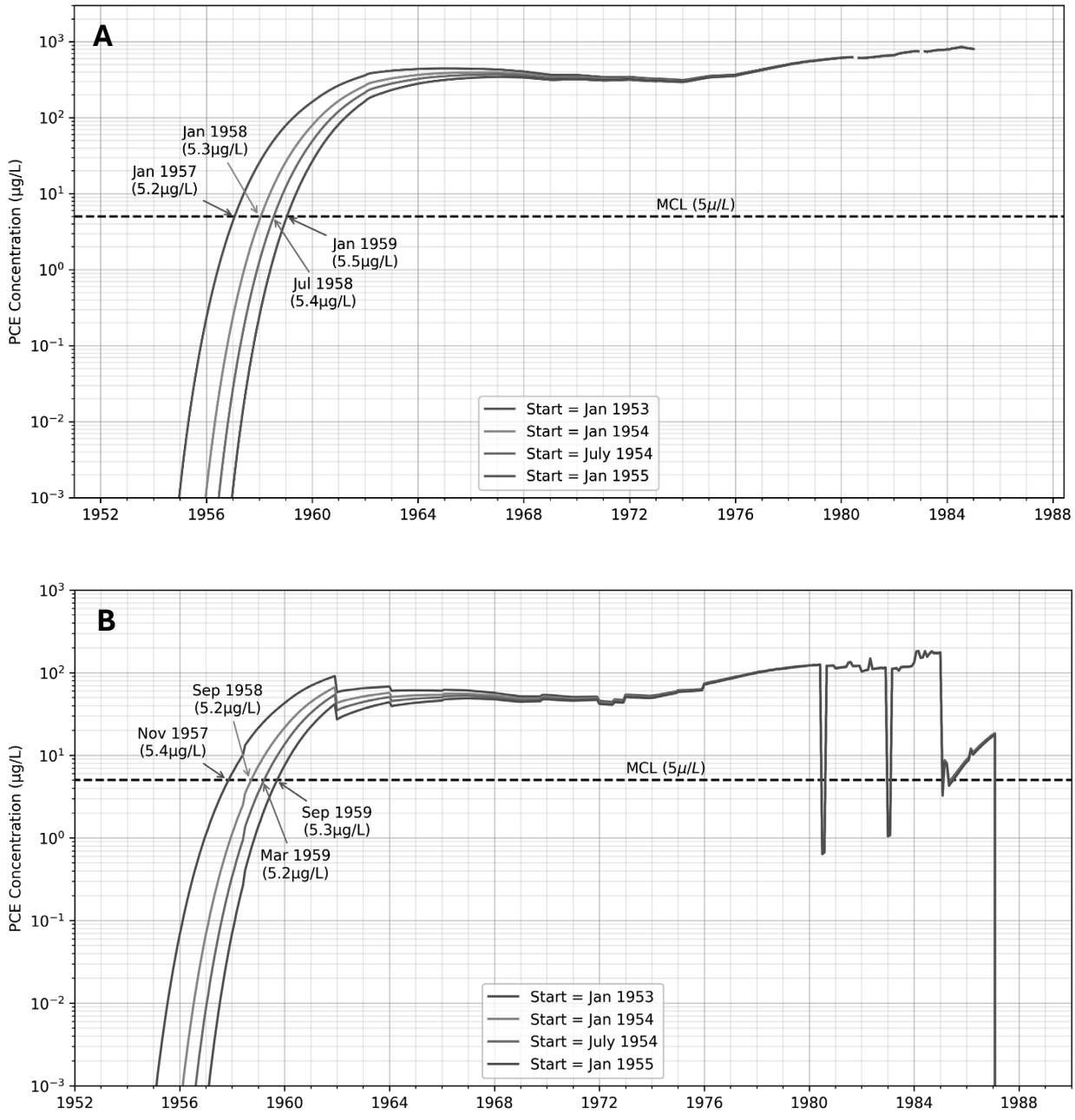



**Figure 4.1.** Plot of Modeled Concentration of tetrachloroethylene (PCE) with source release date variation: A, water-supply well TT-26 and B, Tarawa Terrace water treatment plant (TTWTP)

**Table 4.1.** Reconstructed PCE concentrations for variations in source release date at water-supply well TT-26 and the Tarawa Terrace water treatment plant (TTWTP)[+]

[µg/L, micrograms per liter, PCE, tetrachloroethylene]

| Date[*] | January 1953[+] | January 1954 | July 1954 | January 1955 |
|---|---|---|---|---|
| **Water-supply well TT-26** | | | | |
| January 1968 | 402 | 373 | 356 | 336 |
| January 1985 | 804 | 802 | 801 | 800 |
| **Tarawa Terrace water treatment plant (TTWTP)** | | | | |
| January 1968 | 57 | 53 | 51 | 48 |
| January 1985 | 176 | 176 | 175 | 175 |

[+]Using calibrated ATSDR model parameter values and published model input files (Maslia et al. 2007)

[*]January 1968 is start of ATSDR's epidemiological study; January 1985 is last operating month for well TT-26

**Table 4.2**. Date reconstructed PCE concentration exceeds the MCL (5 µg/L), duration of exceedance, and date of maximum concentration for variations in source release date, at water-supply well TT-26 and at Tarawa Terrace water treatment plant (TTWTP)[+]

[MCL, maximum contaminant level; µg/L, micrograms per liter; PCE, tetrachloroethylene]

| Source release date | Date exceeding MCL (5 µg/L) | Duration exceeding MCL, in months | Maximum PCE, in µg/L (date of occurrence) |
|---|---|---|---|
| **Water-supply well TT-26** | | | |
| Jan 1953[+] | Jan 1957 | 361 | 851 (Jul 1984) |
| Jan 1954 | Jan 1958 | 349 | 849 (Jul 1984) |
| Jul 1954 | Jul 1958 | 343 | 849 (Jul 1984) |
| Jan1955 | Jan 1959 | 337 | 847 (Jul 1984) |
| **Tarawa Terrace water treatment plant (TTWTP)** | | | |
| Jan 1953[+] | Nov 1957 | 351 | 183 (Feb 1984) |
| Jan 1954 | Sept 1958 | 341 | 183 (Feb 1984) |
| Jul 1954 | Mar 1959 | 335 | 182 (Feb 1984) |
| Jan1955 | Sept 1959 | 329 | 182 (Feb 1984) |

[+]Using calibrated ATSDR model parameter values and published model input files (Maslia et al. 2007)

### *4.1.2 Hadnot Point Industrial Area and Landfill*

In Section 4.2.3.2 (Spiliotopoulos, 2024, pp. 78-79), AS notes that ATSDR recognizes the lack of explicit data defining source locations and mass loadings but criticizes ATSDR for "arbitrarily assigning these quantities to the model to fit the limited water-quality data available starting in 1982." However, AS's critique goes to the heart of the model calibration, history matching, and parameter estimation processes used in groundwater modeling. In these processes, parameter values are adjusted (either manually or automatically) to improve the fit (Hill and Tiedeman, 2007).

Furthermore, ATSDR conducted meticulous and detailed source characterization analyses, as documented in Maslia et al. (2013, Tables A6, A7, and A8). Table A8, shown below as Table 4.3 of this report, provides specific information relevant to documented source areas, timelines, primary contaminants, and locations of major dissolved sources for the HPIA and HPLF areas.

**Table 4.3**. Maslia et al. (2013), Table 8.

**Table A8.** Identification of documented source areas, timelines, primary contaminants, and location of major dissolved-phase sources, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[HPFF, Hadnot Point fuel farm; UST, underground storage tank; AS/SVE; air sparging/soil vapor extraction; MW, monitor well; µg/L, microgram per liter; gal, gallon; LUST, leaking underground storage tank; CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act of 1980; TCE, trichloroethylene; PCE, tetrachloroethylene]

| [1]Source-area timeline [reference documents] | Primary contaminant; number of major sources | Location of major dissolved-phase sources |
|---|---|---|
| **Hadnot Point Industrial Area (see Figure A13)** | | |
| **Hadnot Point fuel farm events**<br>**1941**, HPFF USTs installed [UST #669, UST #670]<br>**1942**, Building 1115 USTs installed [UST #670]<br>**1993 January**, HPFF and Building 1115 USTs removed [UST #1186, UST #670]<br>**2000 December**, Piping removal (extensive) at HPFF/Building 1115 [UST #417]<br>**Building 1613 events**<br>**1950s**, USTs installed [UST #548, UST #546]<br>**1995 January**, USTs and contaminated soil removed [UST #535, UST #548]<br>**1998–2004**, AS/SVE remediation system operated<br>**Building 1601 events**<br>**1940s**, Building 1601 built [UST #172, UST #195]<br>UST removal date unknown | Benzene; three sources | HPFF/Building 1115/Building 1101 free product footprint<br>Building 1613 free product footprint<br>Building 1601 locations of maximum measured benzene in groundwater (78-GW75-1 and 78-GW74) and former location of USTs and dispenser island at southeast corner of building;<br>MW 78-GW75-1 (5,500 µg/L in 2003; 3,200 µg/L in 2004);<br>MW 78-GW74 (3,200 µg/L in 2004)<br>(See Figure A9 for building and monitor well [MW] locations) |
| **Building 1601 events**<br>**1940s**, Building 1601 built [UST #172, UST #195]<br>**1942**, 1,500-gal UST install date listed in LUST study completed in 1990 by Geraghty and Miller [UST #504, UST #507]<br>**1993 June 29**, UST excavated/removed [UST #624]<br>**Building 901/902/903 events**<br>**1948**, Buildings 900, 901, 902, 903 constructed [CERCLA #258, p. 149]<br>TCE UST installation date unknown; removal/abandonment date unknown, but probably occurred prior to onset of remediation efforts around January 1995 [Sovereign Consulting, Inc. 2007] | TCE; two sources | Building 1601 locations of maximum measured TCE in groundwater (MW 78-GW09-1 (old) and (new)) and former location of 1,500-gal waste UST on north side of building;<br>MW 78-GW09-1 (old) (5,000–14,000 µg/L during 1987–1991);<br>MW 78-GW09-1 (new) (at/above 1,000 µg/L during 1993–1996)<br>Building 901/902/903 locations of max measured TCE in groundwater (MW 78-GW23; 13,000 µg/L in 1987), maximum measured vinyl chloride in groundwater (MW 78-GW44; 1,600–6,700 µg/L during 2000–2004), and former locations of USTs containing TCE/solvent waste at Building 901 and between Buildings 902/903.<br>(See Figure A9 for building and monitor well [MW] locations) |
| **Hadnot Point landfill area (see Figure A14)** | | |
| **Landfill**<br>**1940s**, reportedly used as a waste disposal area (Site 6 and Site 82; Figure A8) beginning in the 1940s | PCE and TCE; one source | Location of maximum measured concentration of TCE and PCE in groundwater (MW 06-GW01D)<br>TCE ranged from 6,400 to 180,000 µg/L during 1992–2004;<br>PCE ranged from 210 to 6,500 µg/L during 1992–2004<br>(See Figure A10 for monitor well [MW] locations) |

[1] UST # refers to UST Web Management Portal file number (see References section of this report for complete details); CERCLA # refers to CERCLA Administrative Record file number (provided on digital video disc [DVD] in Maslia et al. 2007)

ATSDR does indeed discuss the lack of data to define the source loading terms for the model in the Hadnot Point Industrial Area (HPIA) and Hadnot Point landfill (HPLF) areas. However, as Dr. Konikow (2025) notes and I agree, there is no doubt that these chemical contaminants (including TCE and PCE) were present in the groundwater at toxic concentrations (substantially exceeding the MCLs[6]) in these areas, and that they were pumped out of the aquifer by several operating water-supply wells shown in Maslia et al. (2013, Figures A9 and A10) and provided below as Figures 4.2 and 4.3.

In AS's summary for his Opinion 14 (Spiliotopoulos, 2024, p. 79), ATSDR is criticized for having "assumed constant mass loading of the same magnitude at all sources for more than 40 years," which he believes is "highly uncertain, if not impossible." I disagree. ATSDR applied an average rate over the critical period because there was no basis for determining how the loading might have varied over time. This approach aligns with accepted groundwater flow and contaminant fate and transport modeling best practices. The fact that the model with a constant mass loading adequately reproduced observed concentrations supports ATSDR's method for modeling the sources at Hadnot Point Industrial Area and Hadnot Point landfill. (Konikow 2025)

Finally, ATSDR reviewed an EPA study (USEPA 1986, 1986) of 12,444 leak incident reports to estimate the timing of UST releases at Hadnot Point. This is certainly not "arbitrary and uncertain." Reliance upon such a comprehensive study is an accepted methodology; it is not "arbitrary." In summary, ATSDR based parameter values on the best data it had available, including site-specific and published data. ATSDR also made appropriate adjustments to parameters to fit site-specific conditions.

[6] MCL, maximum contaminant level; 5 μg/L for PCE and 5 μg/L for TCE.

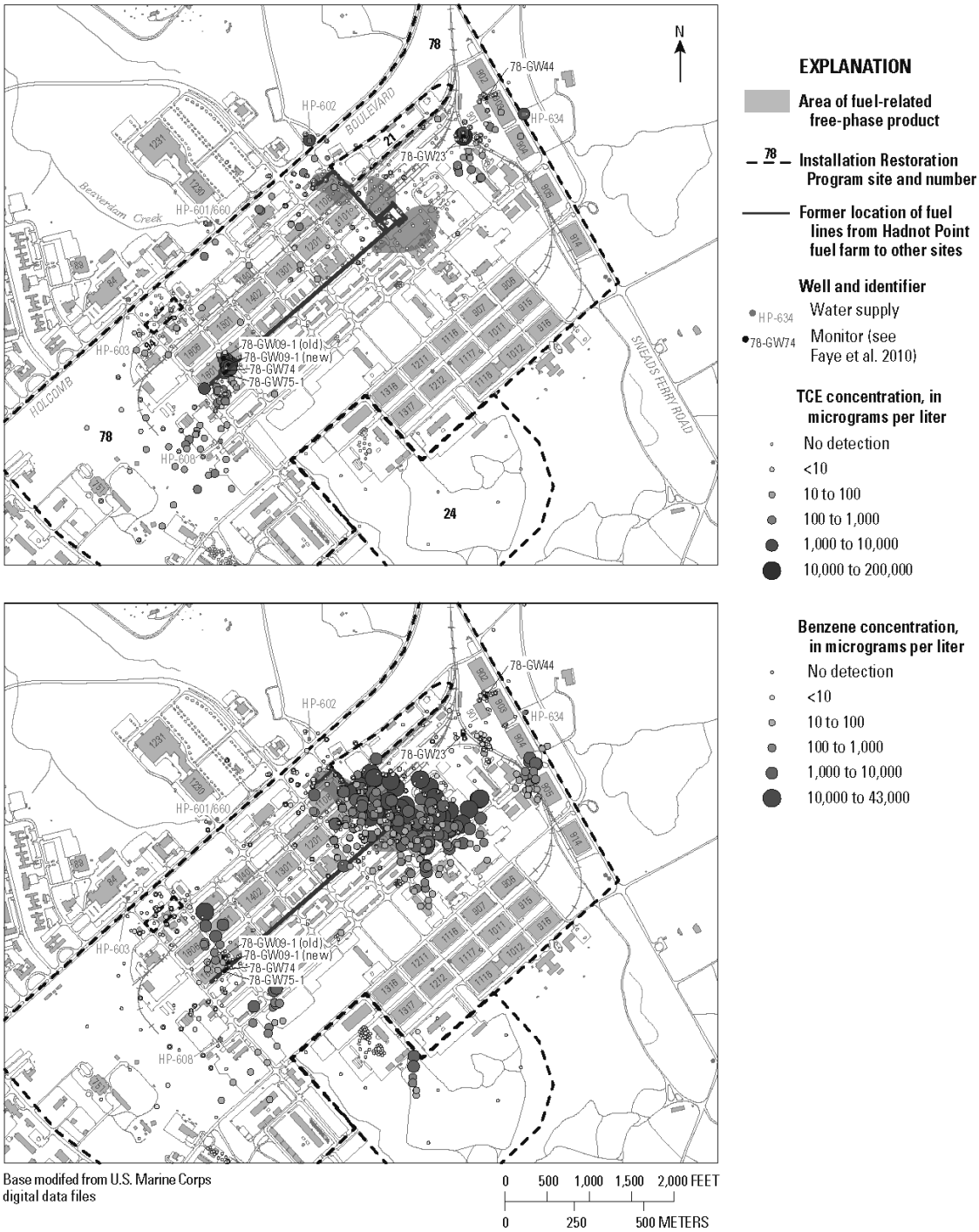



**Figure A9.** Sampling data for trichloroethylene (TCE), benzene, and fuel-related free product in groundwater for the Hadnot Point Industrial Area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A8 for location and Figure A13 for selected building numbers.)

**Figure 4.2.** From Maslia et al. (2013), Figure A9

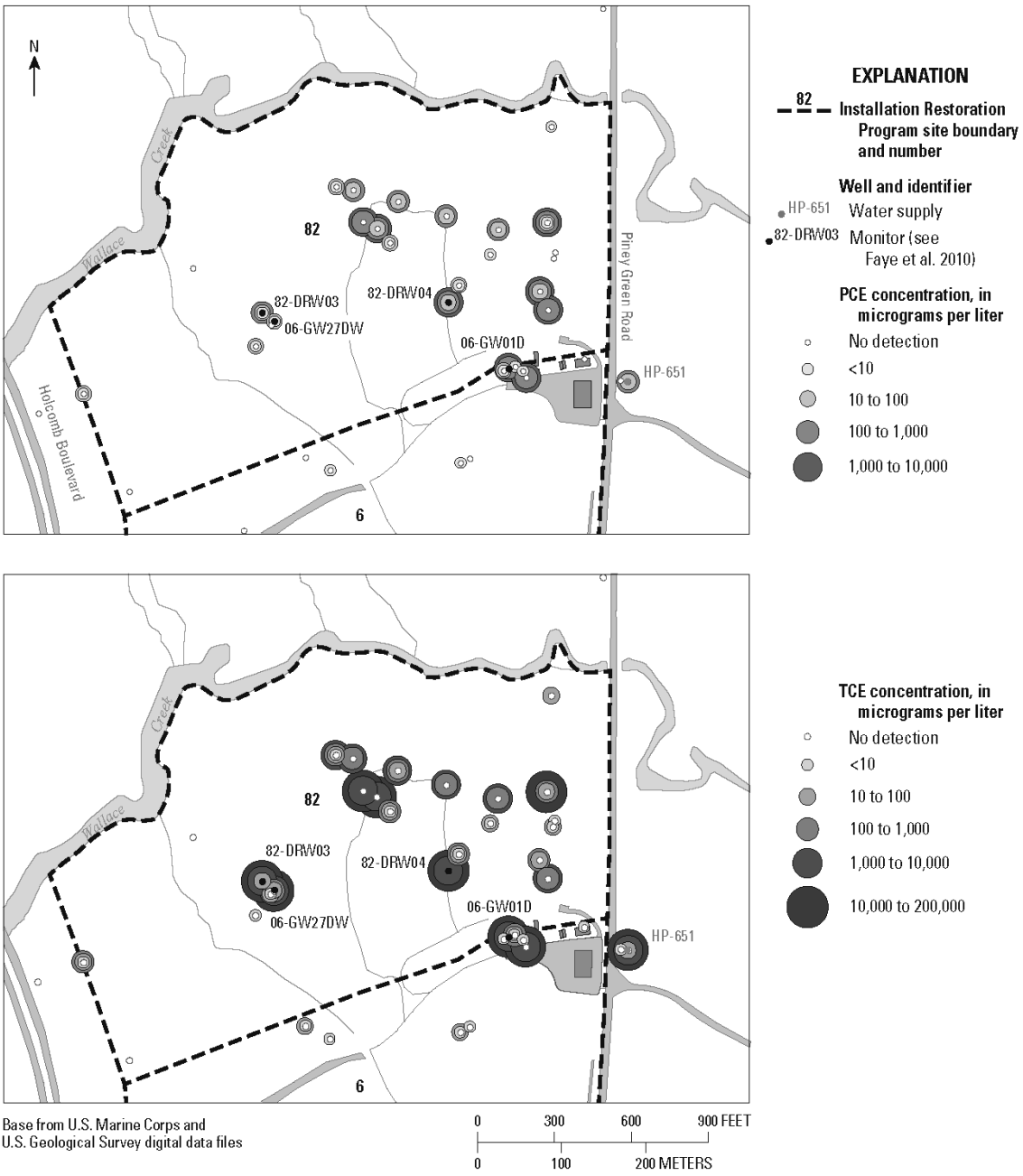



**Figure A10.** Sampling data for tetrachloroethylene (PCE) and trichloroethylene (TCE) in groundwater for the Hadnot Point landfill area, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A8 for location.)

**Figure 4.3.** From Maslia et al. (2013), Figure A10

## 4.2 Water-Supply Well Operations

### *4.2.1 Tarawa Terrace*

In his opinion 5, Spiliotopoulos (2024, Section 4.1.2.6) posits that the ATSDR groundwater model for TT resulted in "biased-high estimates of monthly contaminant concentrations" at water supply well TT-23. (his Section 4.1.2.6). I concur with Dr. Konikow's assessment of opinion 5:

> Section 4.1.2.6 (p. 42) offers no clear evidence that the discrepancy at this one well (out of many) has a substantial impact on the overall results. Based on ATSDR Table E2, of the nine unique sampling dates for this well, six had an observed level of PCE or TCE above the MCL. Furthermore, with respect to the overall effect on concentrations estimated at the WTPs, it is important to note that TT-23 was operational for only about 9 months or less, starting in 1984, and had the shortest operational (pumping) period of any of the 16 pumping wells operating in the TT area (see Table H3 in Chapter H of the TT series of reports). When it was pumping, the contribution from this well provided only a small fraction of the total groundwater inflow to the WTP with concentrations far less than well TT-26 (with its modeled concentrations likely being underestimated). Thus, if indeed the estimates for this well were too high (by less than two times), the effect on calculated concentrations in the WTP would be minimal both in magnitude and in duration.
>
> (Konikow 2025).

With respect to calibrated ATSDR models being "biased high" as posited by DOJ experts, the opposite is true. For example, Figure 4.4 from Faye (2008, Figure F16)[7] shows a plot of observed data (5 of the 6 samples were obtained within a week's time) and reconstructed PCE concentrations for water-supply well TT-26. Note that the highest and first sample was taken during the period when this well was in service, as compared to the remaining samples when this well was out of service. If anything, it could be argued that the model is under-predicting the concentrations. Furthermore, note that reconstructed PCE concentrations fell almost exactly at the midpoint of the range of observed values (about 800 ug/L)—countering the claim of being biased high and confirming the adequateness and acceptability of the calibrated ATSDR models including the reconstructed supply-well operations. As with well TT-23 discussed above, the first sample from well TT-26 was taken when it was operating, and the remainder of the samples were taken after well TT-26 was permanently removed from service.

[7] CLJA_WATERMODELING_01-0000488379.

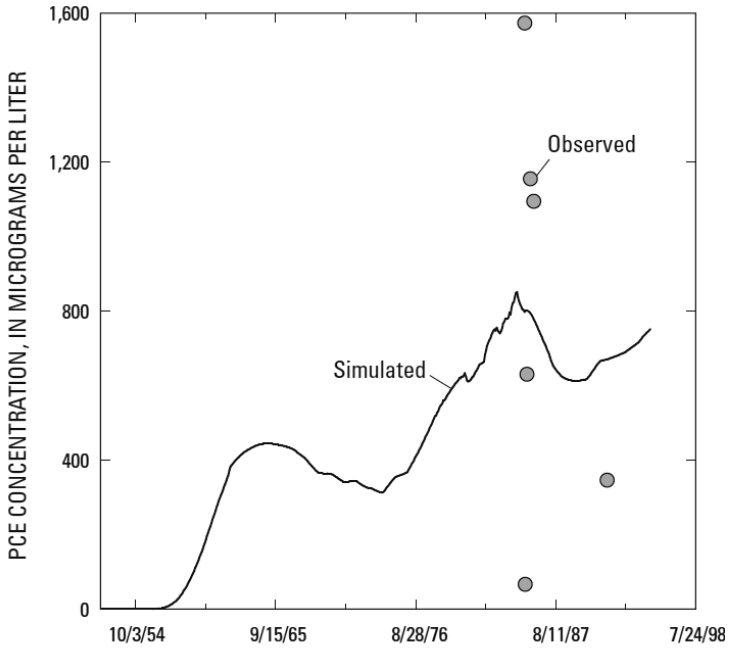



**Figure F16.** Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1952–December 1994 (see Figure F6 for location).

**Figure 4.4.** From Faye (2008), Figure F16.

*4.2.2 Hadnot Point*

In Section 4.2.2 (Spiliotopoulos, 2024, p. 72), the claim is made that ATSDR "made arbitrary assumptions to reconstruct pumping history…" I agree with Dr. Konikow who, after reviewing the ATSDR's historical reconstruction, concluded:

> In my opinion, the assumptions were not arbitrary, but rather were well-informed, well-reasoned, and carefully documented. Assumptions had to be made about the pumping history, and they were made, but they were not arbitrary. For example, Dr. Spiliotopoulos notes that "Yearly volumes are available for some years prior to 1980. A trendline was used to estimate raw-water flows for years prior to 1980 when no data exist." This appears to be a sound statistical approach, and the use of a trend line is certainly not arbitrary.
>
> In Section 4.2.2 (p. 72-73) Dr. Spiliotopoulos offers a further criticism that "it was assumed that a well would be operated in the historical period based on a pattern similar to the more recent 'training period,' with further adjustments to account for information on the varying capacity of wells, where available." Dr. Spiliotopoulos' statement actually

> contradicts his assertion that estimates were arbitrary. Here he describes a reasoned and reasonable approach to estimating a pattern of past water use (well pumpage)—an approach that is not "arbitrary."
>
> In several additional paragraphs on p. 73 (as well as elsewhere), he repeats the claim that pumping rates were based on arbitrary assumptions. ATSDR uses sound statistical methods (such as regression and correlation) to estimate pumpage. This is neither arbitrary nor unreasonable."
>
> (Konikow 2025)

ATSDR developed and applied a sophisticated and novel pumping schedule algorithm for the nearly 100 water-supply wells serving Hadnot Point and Holcomb Boulevard. They did this by using a "training period" when pumping data are known (typically, present-day) and a "predictive period" when pumping data were unknown. Details of this methodology are provided in Telci et al. (2013)[8] and are the basis for the pumping schedules assigned to wells supplying the HP-HB service areas. Similar wells managed by the same operating authority (e.g., the Camp Lejeune Water Utilities Department) are likely to have been operated in a similar manner—however, in the early years of operations they simply were not required to maintain as detailed records (e.g., SCADA data) as would be expected today. AS does not offer a better or more reasonable approach than the one used by ATSDR.

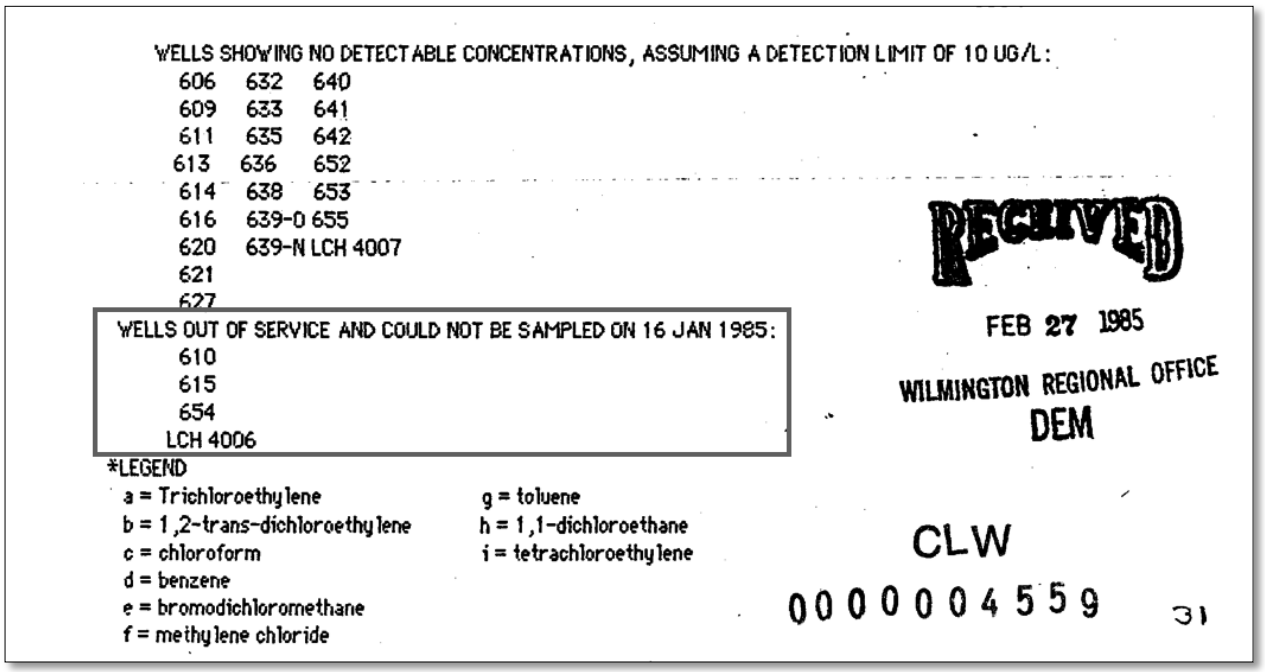
#### 4.2.2.1 HP-634

In Section 4.2.3 (Spiliotopoulos 2024, p. 77), AS states that model calibration was "improperly influenced" by "erroneous concentrations reported for well HP-634 … while non-detections were ignored." Documentation and discussion below provide evidence that the concentration in well HP-634 (sampled on 1/16/1985) of 1,300 µg/L of TCE was not an erroneous concentration. Furthermore, non-detections were not ignored. They are clearly listed and labelled in many tables presented in the ATSDR reports (e.g., Maslia et al. 2013, Table A4) and in many other places in ATSDR reports (Faye et al. 2008; Faye et al. 2012).

There are certain documents that show that well HP- 634 was (temporarily) shut down on 12/10/84 when methylene chloride was found in the sample; however, the documents below demonstrate that well HP-634 was operating until early February 1985.

The first document is cited in RH's footnote 111 (Hennet 2024, p. 5-31, footnote 111).[9] In the callout of the wells out of service on 1/16/1985, HP-634 is not among those listed, suggesting that the well was still in service on this date. January 16th is when the 1,300 µg/L sample was taken at HP-634.

[8] CLJA_WATERMODELING_05-00001005675 – 05_00001005810.
[9] CLJA_CLW00000004559



WELLS SHOWING NO DETECTABLE CONCENTRATIONS, ASSUMING A DETECTION LIMIT OF 10 UG/L:

606 632 640
609 633 641
611 635 642
613 636 652
614 638 653
616 639-0 655
620 639-N LCH 4007
621
627

WELLS OUT OF SERVICE AND COULD NOT BE SAMPLED ON 16 JAN 1985:

610
615
654
LCH 4006

*LEGEND

a = Trichloroethylene
b = 1,2-trans-dichloroethylene
c = chloroform
d = benzene
e = bromodichloromethane
f = methylene chloride
g = toluene
h = 1,1-dichloroethane
i = tetrachloroethylene

RECEIVED
FEB 27 1985
WILMINGTON REGIONAL OFFICE
DEM

CLW

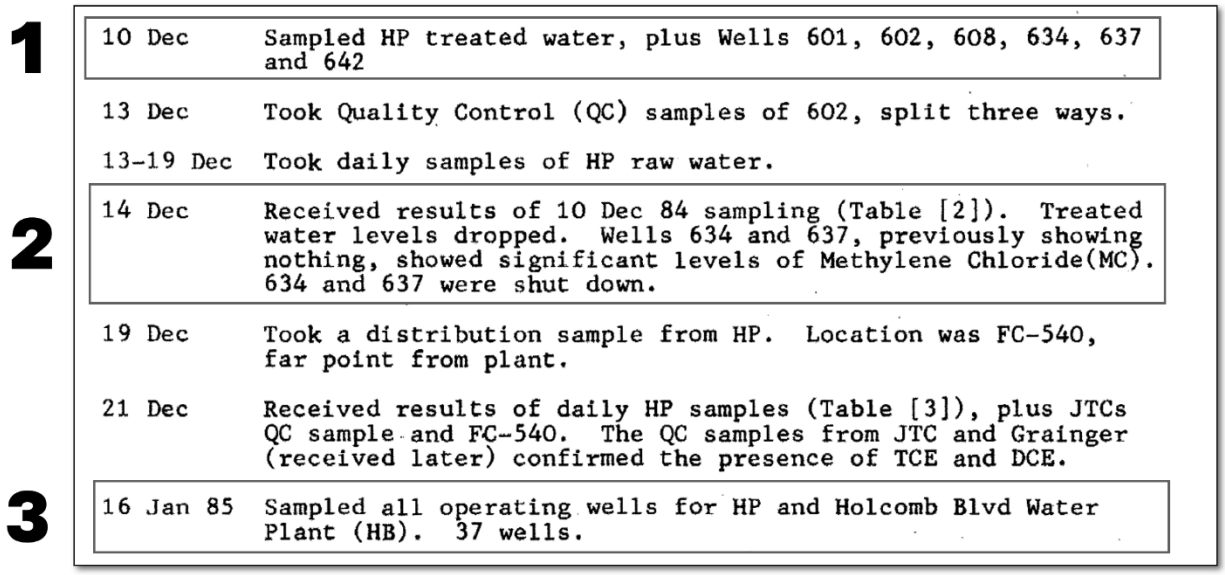
0000004559 31

- **Event #1:** Well HP-634 is tested with other wells on 12/10/1984.

- **Event #2:** Test samples from 12/10/84 are back with "Wells 634 and 637, previously showing nothing, showed significant levels of Methylene Chloride (MC). 634 and 637 were shut down."

- **Event #3:** This is a key statement: On Jan. 16, 1985, "Sampled all operating wells for HP and Holcomb Blvd Water Plant (HB). 37 wells". The key being all **operating** wells.

Further documentation that supports the fact that HP-634 was operating on 1/16/1985 when the sample was taken is provided in CLW4546,[10] which is a chronological listing of events from 11/30/1984 to 2/25/1985. A portion of that document covering 12/10/84 to 1/16/85 is shown below.



| | | |
|---|---|---|
| 1 | 10 Dec | Sampled HP treated water, plus Wells 601, 602, 608, 634, 637 and 642 |
| | 13 Dec | Took Quality Control (QC) samples of 602, split three ways. |
| | 13-19 Dec | Took daily samples of HP raw water. |
| 2 | 14 Dec | Received results of 10 Dec 84 sampling (Table [2]). Treated water levels dropped. Wells 634 and 637, previously showing nothing, showed significant levels of Methylene Chloride(MC). 634 and 637 were shut down. |
| | 19 Dec | Took a distribution sample from HP. Location was FC-540, far point from plant. |
| | 21 Dec | Received results of daily HP samples (Table [3]), plus JTCs QC sample and FC-540. The QC samples from JTC and Grainger (received later) confirmed the presence of TCE and DCE. |
| 3 | 16 Jan 85 | Sampled all operating wells for HP and Holcomb Blvd Water Plant (HB). 37 wells. |

On page 6 of the same document (Table [5])[11] the 37 wells tested on 1/16/85 are listed and HP-634 is on the list, and shows a sampled concentration for TCE of 1,300 µg/L.

Table [5]

LAB: JTC Sampled: 16 January 1985 Detection Limit: 10ppb

| | Well | DCE | TCE | PCE | VC | 11D |
|---|---|---|---|---|---|---|
| 1 | 601 | 8.8 | 26 | ND | ND | ND |
| 2 | 634 | 700 | 1300 | 10 | 6.8 | ND |
| 3 | 651 | 3400 | 3200 | 386 | 655 | 187 |
| 4 | 652 | ND | 9.0 | ND | ND | ND |
| 5 | 653 | ND | 5.5 | ND | ND | ND |

None Dectected:

| | | | |
|---|---|---|---|
| 6 603 | 16 632 | 26 642 | |
| 7 606 | 17 633 | 27 643 | |
| 8 609 | 18 635 | 28 644 | |
| 9 611 | 19 636 | 29 646 | |
| 10 613 | 20 637 | 30 647 | |
| 11 614 | 21 638 | 31 648 | |
| 12 616 | 22 639(OLD) | 32 650 | |
| 13 620 | 23 639(NEW) | 33 655 | |
| 14 621 | 24 640 | 34 LCH 4007 | |
| 15 627 | 25 641 | | |

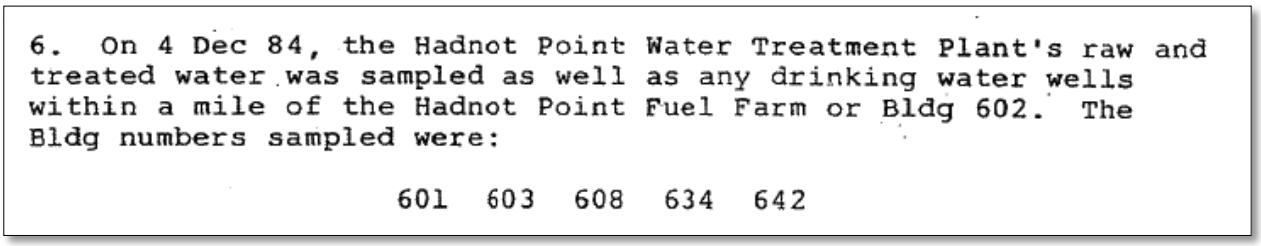
Broken Samples: 35 602, 36 608, 37 645, 651

See Note 3.

[11] CLJA_WATERMODELING_09-0000424938

Further support for the fact that HP-634 was only temporarily closed comes from an email dated 4/11/1989 (Bates CLJ16100/CLW1818) from the Supervisory Chemist to the Director of the Natural Resources and Environmental Affairs Division with the subject "WATER MONITORING RELATED TO THE INSTALLATION RESTORATION (IR) PROGRAM".

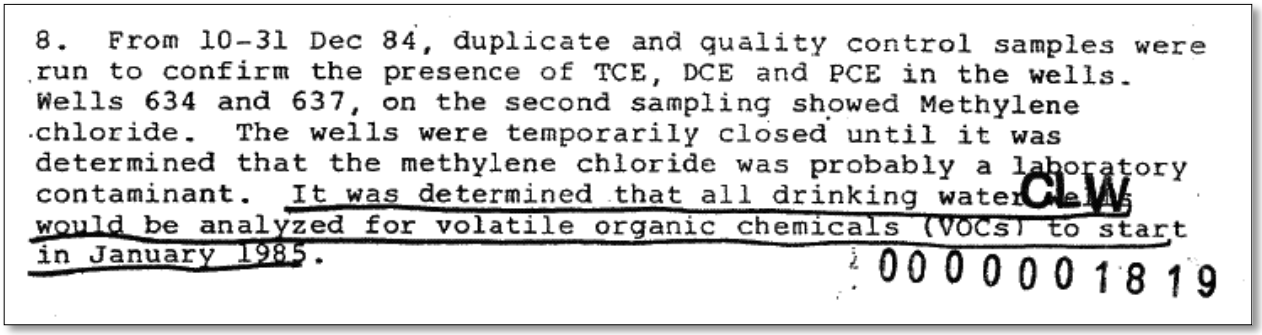
On page 2 of the document (CLJ161101/CLW1819) bullet 6 states certain wells were tested on 12/4/1984 including HP-634:



6. On 4 Dec 84, the Hadnot Point Water Treatment Plant's raw and treated water was sampled as well as any drinking water wells within a mile of the Hadnot Point Fuel Farm or Bldg 602. The Bldg numbers sampled were:

601 603 608 634 642

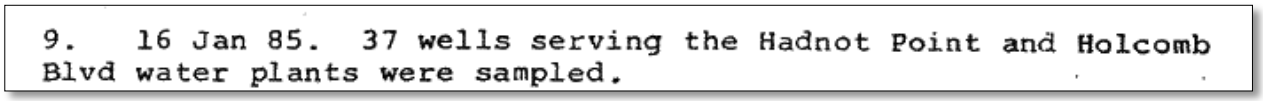
Bullet 8 on the same page states that methylene chloride was found in wells 634 and 637 during a 2nd sampling on 12/10/1984. "The wells were temporarily closed until it was determined that the methylene chloride was probably a laboratory contaminant."



8. From 10-31 Dec 84, duplicate and quality control samples were run to confirm the presence of TCE, DCE and PCE in the wells. Wells 634 and 637, on the second sampling showed Methylene chloride. The wells were temporarily closed until it was determined that the methylene chloride was probably a laboratory contaminant. It was determined that all drinking water wells would be analyzed for volatile organic chemicals (VOCs) to start in January 1985.

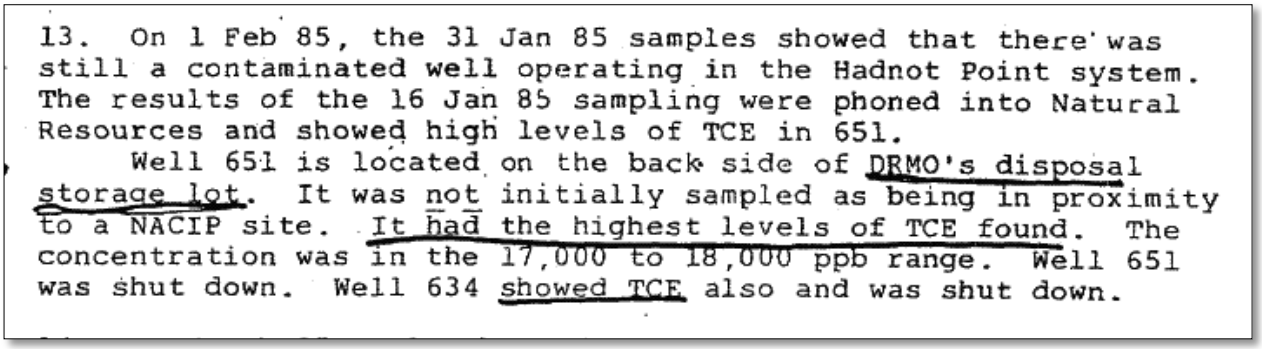
CLW 0000001819

Bullet 9 (CLJ611102/CLW1820) states 37 wells serving HP and HB were tested on 1/16/1985.



9. 16 Jan 85. 37 wells serving the Hadnot Point and Holcomb Blvd water plants were sampled.

Bullet 13 on the same page states “On 1 Feb 85, the 31 Jan 85 samples showed that there was still a contaminated well operating in the Hadnot Point system. The results of the 16 Jan 85 sampling were phoned into Natural Resources and showed high levels of TCE in 651.” At the end of the bullet text it states, “Well 634 showed TCE also and was shut down”.



13. On 1 Feb 85, the 31 Jan 85 samples showed that there was still a contaminated well operating in the Hadnot Point system. The results of the 16 Jan 85 sampling were phoned into Natural Resources and showed high levels of TCE in 651.

Well 651 is located on the back side of DRMO's disposal storage lot. It was not initially sampled as being in proximity to a NACIP site. It had the highest levels of TCE found. The concentration was in the 17,000 to 18,000 ppb range. Well 651 was shut down. Well 634 showed TCE also and was shut down.

This statement supports the facts that HP-634 was “temporarily closed”, as stated in bullet 8, and that the well was shut down for TCE - not methylene chloride.

Therefore, based on the documentation regarding water-supply well HP-634, the claims made by the DOJ Experts (Spiliotopoulos 2024, Hennet 2024) are incorrect. HP-634 was operating on the date it was sampled on Jan. 16, 1985; the result was 1,300 µg/L of TCE; and the well was shut down due to this high TCE concentration.

#### 4.2.2.2 HP-651

RH (Hennet 2024, p. 5-28 and 5-29) posits that well data covering 11/28/1984 to 2/5/1985 (CLJA_CLW00000006590 – 6593) should be used as the basis for determining HP-651’s contribution to the HPWTP finished water concentrations from 1972 to 1985. The paragraph below summarizes RH’s position:

> “The average concentration measured for TCE in HP-WTP over the period January 21 to February 5, 1985,99 is 582 ug/L. During this period it is known that HP-651 was being pumped (RH, p. 4-19, Exhibit I-9). Considering that HP-651 was being pumped 39% of the time (0.39 frequency of pumping; Exhibit I-9) yields a TCE long-time average concentration of 227 ug/L for HP-WTP supplied water.
>
> 0.39 x 582 (ug/L) = 227 (ug/L).”

RH presents a table that represents the data in CLJA_CLW00000006590 – 6593 in an Excel™ spreadsheet. Using these data he determines that over the 69 days covered, well HP-651 only was operating 39% of the time so this is the value that should be used over the entire life of well HP-651, which is from 7/72 to 2/85 or 12.6 years. In doing so RH either fails to realize or does not disclose that these two months of well operation from 11/28/1984 to 2/7/1985 are anything but ordinary and therefore, should not be used as the basis for any long-term forecasting of pumping schedules. Below I discuss the reasons why the 69-day period selected by RH is not reliable and should be disregarded.

- **Point 1:**

The 11/28/1984 to 2/5/1985 period should be broken into months and not as a 69-day pumping period. The ATSDR pumping schedules are based on months as their base unit. If this is done for well HP-651 the results for days of operations and percentage of time operating are as listed in Table 4.4.

**Table 4.4.** Monthly pumping schedule for well HP-651, December 1984 – and January 1985.

| Month | Days of Operation | Percentage on |
|---|---|---|
| December 1984 | 2 | 6% |
| January 1985 | 18 | 58% |

These results should make the modeler question whether there is an explanation for the HP-651's low operation in December. The most logical explanation involves wells New 623, New 622, New 629, New 661 and New 662. These 5 wells were new wells brought online from 6/1984 to 10/1984 and represent over 1,200 (gallons per minute (gpm) of combined capacity. The frequency with which they were in operation ranged from a low of 61% to a high of 94% (Table 4.5). Certainly, the addition of these 5 new wells had an effect on the pumping schedule at HPWTP.

**Table 4.5.** Characteristics of New Hadnot Point Wells, June–October 1984.

[DOB, construction completion date; gpm, gallons per minute; HP, Hadnot Point; %, percent]

| HP Well ID | Other Name | Well DOB | Original Capacity, in gpm | Dec 84 — Jan 85 Capacity, in gpm | Well age as of 2/85 | December 84 Operating Days | % | Jan 85 Operating Days | % | Total Days | % On |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 611 | (New 623) | 8/1/1984 | 360 | 242 (9/85) | 0.5 | 27 | 87% | 30 | 97% | 61 | 87% |
| 614 | (New 622) | 6/1/1984 | 323 | 320 (9/85) | 0.7 | 23 | 74% | 30 | 97% | 57 | 81% |
| 621 | (New 629) | 10/1/1984 | NA | NA | 0.3 | 26 | 84% | 16 | 52% | 43 | 61% |
| 627 | (New 661) | 8/1/1984 | 192 | 280 (10/84) | 0.5 | 28 | 90% | 31 | 100% | 66 | 94% |
| 639 (New) | (New 662) | 10/1/1984 | 146 | 146 (10/83) | 0.3 | 26 | 84% | 26 | 84% | 59 | 84% |

- **Point 2:**

The lack of use of well HP-651 in December 1984 had nothing to do with the well's capacity as demonstrated by its capacity tests. Well HP-651 Capacity Data listed on page S1.71 of the HPHB Chapter A–Supplement 1 (Sautner et al. 2013)[12] Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations show the last capacity test

[12] CLJA_WATERMODELING_05-0000826112, found in CLJW_WATERMODELING_05-0000826036 – 05-0000826153

was 10/29/1984 and the well operated at 242 gpm—which ranks in the Top 10 highest capacity wells at the time.

**Table 4.6.** Sautner et al. (2013), p. S.71.

## Well HP-651

[gpm, gallon per minute; —, no data; VOC, volatile organic compound; USGS, U.S. Geological Survey]

| Date | Capacity, in gpm | Operational status | Data source |
|---|---|---|---|
| 12/30/1971 | 200 | Construction completed | Driller[1] |
| 7/1/1972 | — | In service | Estimated date |
| 1/1976 | — | In service | CLW-4039 |
| 3/31/1977 | 190 | In service | Well capacity test |
| 1/1978 | — | In service | Operation records |
| 1/10/1979 | 167 | In service | Well capacity test |
| 2/13/1980 | 178 | In service | Well capacity test |
| 7/26/1981 | 232 | In service | Well capacity test |
| 1/1982 | — | In service | Operation records |
| 9/14/1983 | 239 | In service | Well capacity test |
| 10/29/1984 | 242 | In service | Well capacity test |
| 1/1985 | — | In service | Operation records |
| 2/1985 | — | "Contaminated" | Operation records |
| 2/4/1985 | — | Out of service | CLW-4913[2] |
| 2/4/1985 | — | Service terminated | CLW-4913[2] |
| 6/1994 | — | Abandonment | AH Environmental Consultants[3] |

[1]Corbin Construction Company, written communication, December 30, 1971

[2]Well secured due to VOC contamination

[3]AH Environmental Consultants, Inc., electronic communication, September 3, 2004

Data sources:

CLW, Camp Lejeune Water Documents 3559–3561, 3573–3575, 3585–3587, 3588–3590, 3641–3643, 3644–3646, 3772–3774, 3775–3777, 3996–3997, 3998–4000, 4044–4046, and 4047–4049

USGS, operation records, written communication, March 2004

- **Point 3:**

When compared to other wells that were supplying raw water during that time, well HP-651's age is also not a reason for its lack of operation in December 1984. Well HP-651's completed construction date (a/k/a/ DOB) was 7/1/1972 making it only 12.6 years old as of 2/1/1985. In comparison, well HP-616 operated at 57% in December 1984 and its DOB is 1/1/1943 making it 42.1 years old on 2/1/1985. Its last capacity test placed it at 210 gpm—still substantial, especially considering its age. The same holds true for well HP-632. In December 1984 it operated at 64% at an age of 27.7 years (DOB 5/27/1957). When tested on 10/1984 its capacity was 201 gpm.

- **Point 4:**

The fact that well HP-651 only operated at 6% could also be attributed to the pumping schedule being used at the time. As outlined extensively in ATSDR's reports (Telci et al. 2013),[13] ATSDR used current (2008) pumping data as a "training period" to reconstruct well operations during the historical period ("predictive period"). On those wells that were shut down due to contamination, "surrogate wells" were used for the "training period" (Telci et al. 2013, Table S2.2)[14]. HP-651 was shut down in February 1985 so well HP-633 was used as its surrogate. If we look at the historic pumping schedule that was created for HP-651 based on HP-633 we see there is a cycle:

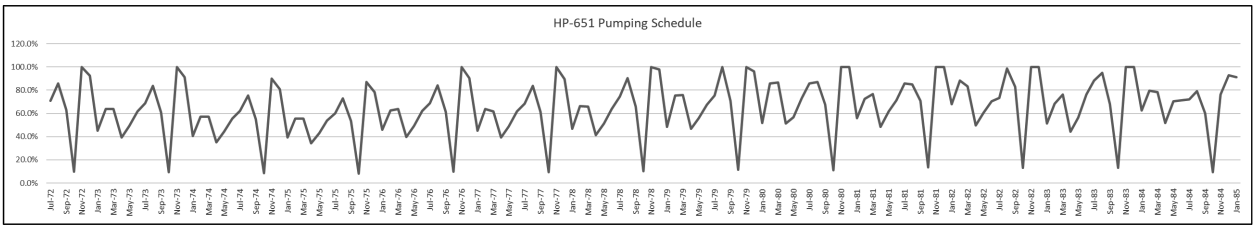



**Figure 4.5.** Reconstructed historical pumping operations for well HP-651 (from Telci et al. 2013)

In the reconstructed pumping operations cycle, well HP-651 drops below 10% every October. This cycling was common for several reasons, including substantial reductions in consumption and demand owing to deployment of troops and climatic conditions where October and generally Fall to early Winter are "wet months." It is very possible that the actual low-cycle month for HP-651 was December and not October, which would explain the 6% value of operation time for December of 1984.

In addition to those points outlined above there are other reasons why this period should not be used to represent normal operation of not only HP-651 but the well field in general.

- **Reason 1**

The first and foremost reason why this is not a representative time period is because November 30, 1984 marked the start of the investigation into the sources of contamination at HP. Well HP-602 was shut down on 11/30/1984. Additional testing on 12/4/1984 and 12/10/1984 resulted in well HP-608 being shut down permanently on 12/6/1984 and wells HP-634 and HP-637 being shut down temporarily on 12/14/1984. This disruption is not a normal occurrence and therefore adds to the reasons why this period of time should not be used to determine historic pumping schedules for any wells.

- **Reason 2**

As outlined in my Expert Report (Maslia 2024) the HBWTP had to be shut down from 1/27/84 to 2/7/85 due to a fuel line contaminating the HB water supply. During this time HPWTP had to supply

[13] CLJA_WATERMODELING_05-00001005675 – 05-00001005810.
[14] CLJA_WATERMODELING_05-00001005695.

all finished water for the HB area, in addition to its own, which is not representative of normal operation.

- **Reason 3**

Based on ATSDR's research into Camp Lejeune's water treatment plant's operations, it became apparent that the WTP operators would not cease operating a 12.6-year-old well (HP-651) that at 12 years of age is still producing more than 240 gpm. In July 1972, well HP-651 would have been operated very similar to that of the new wells discussed previously—wells New 623, New 622, New 629, New 661 and New 662, which were operated at 70% – 100% capacity.

- **Reason 4**

Camp Lejeune is a military base. Therefore, production and consumption of water are determined by demands for: (a) fire protection, (b) housing , facilities, and recreation,(c) utility requirements (steam and heat production), (d) troop deployments, (e) leave for rest and relaxation, and (f) a combination of (a)-(e) above. ATSDR staff observed an example of the impact of troop deployment on production and consumption of water supplies during the conduct of a field test of the HPWTP service area during May 2004 (Sautner et al. 2005). During this field test, ATSDR requested that Camp Lejeune water utility operators increase normal water production of the HPWTP from about 1,600 gpm to about 2,100 gpm so ATSDR could conduct tracer tests. On the final day of the test, water utility staff told ATSDR that they would need to reduce production back to the 1,600 gpm at the HPWTP because they were "spilling water from the elevated storage tanks." Camp Lejeune water utility staff indicated that a substantial reduction in demand was being observed because of troop deployments.

RH's position on well HP-651 is an attempt to lower concentrations that occurred at Camp Lejeune during 1953 – 1987 using incorrect and/or select, non-representative data. RH's contentions regarding HP-634 are incorrect and the same holds true for HP-651. Supply well HP-651 was a major contributor to the raw water supply from June 1972 – February 1985, and the ATSDR reconstructed pumping schedule accurately reflects well HP-651's overall operation. RH's claim of 39% lifetime operation is made without a thorough review of the documents he is relying on to support his position.

## 4.3 Volatilization of VOCs During Water Treatment Process

DOJ expert (RH) posits that a substantial portion of chemicals of concern in the raw water was unavoidably lost during subsequent storage, treatment, and distribution (Hennet 2024, Section 5, Opinion 2). His report goes through numerous calculations that he claims show substantial percentages of VOCs volatilizing off during the water treatment and storage process at the WTPs (Tarawa Terrace and Hadnot Point).[15] For example, in Hennet's Exhibits 2-4 and 2-5 (2024, p. 5-6 – 5-11) he computes an "Overall Evaporative Removal" of VOCs of concern at the HPWTP as: 18.34% (PCE), 17.07% (TCE), 22.41% (1,2-tDCE), 32.48% (VC), and 15.12% (Benzene). For the TTWTP, Hennet computes the "Overall Evaporative Removal" of VOCs of concern as 18.84% (PCE), 17.63% (TCE), 23.23% (1,2-tDCE), 33.41% (VC), and 15.68% (Benzene). These calculations

[15] The Holcomb Boulevard WTP (HBWTP) was never supplied with contaminated raw water.

substantially exceed values of volatilization computed by the consultant to the U.S. Marine Corps (USMC), AH Environmental Consultants in its December 2004 report on Estimation of VOC Removal (AH Consultants 2004).[16] Specifically, Section 5 (Summary) of the AH Consultants report states:

> "The calculations revealed that VOC removal due to volatilization from quiescent basins was negligible at MCB Camp Lejeune. The only significant VOC removals must have occurred at the spiractor effluent pipe, where the falling water undergoes some aeration. Considering the uncertainty in the estimates for the fall height over the weir formed by the pipe, the removals for TCE and PCE were likely to be less than 15%."[17]

Earlier in its report, AH Environmental Consultants (2004, (pages 4-1 – 4-2) found that "volatilization due to aeration at the spiractor effluent pipe resulted in TCE and PCE removals of 6.1% and 7.7% at the design flow rate 700 gpm, respectively. … A sensitivity analysis showed that the fall height has the largest effect on VOC removal at a weir." This sensitivity analysis conducted by AH Environmental Consultants (2004) found that removal of PCE and TCE is nearly proportional to the fall height from the spiractor. AH Environmental Consultants (2004) went on to explain that the fall height at Hadnot Point was only 1 foot but at Holcomb Blvd it was 2 feet. It was this uncertainty along with "additional uncertainties … introduced by varying head losses in the pipes caused by calcium carbonate scale build-up and manual cleaning" that led AH Environmental Consultants (2004) to state at page 4-4 that "it is estimated that PCE and TCE removals due to aeration at the spiractor effluent pipes are likely to be *no larger than* 15%."

To assess the DOJ expert's (RH) calculations and conclusions, Dr. David R. Sabatini conducted a detailed analysis of the volatilization of VOCs for the Camp Lejeune WTPs including volatilization from mobile water units (a/k/a water buffaloes[18]), and this analysis is adopted and incorporated by reference into this report. Results of this analysis are summarized by Sabatini (2025, Section 5.1.4) for the TTWTP and HPWTP are listed Table 4.7 (Sabatini (2025, Table 5.3).

**Table 4.7.** From Sabatini (2025), Table 5.3.

| Source | TCE (%) | PCE (%) | 1,2-tDCE (%) | VC (%) | Bz (%) |
|---|---|---|---|---|---|
| Spiractor (Sec 5.1.1) | 5.2 | 6.2 | 5.9 | 9.9 | 4.3 |
| Storage tanks (Sec 5.1.2) | <1 | <1 | <1 | <1 | <1 |
| Other losses (Sec 5.1.3) | <1 | <1 | <1 | <1 | <1 |
| **My Estimate - overall losses** | **<7.2** | **<8.2** | **<7.9** | **<11.9** | **<6.3** |
| AH Environmental (2004), p.5-1 | <15 | <15 | - | - | - |
| Hennet (2024) Exhibit 2-6, p.5.14 | 17 | 18 | 22 | 32 | 15 |

[16] CLJA_WATERMODELING_01-0000334594 – 01-0000334660.
[17] CLJ_WATERMODELING_01-0000334634.
[18] Detailed analyses and discussions of the water buffalo types used at Camp Lejeune and the filling process during the historical period of VOC exposure are provided in Appendix A to Dr. Sabatini's report and are not discussed in this report.

As Sabatini (2025) states in his report, "As such, I conclude that Hennet (2024) overestimated the potential losses in the water treatment processes. The actual loss values, in my opinion, were less than 6 to 12% for the VOCs of interest versus 15% to 32% as suggested by Hennet (2024)."

For the mobile water units (water buffaloes), Sabatini (2005, Section 5.3) concludes:

"Hennet's calculations overestimated the VOC losses during filling of the water buffaloes; he estimated 41% to 61% for the range of VOCs while I estimate much lower (15 to 22% through filler pipe/strainer and 4.2 to 6.7% through the manhole, including daily use not accounted for by Hennet) for the range of VOCs, I thus conclude that the water buffalo water was only mildly to moderately lower in VOCs, not substantially lower as Hennet (2024) states."

Sabatini's (2025), Table 5.7, provided in this report as Table 4.8, lists a summary of the overall VOC losses in water buffaloes based on Hennet's (2024) calculations and Sabatini's (2025) estimates for filling the water buffaloes from the filler tank and from the manhole cover.

**Table 4.8.** From Sabatini (2025), Table 5.7.

[My estimate refers to Sabatini (2025)]

| Source | TCE (%) | PCE (%) | 1,2-tDCE (%) | VC (%) | Bz (%) |
|---|---|---|---|---|---|
| (1) Hennet – filler pipe/strainer - Overall loss (see Table 5-6, Row 2)) | 41 | 44 | 54 | 61 | 45 |
| (2) My estimate – filler pipe/strainer overall filling losses (see Table 5.6, Row 3) | 14 | 15 | 18 | 20 | 15 |
| (3) My estimate – filled by standpipe through manhole cover – 5.6% of Hennet's Row 1 values in Table 5.6 | 3.0 | 3.2 | 4.0 | 4.5 | 3.3 |
| (4) My estimated losses during daily use of water buffaloes (Exhibit C.4) | 1.2 | 1.0 | 1.9 | 2.2 | 1.2 |
| (5) My estimate – overall losses – filler pipe strainer plus daily use (Row 2+4) | 15 | 16 | 20 | 22 | 16 |
| (6) My estimate – overall losses – standpipe filling through manhole plus daily use (Row 3+4) | 4.2 | 4.2 | 5.9 | 6.7 | 4.5 |

In summary, the detailed calculations of both AH Environmental Consultants (2004) and Dr. Sabatini (2025) demonstrate that the DOJ expert (RH) has vastly overestimated alleged VOC losses

during storage, treatment and distribution. In addition, RH's assertion that ATSDR did not account for such VOC losses (Hennet 2004, Opinion 10, p. 5-36) is incorrect. First, ATSDR analyzed sampling data of water from both pretreatment and post treatment. Table 4.9 lists sampling data for the HPWTP including sampling status (treated or untreated) where known. Out of the 20 water samples taken at the HPWTP, 7 were from treated (finished) water, 4 were from untreated, and 9 had unknown treatment status. Furthermore, for TCE samples taken on 7/27/1982, results show that the concentration for untreated water was 19 µg/L and for treated water was 21 µg/L. Allowing for measurement error, these data indicate no losses to volatilization of TCE during the treatment process.

**Table 4.9.** Treatment status of water samples from the Hadnot Point water treatment plant

| Date | Measured in µg/L | Treatment Status | Reference or Citation | Bates Identification |
|---|---|---|---|---|
| **Tetrachloroethylene (PCE)** | | | | |
| 5/27/1982 | 15 | Unknown | CLW 0606 | CLJA_USMCGEN_0000003332 |
| 7/27/1982 | 100 | Unknown | CLW 0606 | CLJA_USMCGEN_0000003332 |
| 12/4/1984 | 3.9J | Treated | CLW 5632 | CLJA_USMCGEN_0000009913 |
| 2/5/1985 | 7.5J | Treated | CLW 5509 | CLJA_USMCGEN_0000005529 |
| **Trichloroethylene (TCE)** | | | | |
| 5/27/1982 | 1400 | Unknown | CLW 0606 | CLJA_USMCGEN_0000003332 |
| 7/27/1982 | 19 | Untreated | CLW 0606 | CLJA_USMCGEN_0000003332 |
| 7/27/1982 | 21 | Treated | CLW 0606 | CLJA_USMCGEN_0000003332 |
| 12/4/1984 | 46 | Untreated | CLW 5632 | CLJA_USMCGEN_0000009914 |
| 12/4/1984 | 200 | Treated | CLW 5632 | CLJA_USMCGEN_0000009913 |
| 12/12/1984 | 2.3J | Treated | CLW 5644 | CLJA_USMCGEN_0000003979 |
| 12/19/1984 | 1.2 | Untreated | CLW 4546 | ATSDR_WATERMODELING_01-0000886764 |
| 2/5/1985 | 429 | Unknown | CLW 5509 | CLJA_USMCGEN_0000005529 |
| ***Trans*-1,2 Dichloroethylene (1.2-tDCE)** | | | | |
| 12/4/1984 | 83 | Treated | CLW 5632 | CLJA_USMCGEN_0000009913 |
| 12/4/1984 | 15 | Untreated | CLW 5632 | CLJA_USMCGEN_0000009914 |
| 12/12/1984 | 2.3J | Treated | CLW 4546 | ATSDR_WATERMODELING_01-0000886764 |
| 2/5/1985 | 150 | Unknown | CLW 5509 | CLJA_USMCGEN_0000005529 |
| **Vinyl Chloride (VC)** | | | | |
| 2/5/1985 | 2.9J | Unknown | CLW 5509 | CLJA_USMCGEN_0000005529 |
| **Benzene** | | | | |
| 11/19/1985 | 2500 | Unknown | CLW 1355 | CLJA_USMCGEN_0000007001 |
| 12/10/1985 | 3 | Unknown | CLW 1355 | CLJA_USMCGEN_0000007001 |
| 12/18/1985 | 1 | Unknown | CLW 1355 | CLJA_USMCGEN_0000007001 |
| Note 1: J = Estimated | | | | |
| Note 2: Data from Faye et al. (2010, Tables C11 and C12); Maslia et al. (2013, Table A18) | | | | |

At the TTWTP a triplet of measured water samples obtained on 7/28/1982 show results as follows: 104 μg/L in "finished water", 76 μg/L in "untreated water", and 82 μg/L in "treated water",[19] indicating no PCE loss to volatilization during the treatment process.

Additionally, in contrast to RH's contention that ATSDR ignored or did not account for VOC losses during storage, treatment and distribution, this issue (including the results of the AH Environmental Consultants report [2004]) was discussed in detail with the Expert Panels convened by ATSDR in 2005 and 2009 (Maslia, 2005, 2009). During the first day of the meeting in 2005 (March 28) panel members Dr. Tom Walski (Bentley Systems) and Dr. Peter Pommerenk (AH Consultants and consultant to the USMC) responded to a question from panel member Dr. James Uber (University of Cincinnati) to Morris Maslia about whether there are any potential chemical biological processes taking place in the distribution system.[20] Additional discussion occurred during the 2009 Expert Panel meeting (April 30) by Dr. Pommerenk.[21] Excerpts from the verbatim transcript are provided in Appendix **A**. The consensus was that there was negligible volatilization (at most 10% from the spiractors). "So although we said it's probably negligible, and I agree with Tom's number here. At 90 percent, what's going in is coming out on the other end." (see Appendix **A**). In light of the conclusions of AH Environmental Consultants (2004) and the recommendations of its Expert Panels, ATSDR made the decision to consider any potential VOC losses from storage, treatment and distribution as negligible.

Additional support for this decision comes from the eight-day period, January 28-February 8, 1984, when the HBWTP was shut down and not operating. At that time, the HPWTP provided finished (and contaminated) water to the HB water-distribution system by operating booster pump 742 and opening the Marston Pavilion valve (Maslia et al. 2013, p. A2, p. A65). Water samples taken on January 31, 1985, indicated TCE concentrations ranged from 24.1 mg/L to 1,148.4 mg/L, with a sample taken at the HPWTP (Building 20, treatment status unknown) having a TCE concentration of 900 mg/L.[22] Although not a direct indication of negligible TCE loss to volatilization during the treatment process at the HPWTP, these samples, taken from the HB water-distribution system (supplied by contaminated HPWTP finished water), suggest that any loss of VOCs owing to volatilization in the treatment process were consistent with the advice of the ATSDR Expert Panels (Appendix A) and the findings of AH Environmental Consultants (2004) and Sabatini (2025).

## 4.4 Derivation and Computation of Sorption Parameter Values

DOJ experts AS and RH posit that selected geochemical parameters (sorption parameters) were incorrect (Spiliotopoulos 2024, Section 4.1.2.2) and that ATSDR failed to consider site data to parameterize models (Hennet 2024, Opinion 12). Both opinions are incorrect. A detailed response pertinent to sorption parameters for the TT analyses is presented below and is also provided in Konikow (2025).

ATSDR applied and calibrated the MT3DMS model to evaluate the occurrence and migration of contaminated groundwater at TT. MT3DMS, a multi-species, mass transport model, is a widely

[19] CLJA_USMCGEN_0000009869.
[20] CLJA_WATERMODELING_01-0000942379 – 01_0000942381.
[21] CLJA_WATERMODELING_02-0001111469 – 01-0001111472.
[22] CLW 4552, CLJA_WATERMODELING_09-0000424939.

used public domain model code used to simulate the migration of solutes/contaminants in groundwater (Zheng and Wang, 1996; Zheng 2010).

To account for sorption, MT3DMS computes a retardation factor (R), which, in turn, requires the selection of an equilibrium isotherm. A linear equilibrium isotherm was selected for the TT MT3DMS model. The retardation factor and the linear equilibrium isotherm are related by the following formula:

$$R_f = 1 + (K_D \times \rho_b)/n_e \qquad (1)$$

where

$R_f$ = the retardation factor, dimensionless

$K_D$ = the distribution coefficient, in $L^3/M$

$\rho_b$ = the bulk density, in $M/L^3$

$n_e$ = the effective porosity of the porous media, dimensionless

(M=mass; L=length))

The $K_D$ is a parameter that accounts for adsorption to mineral and/or organic material in the soil. While a chemical is adsorbed to soil, it does not move with the groundwater, so that the chemical migrates through the subsurface more slowly than the average groundwater velocity. This slower chemical velocity is quantified by the retardation factor, which is the ratio of the average water velocity to the chemical velocity. A $R_f$ of 2, for example, indicates that the chemical moves at half the average groundwater velocity because of adsorption.

As seen in Equation (1) above, the $R_f$ depends on the product of the $\rho_b$ (bulk density) and $K_D$. Different combinations of $K_D$ and $\rho_b$ (and effective porosity, $n_e$) can thus result in the same retardation factor and will calibrate a model equally well. For example, a $K_D$ value of 0.5 and a $\rho_b$ of 2.0 would result in the same $R_f$ as a $K_D$ value of 0.6 and a $\rho_b$ of 1.67, because 0.5 x 2.0 = 1, and 0.6 x 1.67 also equal 1. Because contaminant movement in groundwater depends on the $R_f$, an erroneous $\rho_b$ and an erroneous $K_D$ can compensate for each other because they are multiplied together, resulting in a $R_f$ that best calibrates a model even though the individual $\rho_b$ and $K_D$ are not correct or are unknown.

During model calibration, the $\rho_b$ and $n_e$ were held constant while $K_D$ was varied (i.e., $K_D$ is a model calibration parameter). This approach was largely dictated not only by the several divergent methodologies used to determine $K_D$, generally batch and column experiments, but also by the high uncertainty and variability of reported $K_D$ values, regardless of methodology. The EPA in its Volume II of *Understanding Variation in Partition Coefficient, $K_D$, Values* (USEPA 1999, Volume II, p 3.4) states *"The $K_D$ values reported in the literature for any given contaminant may vary by as much as 6 orders of magnitude."* Similarly, Spiliotopoulos (2024, Appendix A) tabulates site-specific $K_D$ values for total organic carbon (TOC) at Camp Lejeune that vary by at least 3 orders of magnitude.

The initial $K_D$ values used during calibration of the Tarawa Terrace MT3DMS model were derived largely from Hoffman (1995) and were determined from column experiments performed on sediment samples collected from 240 boreholes drilled into a plume contaminated with PCE and trichloroethylene (TCE). Borehole samples were composed largely of sand, silt and gravel, similar to the subsurface at Tarawa Terrace. Borehole sediments also contained low concentrations of total organic carbon. The $K_D$ values for PCE reported by Hoffman (1995) related to silt and sand ranged from about 0.20 to 0.80 milliliters per gram (ml/g) and averaged 0.40 and 0.39 ml/g, respectively. The $K_D$ determined from the completion of MT3DMS model calibration was 0.14 ml/g and was somewhat less than values determined by Hoffman (1995). The retardation factor ($R_f$) determined from MT3DMS calibration was 2.93 (Faye 2008) and is very close to other values reported in the literature for similar geologic materials (e.g., Rogers 1992)

In his report, Konikow (2025) also discusses Hennet's (2024, Opinion 11) criticism of ATSDR for having failed to consider available site-specific data for $f_{oc}$ (fraction of organic content) to estimate $K_D$ . However, as Konikow (2025) points out:

> "Rogers (1992, p. 51) in discussing the $K_d$ parameter says "Numerous researchers have used theoretical methods correlating the organic carbon content (OCC) of the subsurface material and the $K_d$ (Karickhoff, 1984). Others have used the partitioning between octanol and water to predict the $K_d$ (Kenega, 1980). **These methods are not considered appropriate where the OCC is less than approximately 0.1%**." OCC is equivalent to TOC, and 0.1% is equivalent to a fraction or 0.001. Hennet's Expert report lists (Exhibit 3-2, and p. D-11 to D-12) 21 Camp Lejeune samples where $f_{oc}$ is given. The median value is 0.0013, barely above the indicated limit, and 9 samples (43% of the samples) have values <0.001, indicating that the use of $f_{oc}$ to estimate $K_d$ is not appropriate. If ATSDR had used this approach, it would have introduced additional errors and sources of uncertainty."

Following calibration of the Tarawa Terrace MT3DMS model and the subsequent peer reviews and publication of model results, a member of the 2009 ATSDR Expert Panel (April 29–30) indicated in his pre-meeting comments on published ATSDR analyses that a wet rather than a correct dry bulk density was input to MT3DMS (Maslia 2009, p. 117)[23] . Because transport models depend on the retardation factor which, in turn, is determined by the product of $K_D$ and bulk density (Equation 1), the erroneously high bulk density implied that the value of $K_D$ was too low. Accordingly, project staff resumed calibration of the Tarawa Terrace MT3DMS model by assigning a corrected bulk density ($\rho_b$) of 1.65 g/ml (46,725 g/ft$^3$) to MT3DMS and testing simulated results by varying $K_D$ values ranging from 0.20 to 0.40 g/ml (Hoffman, 1995). Test simulations were determined to be relatively insensitive to changes in $K_D$; however, $K_D$ values near the low part of the range (0.20 ml/g) were determined most comparable to best calibration. Finally, a corrected TT MT3DMS model was achieved using a dry bulk density of 1.65 g/ml and applying Equation (1) to compute a paired $K_D$ value of 0.23 ml/g, thus maintaining the calibrated retardation factor (R) of 2.93 and model results as published (Faye 2008). Thus, the initial erroneous bulk density value had no effect on the final model calibration, which depended only on the product of $K_D$ and $\rho_b$ through the $R_f$. Note, the $K_D$ value of 0.23 ml/g input to the corrected MT3DMS model is within the lower part of the range for this value applicable for PCE published by Hoffman (1995).

[23] CLJA_UST02-0000059851

By comparison, and as Dr. Konikow discusses in his report (Konikow 2025), "Kret et al. (2015) studied a Quaternary sandy aquifer to estimate sorption coefficients for PCE fate and transport modeling. They estimated $K_D$ from both batch and column experiments and concluded that reasonable values for $R_f$ for PCE are typically between 1.1 and 3.6." The ATSDR calibrated value of 2.93 is very near the mean of this range. As Dr. Konikow points out, Rogers (1992) also supports the ATSDR's calibrated value. There, a groundwater transport model was developed for the Lawrence Livermore National Laboratory (LLNL) site in California, which includes "several hundred feet of complexly interbedded, unconsolidated alluvial sediments" with an upper boundary represented by an unconfined water table condition. Their calibration and history matching resulted in reasonable matches for $R_f$ values between 1.0 and 3.0, with their conclusion that "a spatially averaged retardation factor of approximately 3 is recommended...".

The values used by Spiliotopoulos (2024) for $\rho_b$ (1.65 g/cm$^3$) and for $K_D$ (0.30 and 0.40 mL/g) result in $R_f$ values of 3.48 and 4.30, respectively, which are on the high-side of many literature-reported values and the calibrated value of 2.93. Using the Spiliotopoulos (2024) values in effect slows the movement of PCE through the aquifer and increases the time at which PCE-contaminated groundwater arrives at water-supply wells and the TTWTP (Spiliotopoulos 2024, Figures 7 and 8). Spiliotopoulos (2024, p. 37-38) also posits a $R_f$ of 6.44 but provides no supporting evidence or reference for this value. What Spiliotopoulos has done is in essence conduct a sensitivity analysis using $R_f$ as the varied parameter. However, Dr. Spiliotopoulos did not adjust $\rho_b$ and/or $n_e$ to best calibrate the model using his higher $K_D$ values. The higher $R_f$ based on Dr. Spiliotopoulos' larger $K_D$ values do not calibrate the model as well as the $R_f$ used by the ATSDR team. In addition, as shown in Faye (2008), the calibrated TT fate and transport model is relatively insensitive to changes in $R_f$ ($K_D$ being the varied parameter in $R_f$). Instead, the model is substantially more sensitive to changes in mass loading rate and pumping variation.

ATSDR documented the above modifications to $\rho_b$ and $K_D$ in an email (and attachment) dated February 28, 2011.[24] ATSDR had planned to issue an errata pertinent to the updated $\rho_b$ (dry) and $K_D$ as a forthcoming TT Chapter K report (mentioned in the Foreword Section of all published TT reports). Agency budgetary and project completion time constraints prevented the errata and any supplemental information from being formally published and publicly released as the TT Chapter K report.

To test the effect that variations in $R_f$ have on PCE concentrations at water-supply well TT-26 and the TTWTP, a series of simulations were conducted wherein the calibrated retardation factor of 2.93 (Faye 2008) was increased to 3.48 and 4.3 as speculated by AS and RH. As these sensitivity analyses (variations in retardation factor) demonstrate in Figure 4.6 below, the model is insensitive to changes (increases) in the retardation factor. After 1960, simulated results show PCE concentrations at TT-26 and at the TTWTP more than the MCL for PCE of 5 µg/L.

[24] ATSDR_WATERMODELING_01-0000887322 and 01-0000887324.

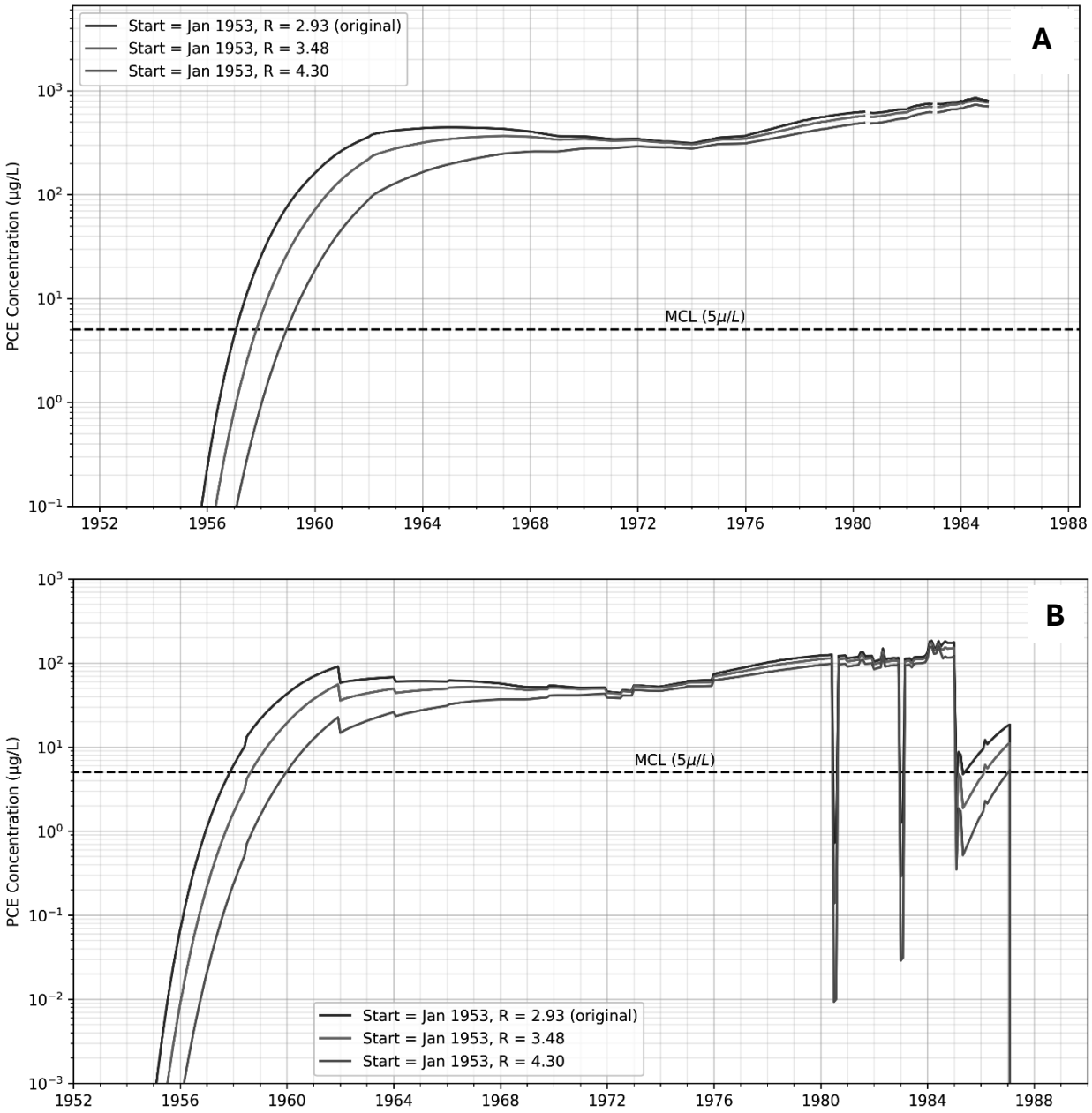



**Figure 4.6.** Comparison of tetrachloroethylene (PCE) reconstructed concentrations for variations in retardation factor for: (A) water-supply well TT-26, and (B) Tarawa Terrace water treatment plant (TTWTP). Note: R = 2.93 is calibrated retardation factor from Faye (2008).

## 4.5 Model Calibration and Uncertainty Analysis

Rebuttal responses to criticisms related to model calibration and uncertainty analysis raised by AS (2024) and RH (2024) are provided below.

### *4.5.1 Model Calibration*

In Opinion 1, AS posits that the ATSDR models were not "calibrated to observed data for the first 30 years of simulation" (Spiliotopoulos, 2024, p. 30). However, it is crucial to understand that concentration data for that period do not exist, which is exactly why reconstruction was performed. The ATSDR models were designed to estimate those concentrations in a state-of-the-art manner, consistent with principles of groundwater flow and fate and transport processes. These models did not generate arbitrary random numbers; rather, the results are reasonable and realistic. The presence of error bands or uncertainty ranges around the estimates is to be expected and is readily acknowledged (Konikow 2025).

In his Opinion 2, AS (2024, p. 33) reproduces ATSDR's Figure F16 (Faye 2008)[25] of TT historical reconstruction results at water supply well TT-26, and states that ASTDR's work resulted in "biased high estimates." As Dr. Konikow notes, Figure F16 (provided in this report as Figure 4.4 in Section 4.2.1) illustrates the opposite and instead "shows 5 measured PCE concentrations in samples from well TT-26 collected within weeks of each other in early 1985. Over this relatively short time span, the concentrations varied greatly (bracketed between a high of 1,580 μg/L on 01/16/1985 to a low of 3.8 μg/L on 02/12/1985)—a rate of change that cannot be replicated in a model using monthly time steps. Most importantly, the plot shows that the model results fell almost exactly at the midpoint of the range of observed values (about 800 ug/L)—countering the claim of being biased high." (Konikow 2025)

The plot shown in Spiliotopoulos (2024, Figure 13) is discussed in AS's Section 4.1.3.2 (p. 50, paragraph 8). It is noted that the results of the calibrated model, as AS states, "sits at the upper bound of the retardation-factor uncertainty range." However, as Dr. Konikow notes and I agree, "that is not true for the majority of the simulation period. It is close to the middle of the range during the period of 1962 through the end (around Dec. 1987). And prior to 1962, it still lies within the uncertainty bounds, which is acceptable and not indicative of bias." (Konikow 2025). Furthermore, calibrated model results do not always lie at the center of the uncertainty band because the response of the model to some parameters can be non-linear, and a model can be insensitive to changes in a model parameter at either high or low extremes.

For water-supply well HP-651, ATSDR applied the Linear Control Model (LCM) to reconstruct concentrations of TCE, PCE, and PCE degradation products (TCE, 1,2-tDCE, and VC). In Opinion 16 (Spiliotopoulos 2024, Section 4.2.4, p. 82-83) AS argues that the model for volatile organic compound (VOC) degradation products was based on limited data, and ATSDR's historical reconstruction prior to December 1984 "cannot be verified."

[25] Figure 4.4 of this report, previously discussed in Section 4.2.1

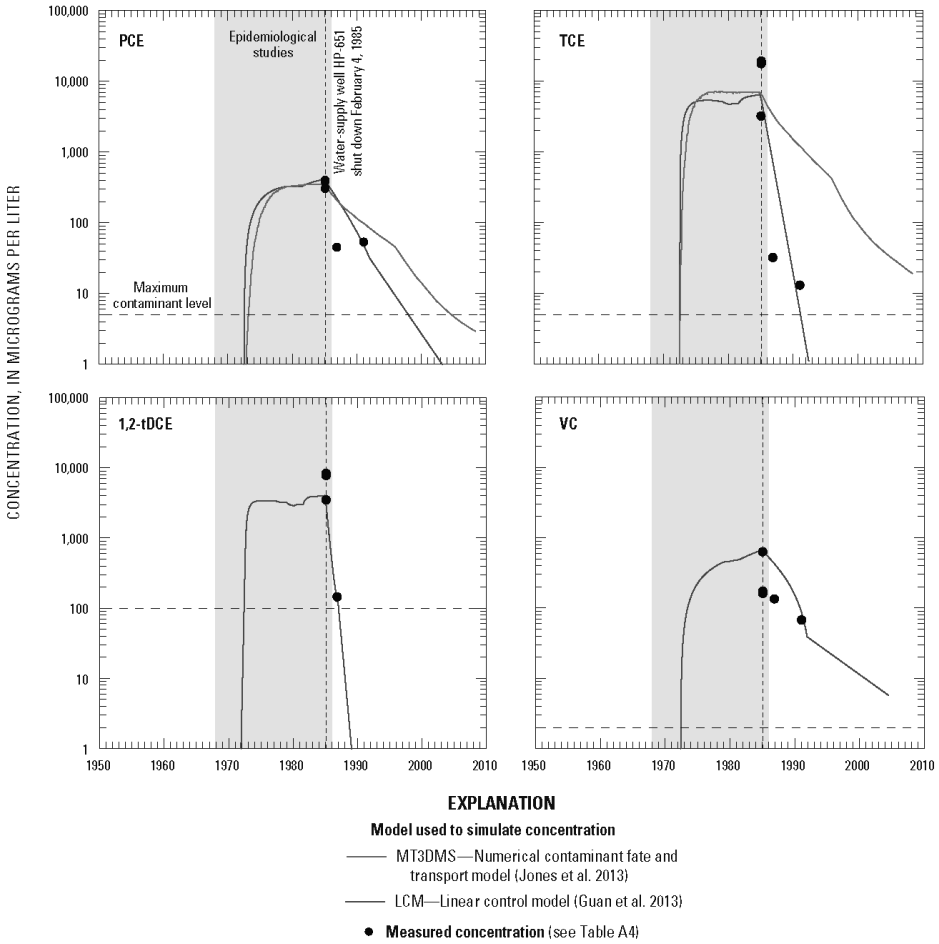



**Figure A25.** Reconstructed (simulated) concentrations of tetrachloroethylene (PCE), trichloroethylene (TCE), *trans*-1,2-dichloroethylene (1,2-tDCE), and vinyl chloride (VC) at water-supply well HP-651 using numerical (MT3DMS) and linear control methodology (TechControl) models, Hadnot Point–Holcomb Boulevard study area, U.S. Marine Corps Base Camp Lejeune, North Carolina. (See Figure A14 for well location.)

**Figure 4.7.** From Maslia et al. (2013), Figure A25.

In section 4.2.4 (p. 82-83), AS states that "As illustrated in Figure 33 [ATSDR Figure A25], the historical reconstruction prior to 1985 cannot be verified, due to lack of observed data for the period." As I have stated previously, and as Dr. Konikow also opines, this is the reason why a simulation model was needed and was developed. For the four contaminants shown in Figure 4.7 the agreement between simulated values and observed data where data was available is excellent in all four plots. If anything, the model results for TCE and 1,2-tDCE are below the peak sampled data points, again suggesting that the model is under-predicting these concentrations. "This close agreement when observations are available builds confidence in the reliability of the model and its predictions," including for the historical reconstruction results for times prior to 1985. (Konikow 2025). The objective was to use a technically sound model that would be calibrated to available data in and after 1985, and to estimate the values during the 15 or so years prior to that calibration period to inform the epidemiological studies.

The objective was to use a technically sound model that could be calibrated to available data in and after 1985 and to estimate the values during the 15 or so years prior to that calibration period to inform the epidemiological studies. As Konikow (2025) observes, for PCE and TCE, the fit with the LCM model was slightly better than with the MT3DMS model, which was not designed to simulate degradation products. The excellent quality of the fit is illustrated in Figure 4.7.

*4.5.2 Uncertainty Analysis*

ATSDR is transparent in its analyses and publications that uncertainty exists about conditions during both the historical reconstruction and calibration period. Results include assessments of uncertainty (Maslia et al. 2007, p. A52; Maslia et al. 2013, p. A92), including an entire Chapter Report (Chapter I) in the Tarawa Terrace report series (Maslia et al. 2009). In fact, the EPA in its Superfund Exposure Assessment Manual (1988, Section 4.4), discusses "Approaches for Dealing with Uncertainty" and the use and application of sensitivity analysis and Monte-Carlo (MC) simulation.

In his Opinion 8 (Section 4.1.3.2, p. 50, paragraph 3), AS criticizes the Monte Carlo (MC) simulation approach used by ATSDR "… because ATSDR implemented a 'probability distribution function' … to describe how values closer to the mean value of the range are more probable than those away from the mean." This is not a problem or issue as posited by AS, but rather, this is one of several accepted methods "for random sampling of parameter values for a MC analysis when information or theory indicates that a parameter has a statistically normal or log-normal distribution." (Konikow 2025). Tung and Yen (2005, Section 6.1, p. 213) state, ". . . due to the complexity of physical systems and mathematical functions, derivation of the exact solution for the probabilistic characteristics of the system response is difficult, if not impossible. In such cases, Monte Carlo simulation is a viable tool to provide numerical estimations of the stochastic features of the system response." Additionally, Bobba et al. (1995) state, "A Monte Carlo model is basically constituted by a deterministic portion (the deterministic model), of variable complexity, that is used to represent mathematically the system under observation, and a probabilistic portion, constituted by the probability distributions of both the parameters of the deterministic model (if available) and the observed variables (conditions)."

In Section 4, Basis for Opinions (p. 29), AS quotes Dr. T.P. Clement's comments about ATSDR's uncertainty analysis (Clement, 2011): "The figure also shows that closer to the initial starting point, the confidence band is almost 100%, implying that our knowledge of initial conditions, initial source loadings, and initial stresses is almost exact." Contrary to Dr. Clement's observations, both Dr. Konikow and I are confident that there was no (or negligible) PCE in the groundwater from ABC One-Hour Cleaners (or any other source) prior to January 1953, and likely very little for several months thereafter. (see Konikow 2025)

Additionally, uncertainty analysis is a process associated with simulations (Bobb et al. 1995). One cannot produce an uncertainty band at the start of simulations. If there is no simulation, there is no uncertainty. Thus, uncertainty at the start is zero when there is no simulation, and it expands as the computation process progresses forward. ATSDR did not consider uncertainty at the start of our source characterization. Instead, ATSDR assumed that prior to the start of operations at ABC One-Hour Cleaners, the concentration of PCE in groundwater was perfectly known, and it was 0 µg/L.

Another point to be made is that the graph in question in AS's critique (Maslia et al. 2007, Figure A26)[26] is the concentration time history at the TTWTP. This plot was created using a mass balance equation:

$$C_{TTWTP} = \frac{\sum_{i=1}^{NW} C_i Q_i}{\sum_{i=1}^{NW} Q_i} \quad (2)$$

where $C_{TTWTP}$ is the concentration of water at the TTWTP for a specific month, *NW* is the number of operating wells for a specific month, $C_i$ is the concentration of well *i* for a specific month, and $Q_i$ is the pumping rate of well *i* for a specific month, featuring water pumped from a variety of supply wells. Most of the PCE comes from Well TT-26. All these wells are down-gradient from the source at ABC One-Hour Cleaners. While the fringe of the plume with very low concentrations arrives fairly soon, it takes several years for the bulk of the plume to arrive. Consequently, the parameter variations in the model instances within the MC simulation will lead to variations in the PCE plume. However, these variations do not manifest at the TTWTP for several years. Therefore, a narrow band early in the TTWTP timeline is expected. Even with the application of source concentration variations by ATSDR, the uncertainty band at the TTWTP would remain relatively narrow in the initial years.

In summary, ATSDR used and applied an accepted methodology for conducting an uncertainty analysis—Monte Carlo simulation using probability distribution functions. This method is described in several references including EPA's Superfund Exposure Assessment Manual (1988, Section 4.4), Tung and Yen (2005), and Zheng and Bennet (2002, p. 353). ATSDR provided specific details on how it carried out its uncertainty analysis with respect to both groundwater-flow model and contaminant fate and transport model parameters (and assigned probability distributions) in the Tarawa Terrace Chapter I report (Maslia et al. 2009, p. I30).[27] I agree with Dr. Konikow's assessment of the ATSDR uncertainty analysis where he states:

> "I do not see a problem here as this is an option within standard practice for random sampling of parameter values for a MC analysis when information or theory indicates that a parameter has a statistically normal or log-normal distribution. Zheng & Bennett (2002, p. 353) say "The Monte Carlo method is by far the most commonly used method for analysis of uncertainty associated with complex numerical methods." They further state (p. 356) "The heart of the Monte Carlo method is the generation of multiple realizations (or samples) of input parameters that are considered to be random variables. Each random variable is assumed to follow a certain probabilistic model characterized by its probability density function (PDF). The probability distributions commonly used in hydrogeologic studies include *normal*, *lognormal*, *exponential*, *uniform*, *triangular*, *Poisson*, and *beta* distributions." It is worth noting that when this book was published, co-author Bennett was an employee of SSP&A and first author Zheng was a former employee and affiliate of SSP&A" (Konikow 2025).

[26] ATSDR_WATERMODELING_01-0000909018.
[27] CLJA_WATERMODELING_01-0000772752.

## 4.6 Post-Audit of the ATSDR Tarawa Terrace Models

Jones and Davis (2024) conducted a post-audit of the Tarawa Terrace groundwater flow and contaminant fate and transport models by extending the TT simulations from 1995–2008 using additional ABC One-Hour Cleaners site data that had become available after ATSDR published results for TT in July 2007 (Maslia et al. 2007). Jones and Davis (2024, Executive Summary) state,

"In summary, this post-audit found that the original Tarawa Terrace groundwater flow and transport models were developed using sound methodology and continue to provide reliable insights into the migration of PCE contamination. Despite the inherent challenges in simulating complex subsurface conditions and dealing with incomplete data, the model effectively simulates long-term trends in contaminant migration. Based on this post-audit, we can find no significant evidence that would invalidate the analyses performed by ATSDR with the original model."

In his Opinion 13, AS states "Prior to offering opinions as experts in this litigation, Mr. Maslia and Dr. Aral should have used the data that Dr. Jones and Mr. Davis used to conduct the Tarawa Terrace Flow and Transport Model Post-Audit to update the calibration of the dose reconstruction groundwater model." (Spiliotopoulos 2024, p. 3).

There are few post-audits for calibrated contaminant fate and transport models to compare approaches with the Tarawa Terrace post-audit (e.g., Person and Konikow, 1986). Most post-audits have been conducted for calibrated groundwater-flow models. The literature on post-audits of groundwater and hydrological model predictions remains limited (Kidmose et al., 2023). Anderson and Woessner (1992) reviewed five post-audits from the 1990s and concluded that original model failures were primarily due to errors in conceptual models or defining future stress (such as pumping).

In reviewing the literature on post-audits (Alley and Emery, 1986; Konikow, 1986; Kidmose et al., 2023), the outcomes are generally used to identify where additional data are required and to enhance the understanding of hydrogeology and transport phenomena (conceptual model improvement). Post-audits are not necessarily conducted, as AS posits in his Opinion 13, to re-calibrate or update a calibrated model based on additional (and future) data.

Alley and Emery (1986) provide general perspectives on groundwater modeling gained from post-audit analysis, noting that "post-audit analysis of groundwater modeling studies is a valuable exercise, particularly considering that historically groundwater modeling studies have not included a strong model verification stage." In conducting a post-audit of a solute-transport model, Person and Konikow (1986) concluded that "the nature of the errors indicated a need to incorporate an additional process into the model (salt transport through the unsaturated zone)."

In extending ATSDR's original TT groundwater-flow and contaminant fate and transport model, Jones and Davis used additional site data such as recovery-well locations and operations, additional monitor-well locations, changes in recharge during the post-audit period (1995–2008), and observed PCE concentration data. Re-calibration of the TT models was not an objective and would not have yielded substantive changes to the original ATSDR results and conclusions because no conceptual model flaws (groundwater flow and contaminate fate and transport) were noted. Thus, AS's Opinion 13 is a moot point.

Finally, it needs to be noted that after the publication of ATSDR's TT Models in 2007 (Maslia et al. 2007)[28], ATSDR modeling staff recognized the value of conducting a post-audit of the TT models and they communicated this to ATSDR Senior Management and representatives of EPA Reion IV. The extension of the TT models from 1994–2007 would have required additional agency resources, modeling time, and coordination with the EPA (Region IV) to obtain all the additional data required for the post-audit.[29]

## 4.7 Graphing and Visualization of Data and Model Results

Konikow (2025) discusses AS's position that the presentation of results of the uncertainty analysis conducted by ATSDR for the TT model is "visually misleading" (Spiliotopoulos, 2024, Section 4.1.3.1). I agree with Dr. Konikow. The cited reason is that "they used a logarithmic scale, which visually compresses the uncertainty range around their calibrated model [results]." However, as Dr. Konikow notes, using a logarithmic scale is an accepted and common approach in engineering and scientific studies, and it is not considered misleading by scientists and engineers. Concentration data often vary over many orders of magnitude, which is why it is frequently presented using a log scale.

Furthermore, AS notes that the plot ranges over six orders of magnitude on the axis for PCE concentration, yet the width of the uncertainty bands does not span an equally wide range. Again, I concur with Dr. Konikow: "When values span such a large range, it is normal and standard to use a log plot. Using just an arithmetic scale would effectively hide all the changes in the lower part of the scale." (Konikow 2025)

AS also states (p. 46, para. 4) that "the difference between the high and low values in his Figure 11 (Maslia et al., 2009, Figure I29) is not significant enough to justify the use of a logarithmic scale." However, because the observed values span more than two orders of magnitude (excluding non-detects) and the simulated values span more than five orders of magnitude, plotting these data and results using a logarithmic scale is reasonable and informative. It is the only way to portray the early time results of the simulation in the same graphic (Konikow 2025).

## 4.8 Non-Degraded and Degraded PCE Historical Reconstructions

In his Summary of Opinions 10 and 11, Spiliotopoulos (2024, Section 4.1.4, p. 58) states,

"ATSDR applied two different numerical codes for modeling dose reconstruction. The results of the two codes are not in agreement. This is due, in part, to inconsistent application of contaminant source terms in the two models. Neither ATSDR, Mr. Maslia, nor Dr. Aral, provided sufficient scientific justification for selecting the higher estimated monthly contaminant concentrations for their dose reconstruction".

ATSDR has been open and transparent about the application of different models to reconstruct historical concentrations of PCE and PCE degradation products (TCE, 1,2-tDCE, and VC). All models are approximations of the real world and site-specific conditions, and modeling objectives determine the simplicity or complexity of a model to be used. Models that include different

[28] Results of the Tarawa Terrace models were publicly release during July 2007.
[29] CLJA_WATERMODELING_01-0000840256 – 01-0000840257; CLJA_WATERMODELING_01-0000070593, 01-0000070594, 01-0000065999, 01-0000021042, 01-0000837170 – 01-0000837172; CLJA_WATERMODELLING_01-0000837170 – 01-0000837171.

physical processes will naturally produce different results. This is an accepted modeling approach practiced by groundwater modelers. In the TT Chapter A report, Summary and Conclusions section (Maslia et al. 2007, p. A70)[30], both the non-degraded analysis for PCE (MODFLOW/MTDMS) and the degraded analysis for PCE (TechFlowMP) are discussed and summarized. ATSDR did not, as AS states "select[ing] the higher estimated monthly contaminant concentrations for their dose reconstruction" (Spiliotopoulos 2024). The water-modeling staff, being blinded to the epidemiological study through the entire water-modeling process, provided both the non-degraded (MODFLOW/MT3DMS) and degraded (TechFLOWMP) historical reconstruction results to the ATSDR health studies staff.

For the Tarawa Terrace historical reconstruction analysis, ATSDR applied a simplification of the biochemical processes such as volatilization and biodegradation taking place in the subsurface and used a model (MODFLOW/MT3DMS) that does not consider the biodegradation of PCE. ATSDR's philosophy was to "start simple" to try to understand aquifer and transport characteristics before attempting a more complex modeling effort that included biochemical processes such as volatilization and biodegradation of PCE. Again, this is a common and accepted modeling approach. Using a four-stage, hierarchical calibration approach, ATSDR achieved acceptable or better calibrations for predevelopment and transient groundwater flow, contaminant fate and transport (using MT3DMS), and the simple mixing model, as evidenced by the comparison of reconstructed and observed PCE concentrations at the TTWTP (Maslia et al., 2007, Figure A39; Fay 2008, Table F14 and Figure F27). Table 4.10 of this report, which is taken from Faye (2008, Table F14), shows that the model achieves acceptable matches between reconstructed and observed PCE concentrations at the TTWTP. In fact, even for observed non-detections, most reconstructed PCE concentrations are within the published detection limits (a non-detect does not imply zero concentration, but that the sampling and testing methodologies were not sensitive enough to detect concentrations). At the TTWTP storage tank (STT-39), the reconstructed PCE concentration was 176 μg/L compared to an observed PCE concentration of 215 μg/L—quite an impressive match for water-quality data—resulting in a geometric model bias of solely 1.5 (Maslia et al. 2007).[31]

[30] ATSDR_WATERMODELING_01-0000909028.
[31] ATSDR_WATERMODELING_01-0000908983 – 01-0000908984.

**Table 4.10.** From Faye (2008). Table F.14.

**Table F14.** Computed and observed tetrachloroethylene (PCE) concentrations in water samples collected at the Tarawa Terrace water treatment plant and calibration target range, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; TTWTP, Tarawa Terrace water treatment plant; ND, not detected]

| Date | PCE concentration, in µg/L | | Calibration target range, in µg/L |
|---|---|---|---|
| | Computed[1] | Observed | |
| [2]TTWTP Building TT-38 | | | |
| 5/27/1982 | 148 | 180 | 25–253 |
| 7/28/1982 | 112 | [3]104 | 33–329 |
| 7/28/1982 | 112 | [3]76 | 24–240 |
| 7/28/1982 | 112 | [3]82 | 26–259 |
| 2/5/1985 | 176 | [3,4]80 | 25–253 |
| 2/13/1985 | 3.6 | [5]ND | 0–10 |
| 2/19/1985 | 3.6 | [6]ND | 0–2 |
| 2/22/1985 | 3.6 | [5]ND | 0–10 |
| 3/11/1985 | 8.7 | [6]ND | 0–2 |
| 3/12/1985 | 8.7 | [6,7]6.6 | 2.1–21 |
| 3/12/1985 | 8.7 | [6,8]21.3 | 6.7–67 |
| 4/22/1985 | 8.1 | [5]1 | 0.3–3.2 |
| 4/23/1985 | 8.1 | [5]ND | 0–10 |
| 4/29/1985 | 8.1 | [5]3.7 | 1.2–11.7 |
| 5/15/1985 | 4.8 | [5]ND | 0–10 |
| 7/1/1985 | 5.5 | [5]ND | 0–10 |
| 7/8/1985 | 5.5 | [5]ND | 0–10 |
| 7/23/1985 | 5.5 | [5]ND | 0–10 |
| 7/31/1985 | 5.5 | [5]ND | 0–10 |
| 8/19/1985 | 6.0 | [5]ND | 0–10 |
| 9/11/1985 | 6.0 | [5]ND | 0–10 |
| 9/17/1985 | 6.0 | [5]ND | 0–10 |
| 9/24/1985 | 6.0 | [5]ND | 0–10 |
| 10/29/1985 | 6.0 | [5]ND | 0–10 |
| [2]TTWTP Tank STT-39 | | | |
| 2/11/1985 | 176 | [5]215 | 0–10 |

[1]Weighted-average computation

[2]See Plate 1, Chapter A report, for location (Maslia et al. 2007)

[3]Detection limit is unknown

[4]Analysis of tap water sample for Tarawa Terrace, address unknown

[5]Detection limit = 10 µg/L

[6]Detection limit = 2 µg/L

[7]Sample collected downstream of TTWTP reservoir after operating well TT-23 for 24 hours

[8]Sample collected upstream of TTWTP reservoir after operating well TT-23 for 22 hours

Next, ATSDR set out to apply a more complex and more sophisticated approximation of transport in the subsurface by using a model that would degrade PCE into TCE, 1,2-tDCE, and VC. As PCE migrates in the subsurface it continues to undergo transformation through physical and biochemical processes such as volatilization and biodegradation. To quantify historical concentrations of PCE degradation by-products observed in groundwater samples reported in Faye and Green, Jr. (2007, Figures E1-E14) and in soil (vapor phase) requires a model capable of simulating multiphase flow and multispecies mass transport such as TechFlowMP (Jang and Aral 2008). ATSDR summarized the second and more complex modeling approach in Maslia et al. (2007, p. A41) and described the detailed development and application of the TechFlowMP model at Tarawa Terrace in Jang and Aral (2008). MT3DMS and TechFlowMP use two entirely different numerical schemes. MT3DMS uses a finite difference scheme to approximate the partial differential equations of saturated groundwater flow and contaminant fate and transport. TechFlowMP uses a Galerkin finite-element based approach with upstream weighting and mass lumping of the time derivative matrices to simulate multiphase flow and multispecies mass transport in the vadose zone and saturated zone.

To simulate groundwater flow conditions at TT, TechflowMP applied the calibrated hydraulic and aquifer properties from MODFLOW, reported in Maslia et al. (2007, Table A11). A correlation between geologic and hydrologic units and the MODFLOW/MTD3DMS and TechflowMP models is provided in Jang and Aral (Table G1), with the main difference between the two modeling approaches being that TechFlowMP has 5 layers assigned to the variably saturated zone. For predevelopment and transient groundwater flow, TechFLowMP applied the same initial and boundary conditions and pumping schedules used in MODFLOW reported in Faye and Valenzuela (2007). Comparisons of simulated groundwater heads between the TechFlowMP and MODFLOW-96 models show good agreement, and comparisons between the two modeling approaches are shown in Jang and Aral (2008, Figure G3) for model layers 1, 3, and 5 (main water-bearing units). Slight differences between groundwater-head simulations obtained using the two models were most likely due to the different numerical methods used by the two models to approximate the equations of groundwater flow. Recall that TechFlowMP uses a finite-element technique, whereas MODFLOW uses a finite-difference technique.

As discussed above, the TechFlowMP model uses a more complex approach for simulating fate and transport of biochemical processes such as volatilization and biodegradation taking place in the subsurface. Additional chemical and physical properties required by TechFLowMP for PCE and its degradation products (TCE, 1,2-tDCE, and VC) are listed in Jang and Aral (2008, Table G2). Other fate and transport properties used for the MT3DMS simulation are listed in Maslia et al. (2007, Table A11). For the source concentration (PCE) at ABC One-Hour Cleaners, MT3DMS applied a mass-loading rate of 1,200 g/d (calibrated) to the saturated zone (MODFLW/MT3DMS model Layer 1). At ABC One-Hour Cleaners the altitude of the source ranges from 0 to 13 ft, which implies that in TechFlowMP the source PCE was partially released into the unsaturated zone and partially released into the saturated zone.

PCE concentrations simulated by TechFlowMP are less than those using MT3DMS (Maslia et al. 2007, Appendix A2; Expert Report of M. Maslia (2024, Appendix H1). This is partially due to TechFlowMP simulating (1) the release of PCE from the subsurface (groundwater) to the atmosphere, (2) PCE partitioning from the water phase to the soil vapor phase, and (3) the

placement of the contaminant source at the ABC One-Hour Cleaners site in the unsaturated and saturated zones**.** The difference between MT3DMS and TechFlowMP in simulating PCE transport at Tarawa Terrace and vicinity is (1) TechFlowMP considers PCE in both water and gas phases while MT3DMS considers PCE only in the water phase and (2) in MT3DMS the source concentration is released solely to the saturated zone. In MT3DMS simulations (Faye 2008), there is no PCE transfer into the gas phase. In TechFlowMP simulations, however, because PCE could be present in the gas phase, a portion of PCE in the gas phase could be released from the subsurface into the atmosphere through the ground surface. This results in the reduction of PCE concentration in the subsurface. The differences in simulated PCE concentrations at Tarawa Terrrace were clearly and transparently presented by ATSDR in Appendix A2 (Maslia et al. 2007) and in the Expert Report of Maslia (2024, Appendix H1). In these appendices, column 3 represents the MODFLOW/MT3DMS simulation of PCE whereas column 4 represents the TechFlowMP simulation of PCE (the same simple mixing model was applied to both simulation methods to obtain PCE concentrations at the TTWTP).

Based on the explanations given above for simulated PCE differences between MODFLOW/MT3DMS and TechFlowMP, it is not clear, evident, or apparent what issue Spiliotopoulos (2024, p. 55) has with simulating different concentrations of PCE using the two different modeling methods. The simulated PCE concentrations using MODFLOW/MT3DMS and TechFlowMP must be different and the PCE concentrations simulated by TechFlowMP should be (and were) less than those simulated by MODFLOW/MT3DMS.

## 4.9 Additional Topics

Below I briefly respond to several additional topics raised in the Expert reports of AS (Spiliotopoulos 2024) and RH (Hennet 2024).

### *4.9.1 Benzene Contamination*

RH posits in his Opinion 4 that the TTWTP was likely not contaminated with benzene (Hennet 2024, p. 5-22). I agree with that opinion because ATSDR analyses indicated that benzene was not detected or detected at trace levels at the TTWTP.

RH posits incorrectly in his Opinion 6 (Hennet 2024, p. 5-32) that the HPWTP was likely not contaminated with benzene. He bases this opinion on a flawed and erroneous assumption that water-supply well HP-602 was operated solely 39% of the time (frequency of use of 0.39). This is the same flawed reasoning that RH used for water-supply well HP-651and which I conclusively discredit (see Section 4.2.2.4 in my report).

Well HP-602's operational log demonstrates the well's long-term operation; even with short-term operation and repairs, it was kept as part of the group of operating wells, even though it was not a high-volume producing well (Sautner et al., 2013, p. S1.17).[32] The last three capacity tests for well HP-602, however, indicated capacities of 130 gpm (8/17/1983), 100 gpm (6/20/1984), and 154 gpm (10/24/1984).

[32] CLJA_WATERMODELING_05-0000826058.

RH's claim that benzene is a recent short-term event does not consider the expansive remediation effort that has taken place at the HPIA and HPFF (Faye et al. 2010, p. C26)[33] and the volumes of estimated benzene in the subsurface as discussed below.

Measured concentrations of benzene have been documented. HPHB Chapter C (Faye et al. 2013), Figure C34[34] shows substantial benzene concentrations from samples within the HPIA. Table C80 (Faye et al 2013)[35] shows substantive benzene concentrations at IRP Sites: 6 (32J μg/L), 22 (29,000 μg/L), 78 (HPIA, 5,500 μg/L), 84 (3,800 μg/L), and 94 (17,300 μg/L). In addition the model TechNAPLVol (Jang et al. 2013)[36] confirmed previous LNAPL (floating benzene) volumes using the SpillCAD™ model (Engineering Science & Technology 1993) and Order of Magnitude analysis (CH2M HILL 2001). Additionally, Faye et al. (2013, Table D10)[37] summarize BTEX contaminants at selected RCRA investigations sites and occurrences of BTEX in nearby supply wells for the HP-HB area—HP-608 (Buildings 1502 and 1601), and HP-602 (HPFF, Building 1115, and Michael Road Fuel Farm). Three samples at the HPWTP, collected after all contaminated water-supply wells had been removed from service show the following benzene concentrations: 11/19/1985 (2,500 μg/L), 12/10/1985 (38 μg/L), and 12/18/1985 (1.0 μg/L). These data in addition to the erroneous assumption of a 39% operational frequency for well HP-602 demonstrate the flaw in RH's logic and reasoning that the HPWTP was likely not contaminated with benzene.

#### *4.9.2 Site-Specific Data*

Both RH and AS posit that ATSDR did not consider site-specific data to parametrize models (RH Opinion #11, page 5-37). Their *only* example of this is ATSDR not using site-specific $f_{oc}$ data, and that has been rebutted above in the section on Derivation and Computation of Sorption Parameter Values. ATSDR provided a long and comprehensive list of documents and data that it used for the historical reconstruction analysis (Maslia et al. 2013, Appendix A2)[38], whose title is "Information sources used to extract model-specific data for historical reconstruction analysis." Examples of the site-specific data sources include water-quality laboratory analyses by Granger laboratory, JTC environmental laboratories, the CERCLA Administrative Record files, solid waste management unit reports, installation restoration program site reports, as well as hundreds of consulting reports providing site-specific data (e.g., AH Environmental Consultants, Baker Environmental, CH2HILL). The claim by AS and RH that ATSDR did not use site-specific data is simply false.

#### *4.9.3 Travel Time for PCE to Reach TT-26*

RH posits that travel time to TT-26 is in the range of 15-25 years (RH 2024, p. 5-15, 5-16, 5-22, and his Attachment D). Konikow (2025) provides a detailed discussion and response to RH, with which I agree and provide below:

> "Dr. Hennet estimates a range of values for travel times of PCE between ABC Cleaners and TT-26 that are stated to be "in the 15 to 25 years range", based on three assumed

[33] CLJA_WATERMODELING_05-0000777129.
[34] CLJA_WATERMODELING_05-0000777170.
[35] CLJA_WATERMODELING_05-0000777384.
[36] CLJA_WATERMODELING_05-0001005553.
[37] CLJA_WATERMODELING_05-0001004009.
[38] CLJA_WATERMODELING_05-0000777681 – 05-0000777688.

"representative" flow paths, indicating the arrival didn't occur until the 1970s. He presents supporting material and calculations in his Attachment D. Dr. Hennet assumes the horizontal travel distance in the shallow aquifer is either (1) 200 ft in the shallow aquifer and 800 ft in the pumped aquifer, (2) 500 ft in the shallow aquifer and 500 ft in the pumped aquifer, or (3) 800 ft in the shallow aquifer and 200 ft in the pumped aquifer. He further assumes that the hydraulic gradient in the layer 2 confining unit is the same in all cases (i.e., at three different distances from the pumping well). This is not a reasonable assumption (for example, see TT Figs. C19 & C21). In the pumped aquifer, a cone of depression will form with lowest heads adjacent to the well and higher heads further from the well. In the shallow aquifer, the heads will not change much due to pumping in the deeper aquifer. This drawdown effect is strongest near the well, and results in a greater hydraulic gradient (and faster velocity) across the confining layer closer to the well.

Pumping also results in a steeper horizontal gradient (and faster velocity) closer to the well in model layer 3, and a shallower gradient further from the well. Dr. Hennet's calculations assume the same horizontal velocity in the pumped aquifer regardless of the distance from the pumped well, which is not a valid assumption.

Examining the heads for model layers 1 and 3 as shown in TT Figs. C18 and C19, and looking at a point about halfway between ABC Cleaners and TT-26 and at a point very close to TT-26, the head difference between the two layers (across the confining bed) is about 10' – 9' = 1 ft at the halfway location and about 5' – 2' = 3 ft at a location close to TT-26. Therefore, the hydraulic gradient potentially driving downward flow is about 3 times greater close to the well than it is halfway between the well and the contaminant source. So this large spatial change in vertical hydraulic gradient must be accounted for, and the assumption that it is the same at all locations cannot be supported. Dr. Hennet does not account for the steeper vertical gradient in layer 2 for the path closer to the pumped well, nor does he account for the faster velocity in layer 3 when the travel distance is only 200 ft.

It is more likely that the travel distance in the shallower aquifer for much of the contaminated shallow groundwater would be more than 800 ft and the corresponding travel distance in the pumped aquifer would be less than 200 ft because (1) the vertically downward transport is more likely to occur where the vertical gradient is the strongest in the confining layer, which is closest to the pumping well, (2) the downward velocity would be fastest where the gradient is steeper close to TT-26, and (3) according to Dr. Hennet's calculations, the downward flux is only about 5% of the horizontal flux in the shallow aquifer, so that even if some contaminant leaked downward at further upgradient distances from TT-26, much would remain in the shallow aquifer to migrate to locations closer to, or even adjacent to, TT-26, where downward leakage would be the fastest. Thus, Dr. Hennet's three "representative" flow paths did not include a more critical flow path in which travel in the shallower aquifer is close to 1,000 ft. For this critical flow path, the travel time would be much less than 15 years—on the order of 3.5 to 5 years. For these several reasons, Dr. Hennet's estimates of travel times from ABC to TT-26 are erroneous, misleading, biased-high, and based on unreliable assumptions." (Konikow 2025).

Based on my and Dr. Konikow's analysis, a summary of my response to RH is as follows:

- **Travel Time Estimates**: RH estimates a 15–25-year range for PCE travel time between ABC Cleaners and TT-26, but his calculations show a 14.9-19.7-year range.
- **Retardation Factor**: RH uses a retardation factor of 3.5, whereas the calibrated value for the TT model is 2.9, overestimating travel times by 20%.
- **Horizontal Travel Distance**: RH assumes horizontal travel distances of either 500 ft in both the shallow and pumped aquifers or 800 ft in the shallow aquifer and 200 ft in the pumped aquifer.
- **Hydraulic Gradient Assumptions**: RH incorrectly assumes consistent hydraulic gradients in layer 2's confining unit at both distances from the pumping well.
- **Cone of Depression**: In the pumped aquifer, a cone of depression forms with the lowest heads near the well and higher heads farther away.
- **Shallow Aquifer Heads**: Heads remain relatively unchanged in the shallow aquifer, affecting horizontal gradients.
- **Gradient Variation**: The hydraulic gradient near the well is three times greater than halfway between the well and the contaminant-source.
- **Gradient and Velocity**: RH does not account for the steeper vertical gradient closer to the pumped well or the higher velocity in layer 3 over a 200 ft travel distance.
- **Travel Distance Plausibility**: It's more likely that the travel distance in the shallow aquifer exceeds 800 ft, with a shorter distance in the pumped aquifer, due to the concentration of vertical downward transport and gradients near the pumping well.
- **Downward Flux**: RH's calculations indicate that downward flux is only about 5% of the horizontal flux in the shallow aquifer.
- **Misguided Assumptions**: RH's estimates are based on an overly simplistic and unreliable methodology.

#### *4.9.4 Purpose of ATSDR Modeling*

AS claims that the ATSDR models cannot be used for the purpose of estimating Plaintiffs' exposures because that was not the stated purpose of the model (Spiliotopoulos 2024, p. 18). This is a flawed rationale because the stated purpose of a model does not limit or determine the value and use of the model and its results.

ATSDR is a Public Health Agency. Therefore, reports reflect (and state) the ATSDR policy that analyses were not being conducted or extrapolated by ATSDR to individuals. This agency policy is not an indication or determination as to the applicability of the model and historical reconstruction results to individuals.

The methodology used by ATSDR was appropriate and reasonable to provide mean monthly contaminant concentrations in finished water. These model results may be used by health professionals for an epidemiology study and/or to estimate past exposures of residents on an "as likely as not" or "more likely than not" basis. The methods used were rigorous and scientifically sound. ATSDR appropriately told the public that "ATSDR's exposure estimates cannot be used *alone* to determine whether you, or your family, suffered any health effects as a result of past exposure to TCE-contaminated drinking water at USMCB Camp Lejeune." A determination of health effects requires interpretation of the exposure and dose data by a health professional.

# 5.0 Summary and Conclusions

I have provided detailed responses to eight topical areas addressed in DOJ's Expert Reports (Brigham 2024, Hennet 2024, Spiliotopoulos 2024). None of the opinions found in the DOJ Expert Reports would substantively or even moderately change any of the conclusions from ATSDR's historical reconstruction and water-modeling analyses reported in Maslia et al. (2007, 2013, and other supporting reports and documents), or the opinions in my October 2024 expert report. In summary, in response to DOJ's expert reports, I offer the following opinions and conclusions within reasonable scientific certainty:

- ATSDR calibrated its models using a four-stage, hierarchical calibration process. Results of the model-calibration process indicated excellent model and observed data comparisons in finished water at the WTPs, which resulted in geometric model biases of solely 1.5 (TTWTP) and 2.3 (HPWTP). This provides confidence that model behavior (i.e., results) for all four calibration stages provide reasonable accuracy and concordance with system behavior. Neither RH (2024) nor AS (2024) address the merits of the four-stage calibration process in their reports.

- AS (2024) repeatedly accuses ATSDR of making "arbitrary" assumptions and of not basing parameter values on site-specific data. Neither accusation has merit. For example, AS (2024) takes the position that adjusting a model parameter value (e.g., mass loading) to fit water quality data, which are of course site-specific data, is an "arbitrary" decision. (For example, AS Report, pages 78-79.) This is not true. Making such an adjustment is an accepted and best-practices part of the methodology of model calibration. As another example, AS asserts (at page 84) that the use of a U.S. EPA study (USEPA 1986, 1987) of 12,444 leak incident reports to estimate the timing of UST releases at Hadnot Point is "arbitrary and uncertain." Again, this is not true. Reliance upon such a comprehensive study is an accepted methodology; it is not "arbitrary." In summary, ATSDR based parameter values on the best data it had available, including site-specific and published data. ATSDR also made appropriate adjustments to parameters to fit site-specific conditions.

- It is precisely because there was limited data prior to 1980 that ATSDR applied the historical reconstruction process, which included information gathering, data analyses, and model simulation to reconstruct historical concentrations of finished water delivered to the residents of Camp Lejeune. Models play an important role in providing insight and information when data are missing, insufficient, or unavailable. Historical reconstruction has been utilized since the 1930s, is a widely accepted analysis method, and has been applied to other high-profile public sites (Konikow 1977, Konikow and Thompson 1984, Rogers 1992, NRC, 1996). This method has also been reviewed extensively by Samhel et al. (2010) and others.

- Owing to the four-stage, hierarchical calibration process that ATSDR used in calibrating its models, the presentations in Tarawa Terrace Chapter A (Maslia et al. 2007) and Chapter F (Faye 2008) reports comparing computed and observed PCE concentrations at the TTWTP

comprise a major part of TT model calibration. Such comparisons indicate that, regardless of simulated concentrations at individual supply wells, the calibrated Tarawa Terrace MT3DMS model delivered a reasonably accurate total PCE mass to the TTWTP during the 1980's.

- ATSDR applied models that have been tested and verified, and that are available in the public domain, as part of its historical reconstruction process for Camp Lejeune. These models approximate the physics of groundwater flow and chemical transport and are not "professional judgment." Professional judgment and experience were used when selecting values for model parameters, but those values were based on both field and literature sources and were adjusted over reasonable ranges during calibration to best replicate the observed data, which is the generally accepted methodology in the hydrogeology and modeling fields.

- Selecting model parameters based on professional judgment is a normal, standard, and accepted practice. Data are always limited, requiring professional judgment to determine how to handle this paucity of data and how much weight to assign to the limited number of measurements. Groundwater modelers always wish for more data, but the reality is that there is never enough data available to avoid relying on professional judgment.

# 6.0 References


AH Environmental Consultants, 2004. ATSDR Support—Estimation of VOC Removal, Marine Corps Base Camp Lejeune, North Carolina, Prepared for: Environmental Management Division, Camp Lejeune, NC 28542-004, Contract No.: DACW56-03-R-1013, December 2004.

Alley, W.M., and Emery, P.A., **1986**. Groundwater Model of the Blue River Basin, Nebraska–Twenty Years Later. *Journal of Hydrology*, vol. 85, pp. 225-249.

Anderson, M.P., and Woessner, W.W. **1992**. The role of the post audit in model validation. *Advances in Water Resources*, vol. 15, pp. 167–173.

ATSDR (Agency for Toxic Substances and Disease Registry), **1980**. Codified under section 104(i) of CERCLA, 42 U.S.C. §9604(i).

Bobba, A.G., Singh, V.P., and Bengtsson, L., **1995**. Application of uncertainty analysis to groundwater pollution modeling. *Environmental Geology*, 1995, v. 26, pp. 89–96.

Brigham, J.L., **2024**. Expert Report of Jay L. Brigham, Ph.D., in the United States Eastern District of North Carolina, No. 7:23-cv-897, Camp Lejeune Water Litigation, Morgan, Angel, Brigham, and Associates, LLC, December 9, 2024.

CH2M HILL,, Inc., **2001**. Hadnot Point Fuel FARM/Building 1101, Remediation Assessment Report, Marine Corps Base Camp Lejeune, North Carolina; 2001. Contract No.: N62470-95-D-6007 (UST Management Web Portal File #670).

Clement, T.P., **2011**. Complexities in Hindcasting Models – When should we Say Enough is Enough. *Groundwater,* v. 49, no. 5, pp. 620-629.

Environmental Systems & Technologies, **1993**. SpillCAD User and Technical Guide, ES&T Software, LTD. Blacksburg, VA; ES&T; 1993.

Faye, R.E., **2008**. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—**Chapter F:** Simulation of the Fate and Transport of Tetrachloroethylene (PCE). Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008.

Faye, R.E., and Green, J.W., Jr., **2007**. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—**Chapter E:** Occurrence of Contaminants in Groundwater. Atlanta, GA: Agency for Toxic Substances and Disease Registry; In press 2007.

Faye, R.E., and Valenzuela, C., **2007**. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—**Chapter C:** Simulation of Groundwater Flow. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007.

Faye, R.E.; Anderson, B.A.; Suárez-Soto, R.J.; Sautner, J.B., **2010**. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—**Chapter C:** Occurrence of Selected Contaminants in Groundwater at Installation Restoration Program Sites; Agency for Toxic Substances and Disease Registry: Atlanta, GA, USA, October 2010.

Hennet, J.-C., **2024**. Expert Report of Remy J.-C. Hennet, in the United States Eastern District of North Carolina, No. 7:23-cv-897, Camp Lejeune Water Litigation, S. S. Papadopulos & Associates, December 9, 2024.

Hill, M.C., and Tiedeman, C.R., **2007**. Effective Groundwater Model Calibration; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2007.

Hoffman, F., **1995**. Retardation of Volatile Organic Compounds in Ground Water in Low Organic Carbon Sediments: Interim Report. Lawrence Livermore National Laboratory, U.S. Department of Energy, 1995 April, Report No.: UCRL-ID-1204711995.

Jang, W., and Aral, M.M., **2008**. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—**Chapter G:** Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2008.

Jang W., Anderson B.A., Suárez-Soto R.J., Aral M.M., and Maslia M.L., **2013**. Source Characterization and Simulation of the Migration of Light Nonaqueous Phase Liquids (LNAPLs) in the Vicinity of the Hadnot Point Industrial Area—Supplement 7. In: Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Jones, N.L. and Davis, R.J., 2024. Tarawa Terrace Flow and Transport Model Post-Audit, Integral Consulting, Inc., October 25, 2024.

Jones, N.L. and Davis, R.J., **2025**. Expert Rebuttal Report of N. L. Jones, Ph.D., and R. J. Davis, Camp Lejeune Water Litigation, January 14, 2025.

Konikow, L.F., **1986**. Predictive Accuracy of a Ground-Water Model — Lessons from a Postaudit. *Ground Water*, vol. 24, no. 2, pp. 173–184.

Konikow, L.F., **2025**. Rebuttal to Reports of Dr. Alex Spiliotopoulos and Dr. Remy J.-C. Hennet. Camp Lejeune Water Litigation, January 13, 2025.

Konikow, L.F., and Thompson, D.W., **1984**, Groundwater contamination and aquifer reclamation at the Rocky Mountain Arsenal, Colorado: *in* Groundwater Contamination, National Academy Press, Washington, D.C., p. 93-103.

Kidmose, J., Troldborg, L., and Refsgaard, J.C., **2023**. Post Audit of Groundwater Model Predictions under Changing Conditions. *Water*, vol. 15, 22 p.

Maslia, M.L., and Aral, M.M., **2004**. ACTS—Analytical Contaminant Transport Analysis System (ACTS)—Multimedia Environmental Fate and Transport. *ASCE Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 2004, v. 8, no. 3, pp.181-198.

Maslia, M.L., editor, **2005**. Expert Peer Review Panel Evaluating ATSDR's Water-Modeling Activities in Support of the Current Study of Childhood Birth Defects and Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina: Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2005.

Maslia, M.L., Sautner J.B., Faye R.E., Suárez-Soto R.J., Aral M.M., Grayman W.M., Jang W., Wang J., Bove F.J., Ruckart P.Z., Valenzuela C., Green J.W. Jr., and Krueger A.L., **2007**. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—**Chapter A:** Summary of Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; July 2007.

Maslia, M.L., editor, **2009**. Expert Panel Assessing Methods and Analyses for Historical Reconstruction of Groundwater Resources and Distribution of Drinking Water at Hadnot Point, Holcomb Boulevard, and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, April 29–30, 2009; *Prepared by* Eastern Research Group, Inc., Atlanta, GA; *Prepared for* Agency for Toxic Substances and Disease Registry (ATSDR), Atlanta, GA, 149 p.

Maslia, M.L., Suárez-Soto, R.J., Wang J., Aral M.M., Faye, R.E., Sautner J.B., Valenzuela C., and Grayman, W.M., **2009**. Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—**Chapter I:** Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water. Atlanta, GA: Agency for Toxic Substances and Disease Registry; February 2009.

Maslia, M.L., Aral, M.M., Faye, R.E., Grayman, W.M., Suárez-Soto, R.J., Anderson, B.A., Bove, F.J., Ruckart, P.Z., and Moore, S.M. **2012**. **Comment on:** "*Complexities in Hindcasting Models—When Should We Say Enough Is Enough,"* by T. Prabhakar Clement, v. 49, no. 5, 620–629: *Ground Water*, v. 50, no. 1, 10–16.

Maslia, M.L., Suárez-Soto R.J., Sautner J.B., Anderson, B.A., Jones, L.E., Faye, R.E., Aral, M.M, Guan, J., Telci, I.T., Grayman, W.M., Bove, F.J., Ruckart, P.Z., and Moore, S.M., **2013**. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—**Chapter A:** Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; February 2013.

Maslia, M.L., **2024**. Expert Report of Morris L. Maslia, P.E., D.WRE, DEE, Fellow EWRI. Camp Lejeune Water Litigation, October 25, 2024.

Melts, V.J., 2001. Deposition, in the General Court of Justice, Superior Court Division; April 12, 2001. Report No.: 01-CVS-566.

NRC (National Research Council), **1996**. *The Waste Isolation Pilot Plant--A Potential Solution for the Disposal of Transuranic Waste*. National Academy Press, Washington, D.C., 169 p.

Person, M., and Konikow, L.F., **1986**. Recalibration and Predictive Reliability of a Solute-Transport Model of an Irrigated Stream-Aquifer System. Journal of Hydrology, vol. 87, pp. 145–165.

Rogers, L. **1992**. History matching to determine the retardation of PCE in ground water. *Groundwater***, vol. 30,** no. 1,p. 50–60.

Roy F. Weston, Inc., **1992**. Remedial Investigation Report, ABC One-Hour Cleaners, Jacksonville, North Carolina: Roy F. Weston, Inc.; 1992.

Roy F. Weston, Inc.,**1994**. Remedial Investigation, ABC One-Hour Cleaners, Operable Unit 2, Jacksonville, North Carolina: Roy F. Weston, Inc.; 1994.

Samhel, J.; Devlin, D.; Paustenbach, D.; Hollins, D.; Gaffney, S., **2010**. The Role of Exposure Reconstruction in Occupational Human Health Risk Assessment: Current Methods and a Recommended Framework. *Critical Reviews in Toxicology.* 2010, *40*, 799–843.

Sabatini, D.R., **2025**. Expert Rebuttal Report of David Sabatini, Ph.D., PE, BCEE,. Camp Lejeune Water Litigation, January 14, 2025.

Sautner JB, Maslia ML, Valenzuela C, Grayman WM, Aral MM, and Green JW Jr., **2005**. Field Testing of Water-Distribution Systems at the U.S. Marine Corps Base Camp Lejeune, North Carolina, in Support of an Epidemiologic Study. Proceedings: World Environmental and Water Resources Congress; 2005 May 15–19, Anchorage, AK.

Sautner, J.B., Anderson, B.A., Suárez-Soto, R.J., and Maslia, M.L., **2013**. Descriptions and Characterizations of Data Pertinent to Water-Supply Well Capacities, Histories, and Operations—**Supplement 1.** In: Maslia ML, Suárez-Soto RJ, Sautner JB, Anderson BA, Jones LE, Faye RE, Aral MM, Guan J, Jang W, Telci IT, Grayman WM, Bove FJ, Ruckart PZ, and Moore SM. Analyses and Historical Reconstruction of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water Within the Service Areas of the Hadnot Point and Holcomb Boulevard Water Treatment Plants and Vicinities, U.S. Marine Corps Base Camp Lejeune, North Carolina—Chapter A: Summary and Findings. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2013.

Spiliotopoulos, A., **2024**. Expert Report of Alexandros Spiliotopoulos, Ph.D., in the United States Eastern District of North Carolina, No. 7:23-cv-897, Camp Lejeune Water Litigation, S. S. Papadopulos & Associates, December 9, 2024.

Wilcox, D.A, Thompson, T.A., Booth, R.K., and Nicholas, J.R., **2007**. Lake-level variability and water availability in the Great Lakes: U.S. Geological Survey Circular 1311, 25 p.

Tung, Y-K., and Yen, B-C., 2005. Hydrosystems Engineering Uncertainty Analysis, McGraw-Hill, 273 p.

USEPA (U.S. Environmental Protection Agency), **1986**. Underground Motor Fuel Storage Tanks: A National Survey. Washington, DC: U.S. Environmental Protection Agency; 1986. Report No.: EPA-560/5-86-013.

USEPA , **1988**. Superfund Exposure Assessment Manual. Washington, DC: U.S. Environmental Protection Agency, April1988. Report No. EPA/540/1-88/001.

USEPA, **1987**. Causes of Release From UST Systems. Washington, DC: U.S. Environmental Protection Agency; 1987. Report No.: EPA 510-R-92-702.

USEPA, **1999**. Understanding Variation in Partition Coefficient, $K_d$, Values, Volume II. Washington, DC: Unites States Environmental Protection Agency, 1999 August. Report No.: EPA 402-R-99-004B.

Zheng C., **2010**. MT3DMS v5.3 Supplemental User's Guide. Technical Report to the U.S. Army Engineer Research and Development Center. Tuscaloosa, AL: Department of Geological Sciences, University of Alabama; 2010.

Zheng C., and Bennet, G.D., **2002**. Applied Contaminant Transport Modeling, Second Edition. John Wiley and Sons, Inc., New York, 621 p.

Zheng C., and Wang P.P., **1999**. MT3DMS: A Modular Three-Dimensional Multi-Species Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems: Documentation and User's Guide. Vicksburg, MS: U.S. Army Engineer Research and Development Center; 1999. Report No.: SERDP-99.

# Appendix A — Volatilization Issues: Excerpts From the ATSDR Expert Panel Meetings of March 28, 2005 and April 30, 2009

**2005-03-28 Panel Meeting Transcript at 55:2-57:14**

Panel members Thomas Walski and Peter Pommerenk (AH Environmental consultant) respond to a question from Dr. James Uber to Morris Maslia about whether there are any potential chemical biological processes taking place in the distribution system.

**Dr. Thomas Walksi, 55:2-56:1**: "To give you a little answer to your question, Jim, on the processes, most of the things that happen to the VOCs in pipes don't really -- I mean, there's not much that can happen to them. I mean, in pipes, the only place where you could have much of a process affecting them is usually in tanks where you have a free water surface and they can volatize. But when Ben and I did the work in Phoenix/Scottsdale, we looked at that, then went back to Henry's Law and looked at stuff like that. And we did -- you know, since you don't really -- it's hard to measure these kind of things, and there's not a lot of literature on Henry's Law in a perfectly still tank. Usually, if it's for stripping towers and stuff like that, you have a lot of literature data.

But going back and trying to reconstruct this, we estimated 97 percent of what went into a tank came out. Very little is really lost through the surface, and that's about the only process that you lose VOCs is through the surface of the tank. So basically, assuming that it's -- what goes in the system goes to the tap is probably, you know, a reasonable assumption if there's not processes occurring. At least, we couldn't figure out any processes that would knock down the concentration significantly."

**Dr. Pommerenk, 56:2-57:14:** "Yeah. I have some supporting information on that. Because that question was asked by Camp Lejeune to us as their consultants, we looked into literature and tried to come up with a rough estimate of would there be any removal within the treatment plant. And since, you know, we had to review all of the drawings of the existing plants, we knew the surface areas that are available. We made certain assumptions: You know, is the water quiescent in that tank, or, you know, is there any agitation anywhere?
In all the tanks that we looked in -- and some of the tanks are newer. There's more surface area available today than there used to be early in the seventies. But removal due to volatilization was negligible. I mean, it was less than a tenth of percent. The only location where there would be some removal was in the spiractors that were operated in all these Hadnot Point, Holcomb Boulevard, and Tarawa Terrace plants. And even there, there was a certain uncertainty, depending on they had conditions downstream you would get some agitation at the effluent pipe. So although we said it's probably negligible, and I agree with Tom's number here. At 90 percent, what's going in is coming out on the other end."

**2009-04-30 Panel Meeting Transcript**

**Dr. Pommerenk, 178:18-181:19:** " . . .there's a big five treatment plant in between, between the groundwater collection system and the distribution system.

It consists -- and correct me if I'm wrong -- of a [ground storage –ed.] tank. I don't remember what the size is, but it's probably a million gallon or larger. The Hadnot Point plant has a pump station that pumps water from that water collection tank into what are called catalytic softening units or [spiractor –ed.] cones to which [lime –ed.] is injected to facilitate softening and it overflows into a central pipe.

It goes from there through a rectangular basin that used to be a re-carbonation base, and I'll get back to that. And from there into gravity filters and you know after chlorination and fluorination into a finished water clear well.

Obviously, in this facility there's several quiescent or not so quiescent surfaces from which volatile –ed.] organic compounds can escape. And that kind of depends on the physical properties of these compounds, PCE more so than TCE and so on. We made an estimate a few years ago, a rough estimate, that probably PCE and TCE, we didn't look at BTEX, removal would be incidental, minor, probably. The tanks are covered so there's no way effluents could stir up things.

However, what was not looked at that was, because of lack of information is the re- carbonation basin. The re-carbonation basin serves to, it's typically a small, flow-though basin to which you inject carbon dioxide that is generated from a propane generator or from gas bottles. And carbon dioxide is an [acid –ed.] in water and [decreases –ed.] the pH which has been pretty high prior to, because of lime addition.

So that's how this whole softening process works. You bring the pH up you're still going to have calcium carbonate. Bring the pH back down within the allowable limits. So as far as I know, and as far as I can recall, I've never seen this basin in operation. It was just water flowing through. However, it was put in for a purpose originally some time in the '40s, and nobody can tell me exactly if it ever has been operated and how long it has been operated. Because if it has been operated, it could have [caused –ed.] substantial removal of PCE and TCE. It would have been in the 90 percent removal.

And it kind of depends on the gas flow rates. It kind of depends on the turbulence that got generated. So there's a variety of factors that would have presented. But it could have affected removal of these compounds in the plant. And again, we just looked at PCE and TCE as from volatilization from the basins that are there, not [re-carbonation –ed.] because we didn't have any additional information.

But it might be worth looking into BTEX volatilization from the basins, you know, whether that as a source is uncertainty again. And I'm not trying to get exact numbers or anything, but it's another source of uncertainty for the exposure calculations for what could potentially be the removal of these compounds from the plant, A. And B, finding out whether this has ever been online, this re-carbonization basin