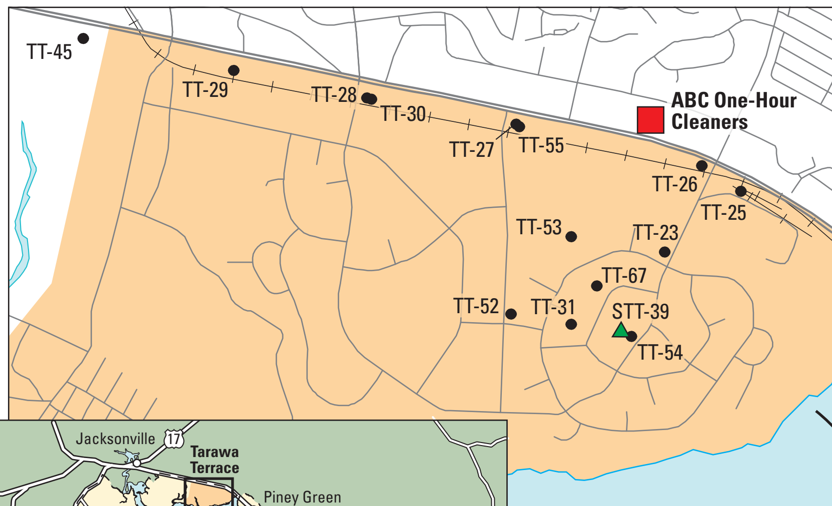
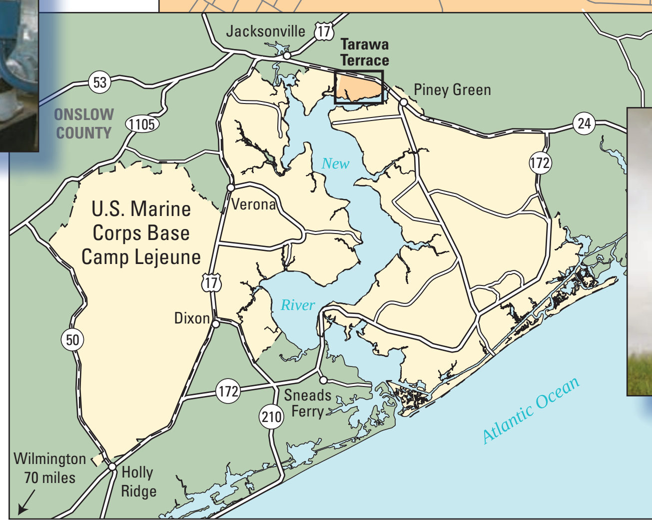
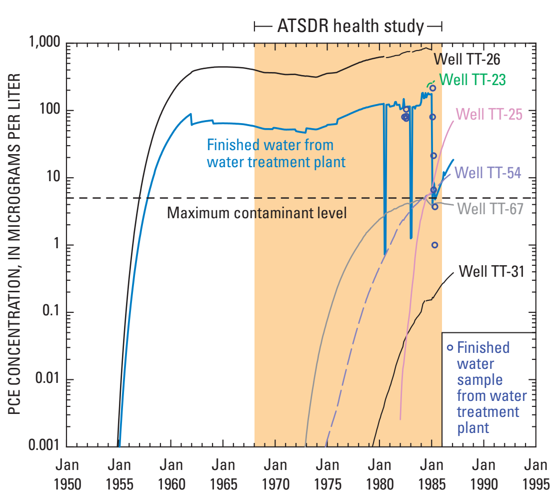
Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Response to the Department of the Navy's Letter on: Assessment of ATSDR Water Modeling for Tarawa Terrace







DEPARTMENT OF HEALTH & HUMAN SERVICES • USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–March 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

DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Agency for Toxic Substances
and Disease Registry
Atlanta, GA 30333

March 10, 2009

Brian P. Harrison, M.P.A., P.E.
Department of the Navy
Naval Facilities Engineering Command
1322 Patterson Avenue, SE
Suite 1000
Washington Navy Yard, D.C. 20374-5065

Dear Mr. Harrison:

I am writing this letter in response to the Department of Navy's (DON) letter dated June 19, 2008. In that letter you reiterated the DON's continued support for working with the Agency for Toxic Substances and Disease Registry (ATSDR) and brought to my attention issues of concern to the DON regarding ATSDR's current health study. This health study uses results of water-modeling analyses to reconstruct historical levels of contaminants in base housing drinking-water supplies during the health study period of 1968–1985.

I have requested ATSDR technical staff working on the current health study at Camp Lejeune to compile responses to the scientific and technical issues you describe in your letter. These responses are enclosed. As a particular response warrants, the response is supported with additional technical and scientific documentation. Technical points of contact for responses to the DON letter are listed below:

Health study/epidemiology, Dr. Frank J. Bove, (770) 488-3809, fbove@cdc.gov
Historical reconstruction/modeling, Mr. Morris L. Maslia, (770) 488-3842, mmaslia@cdc.gov.

ATSDR appreciates the DON's support and commitment to working with us on this scientifically complex and technically challenging project. One of the benefits to the public from a complex project of this type is a demonstration of how two independent Federal Government agencies can work together for the betterment of public health.

Sincerely,

Thomas H. Sinks, Ph.D.
Deputy Director
National Center for Environmental Health/
Agency for Toxic Substances and Disease Registry

Enclosure

cc:
H. Frumkin, NCEH/ATSDR/OD
C. Aloisio, NCEH/ATSDR/OFAS
M. Campbell, NCEH/ATSDR/OFAS
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R. Mach, DON/ASN(E)
K. Brown, DON/NAVFACHQ
D. Waddill, DON/NAVFAC ATLANTIC
M. Simmons, DON/NMCPHC
C. Rennix, DON/NMCPHC
C. Sakai, USMCHQ
S. Williams, USMCHQ

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

INTRODUCTION

The Agency for Toxic Substances and Disease Registry (ATSDR) has used the following referencing format in responding to the Department of the Navy (DON) comments contained in their letter of June 19, 2008. A comment is identified in the DON letter by a number (e.g., 1.1, 2.1, 3.1, etc.), and the ATSDR response to that particular comment is identified with a sequential number (e.g., 1.2, 2.2, 3.2, etc.). To facilitate comparison of DON comments with ATSDR responses, DON comment identifiers (e.g., 1.1, 2.1, 3.1, etc.) have been placed in the margins of the DON letter. This "marked up" letter is provided as a reference and is identified herein as Attachment 1.

BACKGROUND

This ATSDR response and related attachments are part of a continuing effort on the part of ATSDR to maintain a high level of communication between ATSDR and other agencies responsible for the current health study at Camp Lejeune. To reiterate those efforts, Attachment 2 presents information pertinent to previous meetings, presentations, and conversations between ATSDR and the Department of Defense (DOD), the DON, and the U.S. Marine Corps (USMC). Since ATSDR proposed using the historical reconstruction approach as part of the current health study during October 2003, ATSDR staff have kept the DOD, DON, and USMC fully informed, at the highest levels of command, regarding ATSDR's work plans, activities, progress, and results. Attachment 2 provides a complete chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at Tarawa Terrace and vicinity. Three examples, we believe, are noteworthy:

(1) On October 8, 2003, ATSDR presented its proposed modeling approach to support the current health study—historical reconstruction—during a meeting at ATSDR headquarters. Attending the meeting were representatives from the DOD, DON, and USMC (headquarters and Camp Lejeune). A copy of the meeting sign-in sheet and sample presentation slides also are provided in Attachment 2.

(2) On August 26, 2005, ATSDR health study and water-modeling staff met with Lt. General Kelly and his staff at USMC headquarters and presented initial water-modeling results indicating tetrachloroethylene (PCE) had reached Tarawa Terrace water-supply wells as early as 1960.

(3) On June 11, 2007, ATSDR health study and water-modeling staff met with Lt. General Kramlich and his staff at USMC headquarters and presented final water-modeling results. These results indicated that PCE dissolved in groundwater had reached Tarawa Terrace water-supply wells as early as November 1957. ATSDR also presented Lt. General Kramlich and his staff with printed copies of the Executive Summary report (Maslia et al. 2007a) that would be publicly released the following day (June 12, 2007).

RESPONSE TO SPECIFIC COMMENTS

1.1 DON Comment/Statement

During a Technical Information Meeting with the Marine Corps and Navy on March 26, 2008, the ATSDR presented their water modeling efforts in a summary report entitled "Exposure to Volatile Organic Compounds in Drinking Water and Specific Birth Defects and Childhood Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina."

1.2 ATSDR Response

During the aforementioned meeting on March 26, 2008, in Atlanta, ATSDR presented water-modeling results for Tarawa Terrace and vicinity. Staff and technical representatives from ATSDR, DON, and USMC headquarters attended the meeting. ATSDR presented a summary of published results and a list of Tarawa Terrace chapter reports to be completed. Attendees were provided with a copy of the ATSDR PowerPoint® presentation that was used during the meeting.

Note that all reports of technical analyses and water-modeling results pertinent to historical reconstruction of exposure to volatile organic compounds (VOCs) at Tarawa Terrace and vicinity published to date by ATSDR have been available on the agency's Camp Lejeune Web site (*http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html*) since June 2007. For example, the Executive Summary (Maslia et al. 2007a) and Chapter A (Maslia et al. 2007b) reports were released publicly during June and July 2007, respectively. As agreed upon with USMC headquarters staff, ATSDR provided Camp Lejeune and USMC headquarters staff with advanced electronic copies (508-compliant PDF® files) of the aforementioned reports 24 hours prior to their public release.

2.1 DON Comment/Statement

Monthly PCE concentrations are required for the ATSDR health study, which will examine births that occurred from 1968 (when North Carolina computerized its birth certificates) to 1985 (when the contaminated water supply wells were removed from service).

2. 2 ATSDR Response

In general, ATSDR is in agreement with this statement. Specifically, however, historical and water treatment plant (WTP) operations records indicate that only the most contaminated wells were removed from continuous service during 1985. For example, water-supply wells TT-26 and TT-23 were removed from continuous service during February and May 1985, respectively. Remaining Tarawa Terrace water-supply wells continued to operate continuously and intermittently until the Tarawa Terrace WTP was permanently shut down during March 1987 (Maslia et al. 2007b, Table A6). Thus, ATSDR is not in agreement with the DON statement in parentheses that incorrectly describes the schedule for the removal of water-supply wells from service at Tarawa Terrace.

3.1 DON Comment/Statement

Due to lack of measured concentrations, the ATSDR used groundwater flow and contaminant transport modeling in a historical reconstruction process to simulate PCE concentrations in the drinking water on a monthly basis from 1952 to 1987.

3.2 ATSDR Response

To reconstruct monthly concentrations of PCE in drinking water, ATSDR used three types of models: (1) groundwater flow, (2) contaminant fate and transport, and (3) simple mixing based on the concepts of continuity and mass balance. The mixing model was necessary to account for the mixing of uncontaminated and contaminated water-supply wells contributing to the water supply at the Tarawa Terrace WTP. The mixing model provided the final "mixed" drinking-water concentrations on a monthly basis, and these are the values that are available on the ATSDR Web site and published in the Chapter A report (Maslia et al. 2007b).

4.1 DON Comment/Statement

Figure 1 shows the simulated concentrations of PCE versus measured concentrations in finished water from the WTP. Significantly, measured concentrations of PCE are available only in 1982 and 1985, near the end of the overall time period. Thus, the majority of the simulated concentrations cannot be compared to measured data.

4.2 ATSDR Response

ATSDR agrees that there is a lack of historical contaminant concentration data. That is why ATSDR applied the historical reconstruction process to reconstruct (or synthesize) water levels, groundwater concentrations, and drinking-water concentrations of PCE for historical periods (months) when data were not available. Note that data used to calibrate the model(s) in the historical reconstruction process can either be historical data (as was the situation for Tarawa Terrace), or present-day data obtained through a field-test program—as was the case for the water-distribution system model developed by ATSDR for the Dover Township (Toms River), New Jersey, childhood cancer cluster investigation (Maslia et al. 2000).

5.1 DON Comment/Statement

Furthermore, all of the measured concentrations were used during model calibration, leaving no data available for model validation. As a result, the Tarawa Terrace model was not validated.

5.2 ATSDR Response

A number of terms have been used throughout the published literature that reference the adequacy of model simulation to reliably reproduce real-world conditions based on the fidelity of the model and its intended use. Many groundwater modelers and hydrologists have abandoned the use of terms such as model verification and validation for the terms of history matching and post audits (Bredehoeft and Konikow 1993, Oreskes et al. 1994). However, ATSDR understands that the DON comment was intended to express the DON's concern that the calibrated Tarawa Terrace models were not compared to multiple independent sets of measured data (water levels and concentrations) as part of ATSDR's model calibration process and strategy. To address this concern, definitions of terms such as "verification" and "validation" should be agreed upon, and the consequences of undertaking a useful "validation" program for Tarawa Terrace should be completely understood by ATSDR and the DON. Model verification requires that multiple sets of field data be available for model calibration. These sets of field data should be sufficiently large in quantity and distribution and of sufficient quality to provide at least two equally useful calibration data sets. Each data set also should be sufficiently separated in time so as to represent significantly different water-level and contaminant conditions within the model domain. The field data set at Tarawa Terrace used for model calibration was not of sufficient quantity and was too compressed in time to implement a verification procedure. To appropriately calibrate the Tarawa Terrace models, all available field data were required for a single calibration data set and effort. This is consistent with and follows ASTM D5981-96, Standard Guide for Calibrating a Ground-Water Flow Model Application (1996, Note 4), that states: *"When only one data set is available, it is inadvisable to artificially split it into separate 'calibration' and 'verification' data sets. It is usually more important to calibrate to data spanning as much of the modeled domain as possible."*

To meaningfully validate the Tarawa Terrace models (or more appropriately, to conduct a post audit), sufficient time should elapse between individual sets of field data to ensure that significant changes in field conditions have occurred compared to calibrated conditions. At Tarawa Terrace, such changes, by necessity, would require the migration of the contaminant mass to a completely new location and for contaminant concentrations to change significantly when compared to calibrated conditions. Additionally, at Tarawa Terrace, validation (a post audit) would require the collection and analyses of substantial quantities of additional field data, similar to Weston's Operational Units 1 and 2 (Roy F. Weston, Inc. 1992, 1994).

Note, once an acceptable calibration was achieved (using a four-stage calibration strategy described in Maslia et al. [2007a], Faye and Valenzuela [2007], and Faye [2008]), the calibrated models were used to reconstruct historical monthly PCE and PCE degradation by-product concentrations in groundwater and drinking water (Jang and Aral 2008). This is standard practice in the modeling community—using a calibrated model to "predict" (in ATSDR's situation, "reconstruct") results for a period of time when data are not available or cannot be obtained. An example using this same approach is the application of fate and transport modeling to chlorinated organic compounds at Operable Unit 1, U.S. Naval Air Station, Jacksonville, Florida (NASJF), conducted by Davis (2007, Figures 28–31). At this site, the earliest water-quality data that are available were collected during 1992, but the fate and transport model simulations reconstruct concentrations as far back as 1945.

6.1 DON Comment/Statement

For PCE detections, the ATSDR chose the calibration standard to be "±1/2-order of magnitude of the observed valued," such that the higher value in the calibration target range is 10 times greater than the lower value …. In other words, a model-derived PCE concentration can be approximately 3 times higher or 3 times lower than the measured concentration and still fall within the calibration range.

6.2 ATSDR Response

ATSDR generally is in agreement with this statement. For model calibration, ATSDR established, *a priori*, calibration "targets" that were based on the reported accuracy of the available water-level and water-quality measurements. This is in keeping with, and following, the ASTM Standard Guide for Calibrating a Ground-Water Flow Model Application (ASTM 1996). Note, however, that published or accepted groundwater-flow or contaminant fate and transport model calibration standards are currently not established. The lack of model calibration standards is further emphasized by Anderson and Woessner (1992) who state: *"To date, there is no standard protocol for evaluating the calibration process, although the need for a standard methodology is recognized as an important part of the quality assurance in code application (National Research Council 1990)."* In thoroughly reviewing the published literature for contaminant fate and transport model applications, ATSDR did not find any examples wherein calibration targets were established *a priori* and then were followed by a comparison of model simulation results to the calibration targets, as was done in the ATSDR analyses (Maslia et al. 2007b, Faye 2008). For example, at another DON site—the NASJF—contaminant fate and transport simulations of selected chlorinated organic solvents were accepted by the DON, but the simulations did not include any *a priori* contaminant fate and transport calibration targets (Davis 2003, 2007).

7.1 DON Comment/Statement

However, all comparisons did not fall within the calibration range. At the WTP, 12% of the simulated PCE concentrations failed the calibration standard …. at the water supply wells, a majority (53%) of the simulated concentrations fell outside the calibration standard….

7.2 ATSDR Response

ATSDR will address three issues pertinent to the aforementioned DON statement:

(1) ATSDR acknowledges that several simulated head and concentration data fall outside of the range of the ATSDR established calibration targets. As discussed above, ATSDR used available data provided by the U.S. Environmental Protection Agency (USEPA), U.S. Geological Survey (USGS), USMC, and DON, and based on these data, established calibration targets *a priori*, as prescribed in ASTM D5981-96 (1996, Section 6). Furthermore, ATSDR clearly identified and conveyed to the reader (and the public) those data that met and did not meet calibration targets by providing illustrations comparing observed (measured) data, nondetect data, and simulated results with calibration targets for water-supply wells and the Tarawa Terrace WTP. These illustrations are designated as Figures A11 for water-supply wells and A12 for the WTP of the Chapter A report and are located on pages A30 and A31, respectively (Maslia et al. 2007b).

(2) Note, as well, that ATSDR did not discard any nondetect data, as is done in many environmental analyses (Helsel 2005). Rather, ATSDR clearly identified the nondetect data on the aforementioned illustrations so the reader could judge for themselves the usefulness of these data and their relation to the calibration targets. This is very much in keeping with the approach stated by Helsel (2005): "*Deleting nondetects, concentrations below a measured threshold, obscures the information in graphs and numerical summaries*."

(3) 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 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?

To possibly answer the first two questions, ATSDR looks forward to discussing with the DON the results of other modeling studies of contaminant fate and transport similar to the ATSDR study at Tarawa Terrace and comparing the results of other studies to the calibration targets used by ATSDR at Tarawa Terrace. For example, the results of the ATSDR fate and transport simulations at Tarawa Terrace were compared to results of a similar study of the fate and transport modeling of chlorinated solvents at the NASJF, reported by Davis (2003). The report by Davis (2003) was peer reviewed and published by the USGS, and the published results were subsequently deemed totally acceptable to the DON. No calibration targets for contaminant concentrations were established during the NASJF study. Therefore, to directly compare Tarawa Terrace and NASJF simulation results, the ATSDR calibration targets of ±1/2-order of magnitude were applied to data and simulation results reported in Davis (2003, Figure 34). Attachment 3 shows this comparison along with similar results reported by Maslia et al. (2007b, Tables A9 and A10). The percentage of NASJF simulation results that fell within the calibration target range (passed the calibration target test) is 56% compared with 59% for the ATSDR study (44% of the NASJF results failed the calibration test compared with a failure rate of 41% for ATSDR results). Furthermore, the root-mean-square of concentration difference for the NASJF analysis is 329 μg/L compared with 337 μg/L for the ATSDR analysis. (Data used to conduct these comparisons also are included in Attachment 3.) Thus, one can conclude that the ATSDR analysis is comparable to and of the same order of accuracy and quality as the NASJF analysis that was accepted by the DON.

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 <u>relative</u> 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.

8.1 DON Comment/Statement

It seems reasonable to conclude that the accuracy of the historically reconstructed PCE concentrations would be less than the calibration standard of ±1/2-order of magnitude. Thus, the historical reconstructions may be viewed as rough estimates of actual exposure concentrations, with model-derived PCE concentrations representing a relatively wide range of possible exposures. It is essential that this concept be expressed clearly and consistently to all stakeholders.

8.2 ATSDR Response

ATSDR is in disagreement with DON's assessment and interpretation as expressed in the first two sentences above. As previously discussed, there are no established calibration targets or standards that are universally accepted or used by the contaminant fate and transport modeling community. With respect to the Tarawa Terrace models, the failure of a percentage of data to conform to a designated calibration target is more a commentary on the accuracy and variability of field data used for model calibration than the model's ability to accurately simulate true field conditions. These issues are thoroughly discussed in the "Discussion" sections of the Tarawa Terrace Chapter C and F reports (Faye and Valenzuela 2007, Faye 2008) For example, note on Attachment 3 of this letter the radical changes in PCE concentration at well TT-26 during the approximately 1-month period between January 16 and February 19, 1985. Of the four comparisons of measured PCE concentrations with simulated PCE concentrations, three comparisons failed the calibration target test of ±1/2-order of magnitude while the field data varied by as much as 2.5 orders of magnitude. The two analyses recorded for February 19, 1985, are duplicative but were nonetheless counted as two failures with respect to computing a percentage of comparisons that failed the calibration target test. Furthermore, ATSDR is not aware of any other published report that establishes, *a priori*, contaminant fate and transport calibration targets. ATSDR based its calibration target of ±1/2-order of magnitude on the assumption that very restrictive or "tight" control on model calibration was desired. With 59% of the water-supply well and water treatment plant paired data points meeting these targets, ATSDR believes it met its model calibration goals.

ATSDR is in disagreement with the DON statement that the historical reconstruction results of PCE concentrations are "*rough estimates*" and represent a "*relatively wide range of possible exposures*." Results presented in the Chapter A report (Maslia et al. 2007b) demonstrate just the opposite. ATSDR meticulously followed accepted modeling standards (ASTM 1996, Hill and Tiedeman 2007) for both deterministic (single-valued input and output) and probabilistic (distributed-value input and output) modeling analyses. Results obtained are accurate on a monthly basis within the variability bands indicated, given the quality and quantity of available data, and the uncertainty and variability of input data, pumping and water treatment plant operations, and quantity of mass released. The monthly resolutions of simulated PCE concentrations are sufficiently refined for the intended use of the epidemiological case-control study. Furthermore, as shown in Figures A25 and A26 (Maslia et al. 2007b), ATSDR clearly described and communicated that reconstructed (simulated) PCE concentrations for a specified month do have a range of values. A tabular listing of these values is provided in the Chapter I report (Maslia et al. 2009) and will be made available to the public on the ATSDR Web site. These tabular values also are provided herein as Attachment 4. A review of Attachment 4 indicates that during the period of interest to the epidemiological study (1968–1985), when water-supply well TT-26 was pumping, the range of 95% of the Monte Carlo simulated PCE concentration values differ by a factor of about 2 when pumping uncertainty is not considered (e.g., for January 1968, $P_{97.5}$ = 76.43 µg/L and $P_{2.5}$ = 38.91 µg/L). PCE concentration values differ by a factor of about 2.5 when pumping uncertainty is considered (e.g., for January 1968, $P_{97.5}$ = 98.22 µg/L and $P_{2.5}$ = 40.60 µg/L). These ranges are, in fact, very narrow and provide both quantitative and qualitative indications of the precision of the ATSDR historically reconstructed PCE concentrations in drinking water.

ATSDR is in agreement with the DON statement that "*It is essential that this concept be expressed clearly and consistently to all stakeholders.*" Upon the release of the Chapter I report (Maslia et al. 2009), ATSDR intends to revise the Camp Lejeune water-modeling Web site to include a listing of ranges of PCE concentrations for a given month and year of interest. When a person queries the ATSDR Web site, they will be provided with a mean exposure concentration and the 95% Monte Carlo simulated range of values.

9.1 DON Comment/Statement

For example, the public needs to understand that the model-derived PCE concentrations represent a range of possible exposures . . . . The usefulness of the website would be enhanced if it accurately conveyed the degree of uncertainty in the model-derived concentrations.

9.2 ATSDR Response

ATSDR is in agreement with this DON statement. As stated above, ATSDR has revised the Camp Lejeune water-modeling Web site to include a listing of ranges of PCE concentrations for a given month and year of interest. When a person links to the ATSDR Web site, they will be provided with a mean exposure concentration and the 95% Monte Carlo simulated range of values.

10.1 DON Comment/Statement

Other concerns with model calibration include the simulation of contaminant mass loading and groundwater flow. With Dense, Non-Aqueous Phase Liquids (DNAPLs) such as PCE, mass estimation is always quite difficult and subject to very high uncertainty due to irregular movement and distribution of DNAPL in the subsurface.

10.2 ATSDR Response

In principle, ATSDR is in agreement with the DON statement that DNAPL movement and distribution makes it difficult to estimate contaminant mass. However, water-quality data obtained from the USEPA for the unsaturated zone in the vicinity of ABC One-Hour Cleaners and in the Upper Castle Hayne aquifer at Tarawa Terrace (Roy F. Weston, Inc. 1992, 1994; Faye and Green 2007) indicated that measured PCE concentrations in water-quality samples were <u>significantly below</u> the solubility limit of PCE in water. Typical solubility limits for PCE in water reported in the scientific literature range from 150–210 mg/L (Schwille 1988, Pankow and Cherry 1996, ATSDR 1997, Lawrence 2007). Reported concentrations of PCE in all water-quality samples made available to ATSDR were less than 20% of the solubility limit and most concentrations were in the range of less than 1% to 5% of the solubility limit (Faye and Green 2007). Thus, with PCE concentrations well below their solubility limit, the movement of PCE-contaminated groundwater would not be subjected to the complexities and difficulties encountered with estimating mass of density-driven flows. This concept is further borne out by Schwille (1988) who states, in referring to chlorinated hydrocarbons (CHCs): "*In most cases, the concentrations near all CHC spill sites are very low—usually far below the saturation values. This indicates that it may be assumed that density-affected flow will be the exception in real-world situations.*"

In addition, mass computations similar to those described in Pankow and Cherry (1996) were accomplished for the saturated and unsaturated zones in the vicinity of ABC One-Hour Cleaners, using hydrocone and well data made available to ATSDR by USEPA and USMC (Roy F. Weston, Inc. 1992, 1994; Faye and Green 2007). These mass computations provided a <u>lower-limit estimate</u> for dissolved PCE mass in groundwater needed for simulating the contaminant fate and transport of PCE at Tarawa Terrace. Furthermore, the calibration of the Tarawa Terrace fate and transport model is additionally corroborated by comparing the computed mass residing in the saturated zone from December 1991 to April 1992 (1.5×10^6 grams) to the simulated mass residing in the saturated zone during February 1992 (1.0×10^6 grams) (Faye 2008). The mass computation method described in Pankow and Cherry (1996) and similar to that used by Faye and Green (2007) has been further refined. As explained in Ricker (2008): "*this method is applicable to any contaminant dissolved in ground water.*" A copy of the paper by Ricker (2008) is provided as Attachment 5.

11.1 DON Comment/Statement

For Tarawa Terrace groundwater, the difference between observed and simulated elevations is 5 to 10 feet at many times during the 1970's and 1980's. This is a significant disparity because the total change in groundwater elevation from the source area to the receptor wells is approximately 10 to 12 feet.

11.2 ATSDR Response

This DON approach to evaluating model calibration applies a generalized “rule of thumb” to the Tarawa Terrace groundwater-flow models and is possibly based on wording found in ASTM Guide D5981-96, Standard Guide for Calibrating a Ground-Water Flow Model Application, (ASTM 1996, section 6.4.1): *“the acceptable residual should be a small fraction of the difference between the highest and lowest heads across the site.”* ATSDR is not in agreement with this approach to evaluate model calibration. A careful review of ASTM D5981-96 in its entirety indicates that the DON’s comment, as stated, is totally removed from the context of Section 6 of the ASTM Standard Guide as well as the context of the accuracy of field data used to calibrate the Tarawa Terrace groundwater-flow model, as described in the Chapter C report (Faye and Valenzuela 2007). For example, in Section 6.4, ASTM D5981-96 states: *“the magnitude of the acceptable residual depends partly upon the magnitude of the error of the measurement or the estimate of the calibration target and partly upon the degree of accuracy and precision required of the model’s prediction.”* Furthermore, Note 2 of ASTM D5981-96 states: “*Acceptable residuals may differ for different hydraulic head calibration targets within a particular model. This may be due to different errors in measurement.”* The Tarawa Terrace Chapter C report (Faye and Valenzuela 2007, p. C24) provides a comprehensive discussion of water-level measurement errors arising from the use of airlines and pressure gages to measure water levels. Faye and Valenzuela also point out that this is consistent with the discussions of LeGrand (1959) who described problems associated with the use of airlines to measure water levels at Camp Lejeune as far back as 1959. As pointed out in Faye and Valenzuela (2007, p. C24): *“Typically, reported water levels* [at supply wells] *vary in excess of 20 ft during the period of measurement, and frequently 10 ft or more from month to month…. Such variability also may indicate leaking or damaged airlines or pressure gages.”*

Faye and Valenzuela (2007, p. C24) also provide detailed discussions as to the rationale for selecting two calibration target ranges for the transient groundwater-flow model. At wells where water-level measurements were obtained using airlines and pressure gages, the calibration target was selected as an absolute difference of 12 ft between simulated and measured water levels. This target was based on well-known disadvantages of using pressure gages and airlines to obtain accurate water-level measurements. Where water-level measurements were obtained using the more highly accurate tapes and similar devices at monitor wells, the calibration target was selected as an absolute difference of 3 ft between simulated and measured water levels. This target was based on the least accurate of these water-level measurements where topographic maps were used to estimate the altitude of a measuring point.

Evaluating model calibration using the “rule of thumb,” as the DON has suggested, also assumes that no other information is available to determine calibration targets. When information is available, such as direct knowledge of methods of water-level measurements and information characterizing the measurement device(s), the calibration targets should be based on these data, not on a “rule of thumb.” Faye and Valenzuela (2007) provide detailed listings of measured water levels in supply and monitor wells throughout Tarawa Terrace (Appendix C5).

The calibration of the Tarawa Terrace groundwater-flow and contaminant fate and transport models and the computation of related calibration metrics are described in great detail in published ATSDR reports (Faye and Valenzuela 2007, Maslia et al. 2007b, Faye 2008). The calibration approach used by ATSDR closely follows published guidelines for model calibration (National Research Council 1990;Anderson and Woessner 1992; ASTM 2004, 2006, 2008). Nowhere in these publications could we find any reference to the "rule of thumb" for model calibration found in ASTM (1996) and subsequently promoted by the DON. The use of hydraulic head change over a model domain to define an acceptable residual for groundwater model calibration is not found or discussed in any of the aforementioned references. Anderson and Woessner (1992) and ASTM D5940-93 (2008) provide several metrics for evaluating the calibration process and comparing groundwater-flow model simulation to site-specific information. Among these metrics are the use of a scatter diagram and the computation of the mean error, the mean absolute error, the root-mean-square (*RMS*) of error, and standard deviation of error.[1] In conformance with these metrics, the calibration of the ATSDR groundwater-flow models was evaluated using scatter diagrams (Figures C9 and C20 in Faye and Valenzuela [2007] and Figure A10 in Maslia et al. [2007b]) and by computing the mean absolute error of the differences between simulated and observed head at all known observation and water-supply wells within the model domain as well as the *RMS* and standard deviation of these differences (Table C10 in Faye and Valenzuela [2007] and Table A8 in Maslia et al. [2007b]). Attachment 6 to this letter, the scatter diagram from Maslia et al. (2007b), and Attachment 7, Table A8 from Maslia et al. 2007b, describe the computation of the absolute error (head difference) and related *RMS* and standard deviation. The calibration of the ATSDR Tarawa Terrace groundwater-flow and contaminant fate and transport models was based on available water-level and water-quality data to determine calibration targets and closely adheres to accepted model calibration standards and evaluation procedures, such as those described in the aforementioned publications.

12.1 DON Comment/Statement

In addition, model results suggest that the simulated PCE concentrations at the WTP depend significantly on the pumping rates at the various water supply wells. The degree to which simulated well operations match actual operations is a concern. The Navy/Marine Corps would welcome the opportunity for further technical discussion with ATSDR on these issues.

12.2 ATSDR Response

ATSDR is in agreement with the DON that PCE concentrations at the WTP are dependent on the pumping rates assigned to water-supply wells. This dependency is based on the principles of continuity and conservation of mass. The PCE concentration in finished water at the WTP is a function of individual water-supply well pumping rates and their simulated PCE concentrations for a given historical month (stress period)—also referred to as a flow-weighted average PCE concentration (Faye 2008). ATSDR shares the DON's concern that simulated operations may not match historical operations. Thus, when monthly pumpage data were available, ATSDR used these data in the transient groundwater-flow model (for example, Table C8 in Faye and Valenzuela [2007] and Table I16 in Maslia et al. [2009]). To address issues of missing pumping operational data and the effect of uncertain pumping rates on simulated PCE concentrations, ATSDR conducted additional and complex analyses that described in detail: (1) issues of pumping schedule variation on the arrival of PCE at water-supply wells and the WTP (Wang and Aral 2008) and (2) assessment of uncertain

[1]The term "error" as used in Anderson and Woessner (1992) and some other references is defined in the ATSDR analyses as "head difference" and refers to the difference between measured and simulated potentiometric heads or water levels.

pumping rates by conducting a probabilistic analysis wherein pumping rate was defined as an uncertain model parameter (Maslia et al. 2009, Figure I25).

13.1 DON Comment/Statement

. . . certain combinations of input parameters resulted in wells drying out, so only 510 physically viable realizations were produced. Thus, 330 out of 840 realizations were not viable, raising concerns about the representativeness of the input parameter distributions.

13.2 ATSDR Response

The issue that should be addressed is not how many realizations produced physically plausible solutions, but rather, are the 510 realizations that were successfully produced sufficient to represent an infinite number of random solutions? The metric that determines whether or not this question is answered in the affirmative is the relative change in stopping criteria between successive model simulations. If this relative change is small within a predetermined range, then additional simulations are redundant and do not statistically contribute to an improvement of the representativeness of the overall results with respect to the statistical distributions. The Chapter I report (Maslia et al. 2009) describes in detail the criteria used to determine when a sufficient number of realizations have been achieved. Three stopping criteria were used to halt the Monte Carlo 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, ΔC_v. Mathematical formulae and definitions of the aforementioned stopping criteria metrics are listed in Table I13 of the Chapter I report (Maslia et al. 2009). In applying the stopping criteria to the Monte Carlo simulations, an upper and lower bound of ±0.25% was used for each metric. When the computed relative change ($\Delta\overline{C}$, $\Delta\sigma_C$, and ΔC_v) was within the aforementioned bounds and the total number of realizations was 500 or more, the Monte Carlo simulation process was halted. Examples of the stopping criteria for each metric are shown graphically in Attachment 8 (Maslia et al. 2009, Figure I26). As can be seen from the stopping criteria, insignificant change (much less than 2.5%) occurs after 300 realizations. Therefore, 510 realizations were more than sufficient to represent an infinite number of random solutions.

14.1 DON Comment/Statement

Although a summary of the probabilistic analysis is presented in Chapter A of the ATSDR modeling report, the details will be in Chapter I, which is not yet available. The Navy/Marine Corps feels that additional information on this matter would likely help our understanding.

14.2 ATSDR Response

An electronic version (508-compliant PDF®) of the Chapter I report (Maslia et al. 2009) was provided to the DON and USMC on February 13, 2009, and is now available on the ATSDR Web site. Printed copies of the report are expected to be available around March 20, 2009. The Chapter I report describes in detail the Monte Carlo simulation process and how this process was incorporated into Tarawa Terrace groundwater-flow and contaminant fate and transport models. Additionally, details pertaining to generating uncertain parameter distributions using Monte Carlo and sequential Gaussian simulation are discussed. Note, however, results presented in the Chapter I report do not change or alter results and interpretations presented in the Chapter A report.

15.1 DON Comment/Statement

The usefulness and applicability of the model-derived PCE concentrations for Tarawa Terrace are affected by the following ….

15.2 ATSDR Response

ATSDR has responded in detail to the items numbered in the Summary Section of the DON letter of June 19, 2008. To summarize, ATSDR used data and information that were provided by the USEPA and the USMC. In addition, other data sources from the USGS also were used. This formed the basis for the conceptual models of groundwater flow and contaminant fate and transport applied to the Tarawa Terrace area.

Calibration targets were selected based on the quality and availability of water-level and water-quality data provided to ATSDR. Model analyses and calibrations were conducted by following accepted and published standards for groundwater-flow and contaminant fate and transport models (ASTM 1996, 2004, 2006). It must be emphasized, however, that model calibration standards or targets for groundwater-flow and contaminant fate and transport modeling analyses do not exist, as stated in Anderson and Woessner (1992): *"To date, there is no standard protocol for evaluating the calibration process, although the need for a standard methodology is recognized as an important part of the quality assurance in code application (National Research Council 1990)."* Thus, 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 for the epidemiological study, previously discussed above in the last paragraph of section 7.2.

The concept behind the historical reconstruction process is as follows: (1) when data are limited or unavailable for a certain time period, the data that are available are used to calibrate a model (or models), and (2) the missing data are "reconstructed" or "synthesized" using the calibrated model(s).

16.1 DON Comment/Statement

Groundwater modeling studies are always subject to a high degree of uncertainty, and in this sense, the Tarawa Terrace water model is no exception …. Any use of reconstructed concentrations must take into account the inherent uncertainty in the model results.

16.2 ATSDR Response

ATSDR is not in agreement with the DON that there is a *"high degree of uncertainty"* associated with the Tarawa Terrace models. ATSDR acknowledges that uncertainty and variability exist in model input parameter values and in model output (simulated water levels and PCE concentrations). However, ATSDR has quantified the uncertainty and variability through the use of probabilistic analyses that apply Monte Carlo and sequential Gaussian simulation methods to the Tarawa Terrace groundwater-flow and contaminant fate and transport models. The probabilistic analyses, summarized in Chapter A and described in detail in Chapter I, indicate that for 95% of the Monte Carlo simulations, there is a PCE-concentration range of about 2 when pumping is not an uncertain input parameter and a factor of about 2.5 when pumping is an uncertain parameter. This is well within acceptable confidence limits for the intended use of the reconstructed PCE concentrations needed by the epidemiological case-control study. As previously discussed in section 7.2 of ATSDR's response, the ATSDR health study is not trying to infer at what specific PCE concentration effects are seen. Instead, the epidemiological analysis is trying to evaluate an exposure-response relationship in which the exposures are categorized levels, not absolute values.

17.1 DON Comment/Statement

Recommendations
1. Improve communication …, 2. Convene an expert panel …, 3. Finalize remaining sections…, 4. Apply all lessons learned from the Tarawa Terrace modeling efforts to the scoping of the approach for Hadnot Point.

17.2 ATSDR Response

1. ATSDR water-modeling and health study staff will be meeting with the ATSDR Office of Communications to develop effective methods to communicate results of the historical reconstruction analyses and the uncertainty associated with reconstructed concentrations. ATSDR has removed the Web application that provides a "single" value estimate of historical PCE concentration in Tarawa Terrace drinking water. This Web application has been replaced with Figure I29 and Appendix I5 (Maslia et al. 2009).

2. ATSDR is in the process of organizing an Expert Panel for the Hadnot Point and Holcomb Boulevard areas. The panel is scheduled to meet on April 29 and 30 at ATSDR headquarters. Initial information packets have been mailed to the 13 panel members and panel chair, and a courtesy packet has also been provided to USMC headquarters staff.

3. Chapter I is complete and was released to the DON and USMC on February 13, 2009. Printed copies should be available after March 20. Chapters J (water-distribution modeling) and K (Supplemental Information) are anticipated to be final during June 2009.

4. ATSDR agrees and is in the process of applying lessons learned from the Tarawa Terrace analyses as work progresses on the Hadnot Point and Holcomb Boulevard areas.

CONCLUSIONS

ATSDR appreciates the DON's continued support for the agency's current health study and completion of water-modeling activities. The issues of concern and recommendations contained in the DON's assessment of water-modeling analyses at Tarawa Terrace and vicinity have been carefully considered and fully addressed in ATSDR's responses. The online release of Tarawa Terrace Chapter I report (Maslia et al. 2009) on February 13, 2009, provides additional confidence that the historically reconstructed PCE concentrations determined by Faye (2008) are reasonable, conform well to field observations, and are reliable for their intended use in the epidemiological study.

REFERENCES

Agency for Toxic Substances and Disease Registry. Toxicological Profile for Tetrachloroethylene. Atlanta, GA: U.S. Department of Health and Human Services; 1997.

Anderson MP, and Woessner WW. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, Inc.; 1992.

ASTM. Standard Guide for Calibrating a Ground-Water Flow Model Application. D5981–96 (Reapproved 2002). West Conshohocken, PA: ASTM International; 1996.

ASTM. Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem. D55447–04. West Conshohocken, PA: ASTM International; 2004.

ASTM. Standard Guide for Subsurface Flow and Transport Modeling. D5880–95 (Reapproved 2006). West Conshohocken, PA: ASTM International; 2006.

ASTM. Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information. D5940-93. West Conshohocken, PA: ASTM International; 2008.

Bredehoeft JD, and Konikow LF. Ground-Water Models: Validate or Invalidate. Ground Water. 1993; 31(2):178–179.

Davis JH. Fate and Transport Modeling of Selected Chlorinated Organic Compounds at Hangar 1000, U.S. Naval Air Station, Jacksonville, Florida. Tallahassee, FL: U.S. Geological Survey Water-Resources Investigations Report 03-4089; 2003.

Davis JH. Fate and Transport Modeling of Selected Chlorinated Organic Compounds at Operable Unit 1, U.S. Naval Air Station, Jacksonville, Florida. Tallahassee, FL: U.S. Geological Survey Scientific Investigations Report 2007-5043; 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.

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.

Helsel DR. Nondetects and Data Analysis: Statistics for Censored Environmental Data. Hoboken, NJ: John Wiley & Sons; 2005.

Hill MC, and Tiedeman CR. Effective Groundwater Model Calibration. Hoboken, NJ: John Wiley & Sons; 2007.

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.

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.

LeGrand HE. Evaluation of Well-Water Supply, Marine Corps Base, Camp Lejeune, North Carolina: Project Report, Contract NBy-7595; 1959.

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 the U.S. Marine Corps Base Camp Lejeune, North Carolina: Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2005.

Maslia ML, Sautner JB, Aral MM, Reyes JJ, Abraham JE, and Williams RC. Using Water-Distribution System Modeling to Assist Epidemiologic Investigations. Journal of Water Resources Planning and Management. 2000; 126(4):180-198.

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—Executive Summary. Atlanta, GA: Agency for Toxic Substances and Disease Registry; 2007a.

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; 2007b.

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.

National Research Council. Ground Water Models: Scientific and Regulatory Applications. Washington, DC: National Academy of Sciences; 1990.

Oreskes N, Shrader-Frechette K, and Belitz K. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. Science. 1994; 263:641–646.

Pankow JF, and Cherry JA. Dense Chlorinated Solvents and Other DNAPLs in Groundwater: History, Behavior, and Remediation. Portland, OR: Waterloo Press; 1996.

Ricker JA. A Practical Method to Evaluate Ground Water Contaminant Plume Stability. Ground Water Monitoring & Remediation. 2008; 28(4):85–94.

Roy F. Weston, Inc. Remedial Investigation Report, ABC One-Hour Cleaners, Jacksonville, North Carolina: Roy F. Weston, Inc.; 1992.

Roy F. Weston, Inc. Remedial Investigation Report, ABC One-Hour Cleaners, Operable Unit 2, Jacksonville, North Carolina: Roy F. Weston, Inc.; 1994.

Schwille F. Dense Chlorinated Solvents in Porous and Fractured Media. Translated by Pankow, JF. Boca Raton: Lewis Publishers (CRC Press); 1988.

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.

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 1: Department of Navy Comments, June 19, 2008

Assessment of ATSDR Water Modeling for Tarawa Terrace

The purpose of this assessment is (1) to document the Navy/Marine Corps' current understanding of the ATSDR water modeling for Tarawa Terrace and (2) to serve as a basis for additional technical discussions between the Navy/Marine Corps and ATSDR.

Background

1.1 During a Technical Information Meeting with the Marine Corps and Navy on March 26, 2008, the ATSDR presented their water modeling efforts in a summary report entitled "Exposure to Volatile Organic Compounds in Drinking Water and Specific Birth Defects and Childhood Cancer at U.S. Marine Corps Base Camp Lejeune, North Carolina," (March 26, 2008). The report indicates that the following specific information is needed in order to conduct a health study on these birth defects:

1. When did contaminated groundwater reach water supply wells? **month and year**
2. What was the timing, level, and duration of maternal or infant exposure to contaminated drinking water:
    a. In which **months** did exposure occur?
    b. What was the **monthly** average level of contamination?
    c. For how many **months** did exposure occur?

Thus, extensive data are required in order to conduct the proposed health study. Since no measured concentrations of PCE (perchloroethylene) are available prior to 1982, the ATSDR has used modeling to simulate these concentrations at Tarawa Terrace, and proposes a similar modeling approach for Hadnot Point. The results of the Tarawa Terrace modeling are being documented in the ATSDR modeling report entitled "Analysis 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" (ongoing, but initial chapters published in 2007 and 2008).

In general, the usefulness of a groundwater flow and contaminant transport model depends on an accurate estimate of numerous model parameters that describe site geology, groundwater velocity, well pumping rates, and contaminant properties. Many of these parameters are highly variable and difficult to estimate directly. Therefore, model calibration and validation are essential steps in the modeling process. Model calibration involves adjusting the initial parameter values until simulated model concentrations match measured concentrations. In a second step, the calibrated model is validated by comparing simulated concentrations to additional measured concentrations that were not used during calibration. During validation, the model is "put at risk," and it may be judged unsuccessful if the simulated and measured concentrations do not match.

Tarawa Terrace Water Modeling

The Tarawa Terrace housing development at Camp Lejeune was constructed in 1951, and the Tarawa Terrace Water Treatment Plant (WTP) began to distribute drinking water during 1952-1953. The only documented source of contamination at Tarawa Terrace is ABC One-Hour

Cleaners, which began operations during 1953, using the chlorinated solvent PCE in its dry cleaning process. PCE concentrations were measured at the WTP in 1982 and 1985, and no measured concentrations of PCE are available prior to 1982.

Monthly PCE concentrations are required for the ATSDR health study, which will examine
2.1 births that occurred from 1968 (when North Carolina computerized its birth certificates) to 1985
(when the contaminated water supply wells were removed from service). Due to lack of
measured concentrations, the ATSDR used groundwater flow and contaminant transport
modeling in a historical reconstruction process to simulate PCE concentrations in the drinking 3.1
water on a monthly basis from 1952 to 1987.

Figure 1 shows the simulated concentrations of PCE versus measured concentrations in finished
4.1 water from the WTP. Significantly, measured concentrations of PCE are available only in 1982
and 1985, near the end of the overall time period. Thus, the majority of the simulated
concentrations cannot be compared to measured data. Furthermore, all of the measured
concentrations were used during model calibration, leaving no data available for model 5.1
validation. As a result, the Tarawa Terrace model was not validated.

During calibration, model parameters were adjusted to cause the simulated concentrations at the
Water Treatment Plant (WTP) to meet the calibration standard to the degree possible. For PCE
detections, the ATSDR chose the calibration standard to be "± 1/2-order of magnitude of the
observed valued," such that the higher value in the calibration target range is 10 times greater
than the lower value. For example, at the WTP in May 1982, the calibration target range was 25
to 253 ug/L, based on the measured PCE concentration of 80 ug/L. The simulated concentration
of 148 ug/L fell within this range. As another example, at supply well TT-26 in January 1985,
the calibration target range was 500 to 5,000 ug/L based on the measured PCE concentration of 6.1
1,580 ug/L. In this case, the range was quite large because it was calculated from a relatively
high measured concentration. The simulated concentration of 804 fell within the range, near the
lower end. In summary, based on the chosen calibration standard, the calibration process was
viewed as "successful" over a range that spanned a factor of 10. In other words, a model-derived
PCE concentration can be approximately 3 times higher or 3 times lower than the measured
concentration and still fall within the calibration range.

Thus, if all comparisons had fallen within the calibration range, the chosen calibration standard
would give an idea of the accuracy, or degree of fit, between simulated and measured
concentrations. However, all comparisons did not fall within the calibration range. At the WTP,
12% of the simulated PCE concentrations failed the calibration standard (p. F42 in the ATSDR
7.1 modeling report). It should be noted that these failures involved non-detects or very low
concentrations. More significantly, at the water supply wells, a majority (53%) of the simulated
concentrations fell outside the calibration standard (p. F33 in the ATSDR modeling report).
Graphs of simulated versus observed concentrations of PCE in water supply wells RW2, TT-23,
TT-25, TT-26, and TT-54 are shown below in Figures F13 through F17 (p. F34 and F35 of the
ATSDR modeling report). The graphs show that only a few observed PCE concentrations are
available, and there are substantial differences between observed and simulated concentrations.
Model performance at the supply wells raises concerns about the degree to which the model
calibration was successful. It seems reasonable to conclude that the accuracy of historically 8.1

reconstructed PCE concentrations would be less than the calibration standard of ± 1/2-order of
8.1 magnitude. Thus, the historical reconstructions may be viewed as rough estimates of actual
exposure concentrations, with model-derived PCE concentrations representing a relatively wide
range of possible exposures. It is essential that this concept be expressed clearly and consistently
to all stakeholders.

For example, the public needs to understand that the model-derived PCE concentrations
represent a range of possible exposures. This concept should be expressed more clearly on the
Camp Lejeune website (http://www.atsdr.cdc.gov/sites/lejeune/watermodeling.html). Currently
the website has a section that says: "Find Out PCE Levels During Your Tour; Find out the levels
of PCE and PCE degradation by-products in the drinking water serving your home in Tarawa
9.1 Terrace by entering the dates you lived in Tarawa Terrace housing from 1952 to 1987."
Following a disclaimer, a search engine produces contaminant concentrations, reported to 4
significant digits, for any or all months between January 1952 and February 1987. With no error
bars or ranges included, this webpage conveys a sense of certainty that is not justified. The
usefulness of the website would be enhanced if it accurately conveyed the degree of uncertainty
in the model-derived concentrations.

Other concerns with model calibration include the simulation of contaminant mass loading and
10.1 groundwater flow. With Dense, Non-Aqueous Phase Liquids (DNAPLs) such as PCE, mass
estimation is always quite difficult and subject to very high uncertainty due to irregular
movement and distribution of DNAPL in the subsurface. For Tarawa Terrace groundwater, the
difference between observed and simulated elevations is 5 to 10 feet at many times during the 11.1
1970's and 1980's. This is a significant disparity because the total change in groundwater
elevation from the source area to the receptor wells is approximately 10 to 12 feet. In addition,
model results suggest that the simulated PCE concentrations at the WTP depend significantly on
12.1 the pumping rates at the various water supply wells. The degree to which simulated well
operations match actual operations is a concern. The Navy/Marine Corps would welcome the
opportunity for further technical discussion with ATSDR on these issues.

The ATSDR performed a sensitivity analysis to determine the relative importance of individual
model parameters. In addition, a probabilistic analysis was performed to assess variability and
uncertainty associated with the model results. Both approaches are standard practice. Chapter A
of the ATSDR modeling report describes the probabilistic analysis, during which input
parameters such as hydraulic conductivity, recharge, and dispersivity were chosen from
distributions of possible values. The model was run 840 times to produce "realizations" that
form a distribution of simulated PCE concentrations, rather than a single result (pp. A52 – A61
of the ATSDR modeling report). However, certain combinations of input parameters resulted in
13.1 wells drying out, so only 510 physically viable realizations were produced. Thus, 330 out of 840
realizations were not viable, raising concerns about the representativeness of the input parameter
distributions. Although a summary of the probabilistic analysis is presented in Chapter A of the
ATSDR modeling report, the details will be in Chapter I, which is not yet available. The
Navy/Marine Corps feels that additional information on this matter would likely help our 14.1
understanding.

Overall, it is important to keep in mind that both the sensitivity analysis and the probabilistic analysis were performed entirely within the "model world," not the "real world." These methods provide valuable insight into the behavior of the model, but they are not a substitute for real, measured PCE concentrations. Again, the Navy/Marine Corps looks forward to additional discussion and clarification of our understanding of these issues.

Summary

15.1 The usefulness and applicability of the model-derived PCE concentrations for Tarawa Terrace are affected by the following:

1. 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.
2. 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.
3. 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.

16.1 Groundwater modeling studies are always subject to a high degree of uncertainty, and in this sense, the Tarawa Terrace water model is no exception. However, the goal of the Tarawa Terrace model is to reconstruct PCE concentrations on a monthly basis over approximately 30 years in order to conduct a health study. This is an extremely difficult goal since measured PCE concentrations are not available prior to 1982, and the historical reconstruction of monthly exposure concentrations must go back to the 1950's. Any use of reconstructed concentrations must take into account the inherent uncertainty in the model results.

Recommendations

17.1 As a starting point for further discussions, the Navy/Marine Corps proposes the following recommendations:

1. 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.
2. 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.
3. Finalize the remaining sections of the Tarawa Terrace water modeling report.
4. Apply all lessons learned from the Tarawa Terrace modeling efforts to the scoping of the approach for Hadnot Point.

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 2: Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina.

[ATSDR, Agency for Toxic Substances and Disease Registry; DOD, Department of Defense; USN, U.S. Navy; USMC, U.S. Marine Corps; USMCHQ; U.S. Marine Corps Headquarters; CL, Camp Lejeune; EMD, Environmental Management Division; GT, Georgia Institute of Technology; AHE, AH Environmental Consultants; USGS, U.S. Geological Survey; PPT, Power Point presentation; N/A, not applicable]

Date	Activity	Location	Attendees	Notes
7 July 2003	ATSDR site visit to Camp Lejeune	Camp Lejeune, NC	ATSDR: Morris Maslia, Jason Sautner CL/EMD: Thomas Burton, Brynn Ashton, Scott Brewer CL/Water Utilities: Mack Frazelle	ATSDR staff described use of water modeling for historical reconstruction approach, requested data and information
8 Oct 2003	Presentation of ATSDR's water modeling approach	ATSDR, Atlanta, GA	ATSDR: Morris Maslia, Jason Sautner, Frank Bove, Wendy Kaye, G. David Williamson GT: Mustafa Aral USMHQ: Nick Ta USMC/CL: Thomas Burton USN: Kim Parker-Brown DOD: T. Michael White	Copies of presentation provided at meeting including CD-ROM containing PPT presentation. See attached meeting sign-in sheet and presentation title slide
11 Mar 2004	Presentation of ATSDR's water modeling approach to USMC/CL, USMCHQ staff, and USMC contractor	Camp Lejeune, NC	ATSDR: Morris Maslia, Jason Sautner, Frank Bove, Claudia Valenzeula USMC/CL: Scott Brewer, Scott Williams, Brynn Ashton, Thomas Burton, Mack Frazelle, Danny Hill, CAPT Kevin Slates (AC/S I&E) USMCHQ: MAJ Harold Graef CONTRACTORS: Robert Faye (ATSDR), AHE (USMC)	Copies of presentation provided to meeting attendees. See attached meeting sign-in sheet, and presentation title slide
28 Mar 2005	Expert Peer Review Panel to review ATSDR's water-modeling activities at Camp Lejeune	ATSDR, Atlanta, GA	Panel members – See attached list	USMC representative sitting on panel–Dr. Peter Pommerenk of AHE. See Maslia (2005) for peer panel report
26 Aug 2005	Meeting with and presentation to Lt. General Kelly	USMCHQ, Washington, DC	ATSDR: Tom Sinks, Frank Bove, Perri Ruckart, Morris Maslia USMCHQ: Lt. Gen. Kelly and staff, Carla Lucchino (ADC/I&L), Kelly Dryer, Craig Sakai, et al. USMC/CL: Scott Williams, Brynn Ashton	ATSDR presents results of arrival of PCE at TT-26 (May 1960) and TT-23 (Summer 1984) above 5 ppb level. See meeting agenda and talking points

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Date	Activity	Location	Attendees	Notes
18 May 2006	Meeting with and presentation to Lt. General Kramlich	USMCHQ, Washington, DC	ATSDR: Tom Sinks, Frank Bove, Perri Ruckart, Morris Maslia USMCHQ: Lt. Gen. Kelly and staff, Carla Lucchino (ADC/I&L), Kelly Dryer, Craig Sakai, et al. USMC/CL: Scott Williams, Brynn Ashton	ATSDR presents approach to water modeling and summary of water-modeling results for Tarawa Terrace area, including graph showing PCE concentrations in well TT-26 and at Tarawa Terrace water treatment plant. Copies of presentation including CD given to Lt. Gen. Kramlich and staff
11 June 2007	Meeting with and presentation to Lt. General Kramlich – Final Tarawa Terrace results (Executive Summary report)	USMCHQ, Washington, DC	ATSDR: Tom Sinks, Frank Bove, Perri Ruckart, Morris Maslia USMCHQ: Lt. Gen. Kelly and staff, Carla Lucchino (ADC/I&L), Kelly Dryer, Craig Sakai, et al. USMC/CL: Fred Cone, Scott Williams, Brynn Ashton	ATSDR summary of FINAL Tarawa Terrace water-modeling results. Provides USMC with copies of Tarawa Terrace Executive Summary report (to be publically released 12 June 2007). Copies of presentation given to Lt. Gen. Kramlich and staff
July 2007 – Feb 2008	Public release of final Tarawa Terrace Chapter Reports (A-H) in hard copy and on ATSDR Web site	Atlanta, GA	N/A	Chapter A (Summary of Findings) released July 2007. Chapter F (Fate and Transport) released February 2008.
26 Mar 2008	Technical information meeting with USN and their consultants	ATSDR, Atlanta, GA	ATSDR: Morris Maslia, Jason Sautner, Frank Bove, Bill Cibulas, Susan Moore, etc. GT: Mustafa Aral ERG: Robert Faye USMC/CL: Scott Williams USN: Kim-Parker Brown, Dan Waddill DOD: T. Michael White USN Consultants: Hall Davis (USGS), Peter Pommerenk (AHE)	ATSDR presents summary details of all Tarawa Terrace water-modeling results. Q&A on technical aspects of historical reconstruction and water-modeling approach. ATSDR also presents work plan for Hadnot Point/Holcomb Boulevard with time line.
19 June 2008	U.S. Navy transmits to ATSDR electronic written comments on: Assessment of ATSDR Water Modeling for Tarawa Terrace	N/A	Letter written to Tom Sinks with copies to H. Frumkin, C. Aloisio, F. Bove, and M. Maslia (and other USN/USMC staff)	Electronic mail transmitting letter from Kim-Parker Brown requests response by 8 July 2008.

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with DOD, US Navy, and US Marine Corps to Present ATSDR's Water-Modeling Approach, 8 October 2003

Historical Reconstruction of Water Resources for Marine Corps Base Camp Lejeune, North Carolina: ATSDR's Approach

October 8, 2003

Sign-in Sheet

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Meeting with DOD, US Navy, and US Marine Corps to Present ATSDR's Water-Modeling Approach, 8 October 2003

Historical Reconstruction of Water Resources for Marine Corps Base Camp Lejeune, North Carolina:

ATSDR's Approach

Morris L. Maslia, P.E.
Research Environmental Engineer
Project Officer, Exposure-Dose Reconstruction Project
Agency for Toxic Substances and Disease Registry

October 8, 2003
Atlanta, Georgia

08 OCT 03

ATSDR

Models to be applied

Groundwater:
MODFLOW

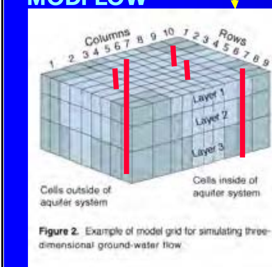
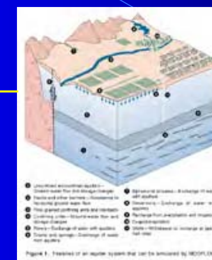
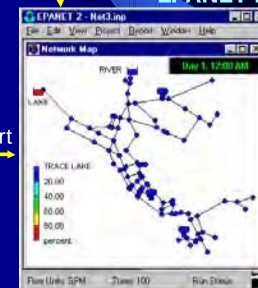


Figure 2. Example of model grid for simulating three-dimensional ground-water flow



Production/fate & transport
uncertainty/variability

Water distribution:
EPANET 2



08 OCT 03

ATSDR

Critical Data Needs (Model Calibration)

- Hydrogeologic characterization (geophysical logs from drilled water-supply wells or test wells)
- Field-test data of water-distribution system
- Water production from groundwater wells
- Operational data (on/off cycling of wells and pumps)
- Distribution of consumption by consumption type (e.g. residential, industrial, recreational, etc. – Conservation study ??)

08 OCT 03

ATSDR

Project Deliverables

Sep 30, 2004	• Groundwater flow model calibration/simulation • Water-distribution system field tests and network
Sep 30, 2005	• Groundwater transport model calibration/simulation • Water-distribution system: Field-test data reports and model calibration • Groundwater flow and transport model report • Initial sensitivity and uncertainty analysis
Sep 30, 2006	• Water-distribution system: Historical network configuration, spatial distribution of contaminants, and present-day model report
Sep 30, 2007	• Assessment/reduction of uncertainty and variability • Final report

08 OCT 03

ATSDR

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Meeting with US Marine Corps and their Consultants to Present ATSDR's Water-Modeling Approach, 11 March 2004

Water Modeling Coordination Meeting
11 March 2004
ATSDR – HQMC/ LFL – MCBCL – AH Environmental

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Neal Paul	EMD/I&E	x5518	paulnn@ "

Meeting with US Marine Corps and their Consultants to Present ATSDR's Water-Modeling Approach, 11 March 2004

Historical Reconstruction of Water Resources for Marine Corps Base Camp Lejeune, North Carolina:
Field-Data Collection and Modeling

Morris L. Maslia, P.E., DEE
Research Environmental Engineer
Project Officer, Exposure-Dose Reconstruction Project
Agency for Toxic Substances and Disease Registry

March 11, 2004
MCB, Camp Lejeune, NC

11 MAR 04 ATSDR

Questions to be Addressed

- What was (were) the source(s) of contaminated potable water?
- Which chemical compounds contaminated the water supply?
- When did contaminated groundwater reach water-supply wells and what was the duration of the contamination?
- How was contaminated water distributed throughout the Camp Lejeune water-distribution system?
- What were the frequency, duration, and spatial distribution of exposure to contaminated water?

11 MAR 04 ATSDR

Critical Data Needs - Groundwater (Model Calibration)

- Hydrogeologic characterization (geophysical logs from drilled water-supply wells or test wells)
- Synoptic water-level measurements (present-day and historical)
- Historical water-quality (contaminant) data

11 MAR 04 ATSDR

Project Deliverables

Sep 30, 2004	• Groundwater flow model calibration/simulation • Water-distribution system field tests and network
Sep 30, 2005	• Groundwater transport model calibration/simulation • Water-distribution system: Field-test data reports and model calibration • Groundwater flow and transport model report • Initial sensitivity and uncertainty analysis
Sep 30, 2006	• Water-distribution system: Historical network configuration, spatial distribution of contaminants, and present-day model report
Sep 30, 2007	• Assessment/reduction of uncertainty and variability • Final report

11 MAR 04 ATSDR

Attachment 2. Chronology of meetings, presentations, and publications related to the historical reconstruction of contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina—continued

Expert Peer Review Panel Meeting, Atlanta, Georgia, March 28–29, 2005

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

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

Analyses of Groundwater Resources and Present-Day (2004) Water-Distribution Systems, March 28-29, 2005

Edited by
Morris L. Maslia

Prepared for:
Agency for Toxic Substances and Disease Registry, Atlanta, Georgia

Prepared by:
Eastern Research Group, Inc., Atlanta, Georgia

Appendix B

Panel Members

Barry L. Johnson, PhD, FCR
Panel Chair, Assistant Surgeon General (ret.)
Adjunct Professor, Rollins School of Public Health, Emory University;
Editor, Journal of Human and Ecological Risk Assessment
Atlanta, Georgia

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Cincinnati, Ohio

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Duxbury, Massachusetts

Benjamin L. Harding, PE
Principal Engineer, Hydrosphere Resource Consultants, Inc.
Boulder, Colorado

Leonard F. Konikow, PhD, PG
Research Hydrologist, U.S. Geological Survey
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Scientist, University of California,
Davis, California

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Project Manager, AH Environmental Consultants, Inc.
Newport News, Virginia

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Louisiana State University
Baton Rouge, Louisiana

James G. Uber, PhD
Associate Professor, Department of Civil and Environmental Engineering, University of Cincinnati, Ohio

Thomas M. Walski, PhD, PE, DEE
Vice President, Engineering Bentley Systems
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List of Presenters and Project Team Attendees

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Expert Peer Review Panel Meeting, Summary and Recommendations, March 28–29, 2005

6.0 Summary of Recommendations from Panel Members and ATSDR's Response

At the end of the meeting, the panel chair, the panel members, and ATSDR agreed that panel members would individually provide overall final comments, recommendations, and conclusions to ATSDR. Specific comments and recommentations from each panel member are provided in the verbatim transcript of the meeting (Volume II) on CD-ROM. The recommendations and ATSDR's responses are grouped into five generalized categories.

6.1 Data Discovery

Panel members recommended that ATSDR expend additional effort and resources in the area of conducting more rigorous data discovery activities. To the extent possible, the agency should augment, enhance, and refine data it is relying on to conduct water-modeling activities.

ATSDR agrees with the panel recommendation. The agency is planning to devote additional resources and work with its partners and contractors to implement data discovery activities.

6.2 Chronology of Events

Panel members recommended that ATSDR focus its next efforts on refining its understanding of chronological events. These need to include documenting periods of known contamination, times when water-distribution systems were interconnected, and the start of operations of the Holcomb Blvd. WTP.

ATSDR agrees with the panel recommendation. The agency is planning to devote additional resources and work with its partners and contractors to obtain updated information so that the water-modeling team can refine its understanding of the chronology of contamination events.

6.3 Groundwater Modeling, Tarawa Terrace Area

Panel members made several recommendations with respect to groundwater modeling and associated activities for the Tarawa Terrace area, including the following:

(1) conduct sensitivity and uncertainty analyses to refine initial estimates of model parameter values,
(2) determine sensitivity of model to grid/cell sizes and boundary conditions,
(3) refine on/off cycling patterns of water-supply wells, and
(4) conduct fate and dispersive transport analyses.

ATSDR agrees in principal with the panel recommendations. The water-modeling team is planning to devote significant effort in conducting sensitivity and uncertainty analyses and in developing a calibrated fate and dispersive transport model for the Tarawa Terrace area.

6.4 Data Analyses, Hadnot Point Area

Panel members recommended that ATSDR proceed with assessment of data to develop an understanding of geohydrologic and groundwater-contamination characteristics for the Hadnot Point area. These activities would be required before initiating additional modeling activities for the Hadnot Point area. Panel members also recommended that additional efforts be put into determining periods of interconnection between the Hadnot Point and Holcomb Blvd. water-distribution systems.

ATSDR agrees with the panel recommendation. The agency is planning to devote additional resources and work with its partners and contractors to implement the panel recommendations.

6.5 Water-Distribution System Analyses

Panel members commended ATSDR for the vigor and quality of its field investigation and current model simulations of the water-distribution systems. Because flowmeters are already installed, members recommended that ATSDR proceed with collecting data from the flowmeters, but not initiate any additional field-testing activities. Panel members recommended that the water-modeling team consider using more simplified mixing models to quantify historical exposures to drinking-water supplies. (More complex modeling might be warranted if data discovery shows that the water-distribution systems had a greater frequency of interconnectivity.)

ATSDR agrees with the panel recommendation. The agency has concluded its water-distribution system field-testing activities. Additionally, the water-modeling team will be using simplified mixing models as a first estimate of historical exposures to contaminated drinking-water supplies.

Meeting with Lt. General Kelly and Staff, U.S. Marine Corps Headquarters, 26 August 2005

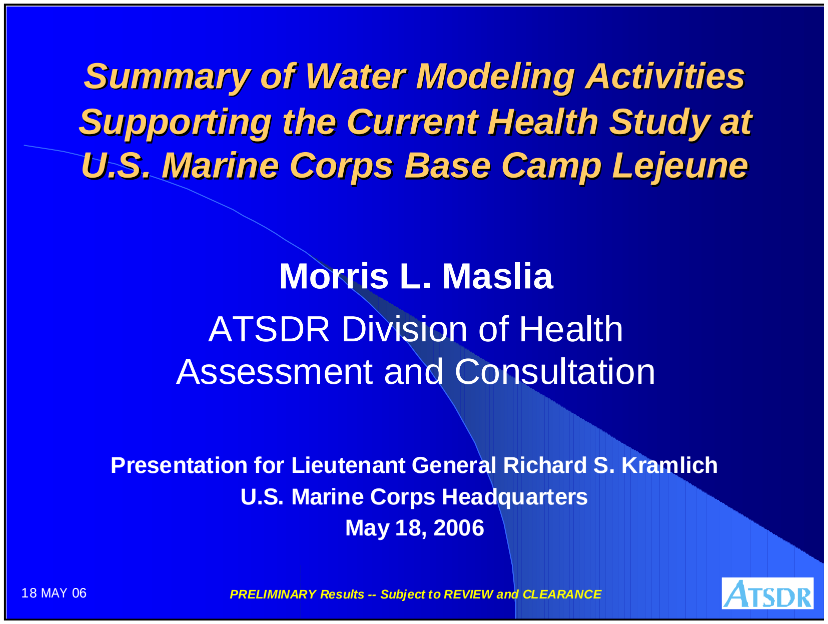
Agenda
Agency for Toxic Substances and Disease Registry (ATSDR)
and U.S. Marines
Camp Lejeune Health Study
August 26, 2005
Marine Corps Headquarters, Washington D.C.
2:30 to 4:30 PM

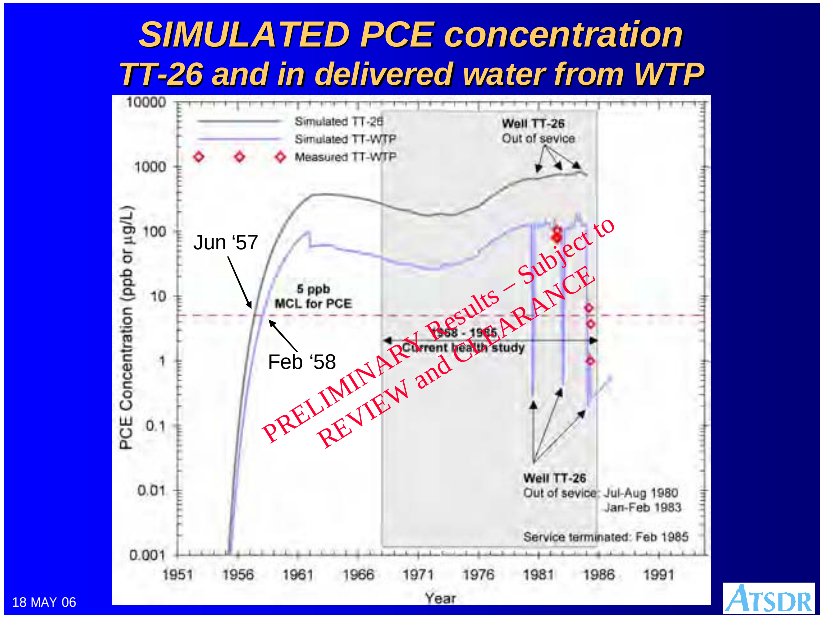
Introductions	Dr. Thomas Sinks ATSDR) LtGen. Kelly (USMC)
Peer Panel Recommendations- Response	Dr. Frank Bove
Release of ATSDR Response	Dr. Thomas Sinks
Update on Current Study Status	Dr. Perri Ruckart Mr. Morris Maslia
Questions & Answers	

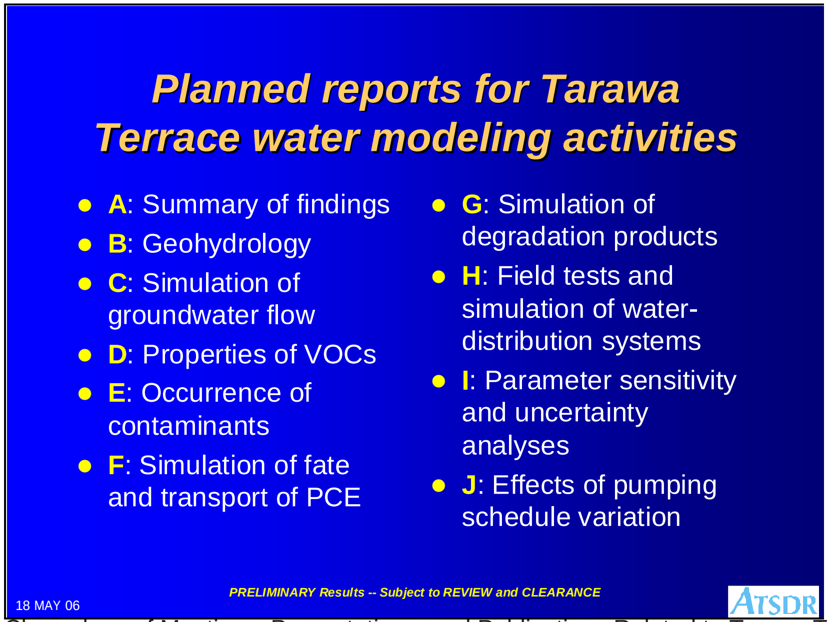
Talking Points for Meeting with Lt. General Kelley
August 26, 2005

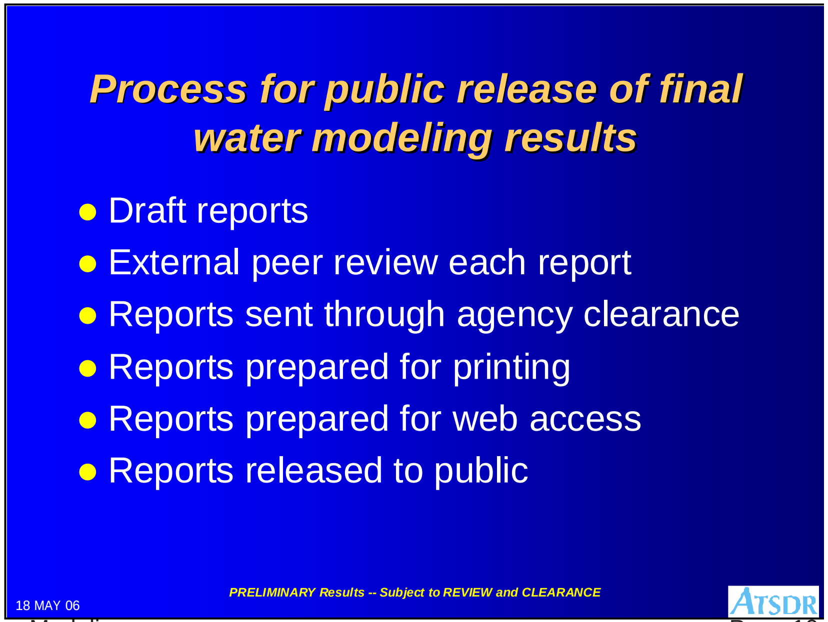
- Schedule indicates knowledge of arrival of contaminants at wells by September 30, 2005. We have that information NOW!
  - PCE at 5 ppb (MCL) arrived at well TT-26 in May 1960
  - PCE at 5 ppb (MCL) arrived at well TT-23 –Summer 1984 (no specific data on in service data for well, but simulations required use of well)
- Present-day water-distribution system models are calibrated
  - Some refinement based on most recent field data and flow meter data that we have been collecting since May 2005
  - ATSDR will remove all field testing equipment (complete all field test activities) on 7 September 2005
- Release report on Water Modeling Expert Peer Review Panel — September 30, 2005
- Recommendation for Water Modeling Expert Peer Review Panel
  - Conducting Data Discovery activities to determine issues w.r.t. interconnections
  - Conducting sensitivity and uncertainty analyses to provide epidemiologist with ranges of exposure concentrations
  - Developing geohydrologic framework and groundwater contamination data in Hadnot Point area
- Ongoing Activities
  - Data Discovery (per recommendation of Expert Panel)
    - ERG got MOD last week
    - ERG searching of Jr. Level engineers for CL, LANDTIV, and MCHQ
    - Searching for data on interconnections, well operations, Hadnot Point
  - Sensitivity/Uncertainty analyses
    - Groundwater flow models
    - Contaminant fate and transport models
    - Water-distribution system models
  - Geohydrologic framework and characterization of contamination at Hadnot Point
- Reports
  - Water modeling expert peer review panel
  - Geohydrology at Tarawa Terrace area
  - Characterization of contamination at Tarawa Terrace area
  - Groundwater flow, fate and transport at Tarawa Terrace area
  - Water-distribution system field tests
  - Present-day water-distribution systems

Meeting with Lt. General Richard Kramlich and Staff, U.S. Marine Corps Headquarters, 18 May 2006

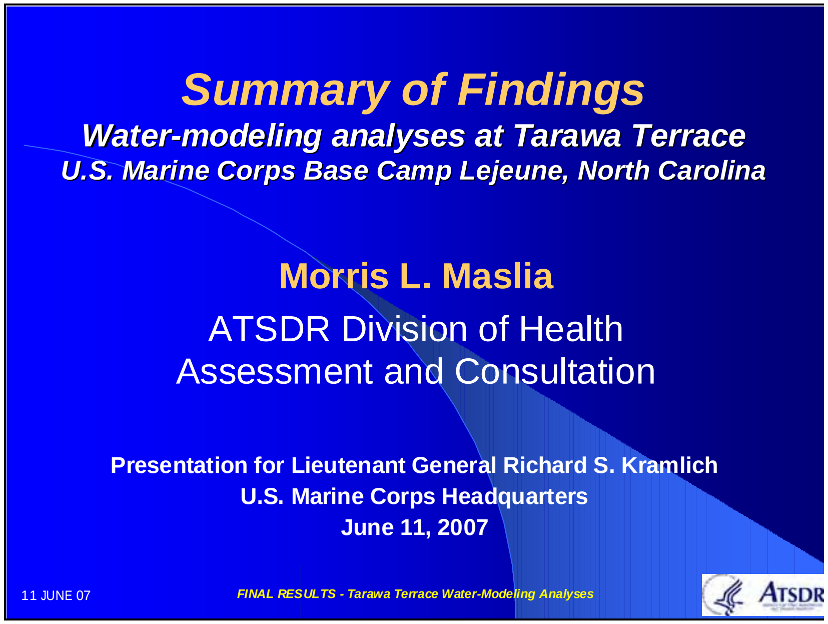


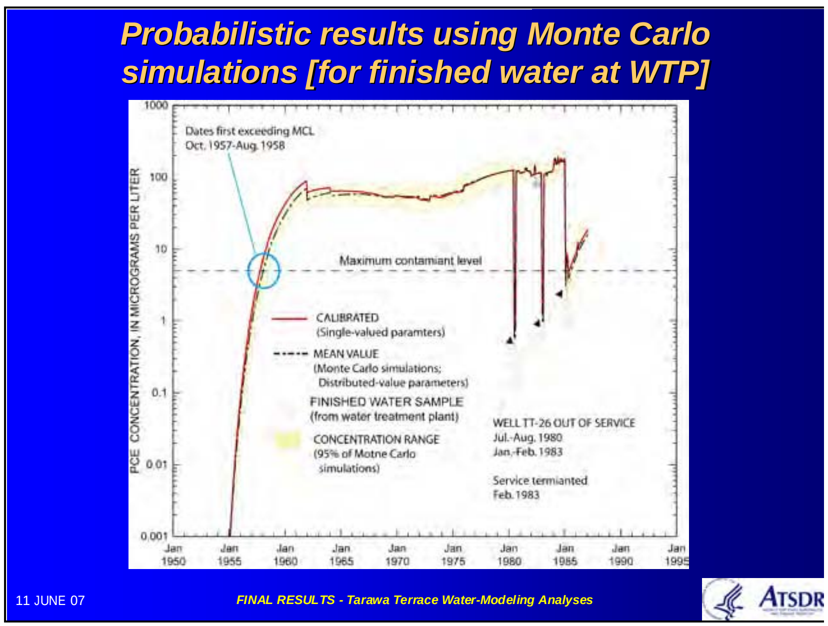


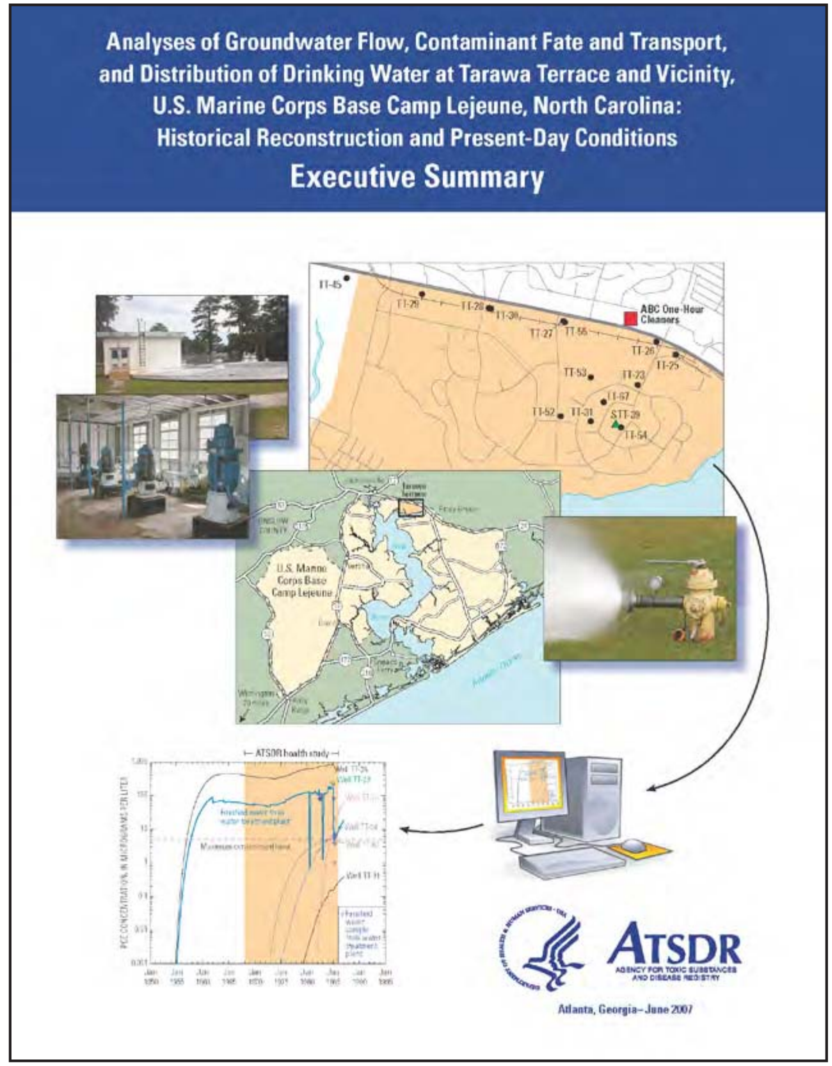




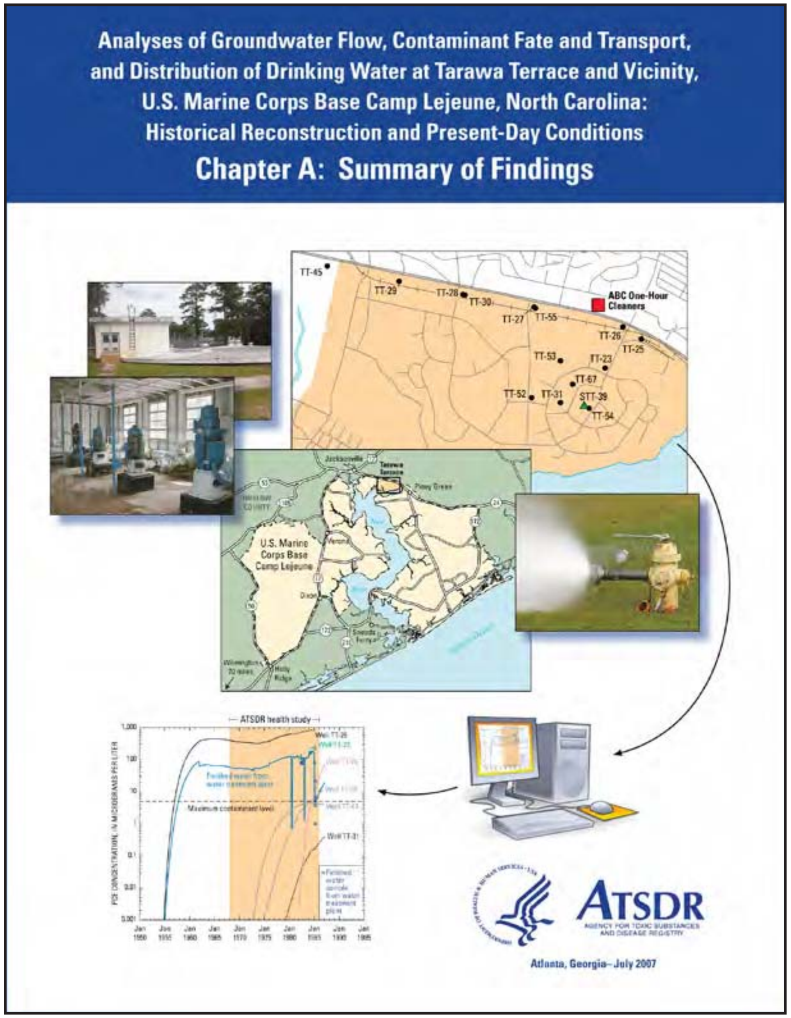
Meeting with Lt. General Richard Kramlich and Staff, U.S. Marine Corps Headquarters, 11 June 2007



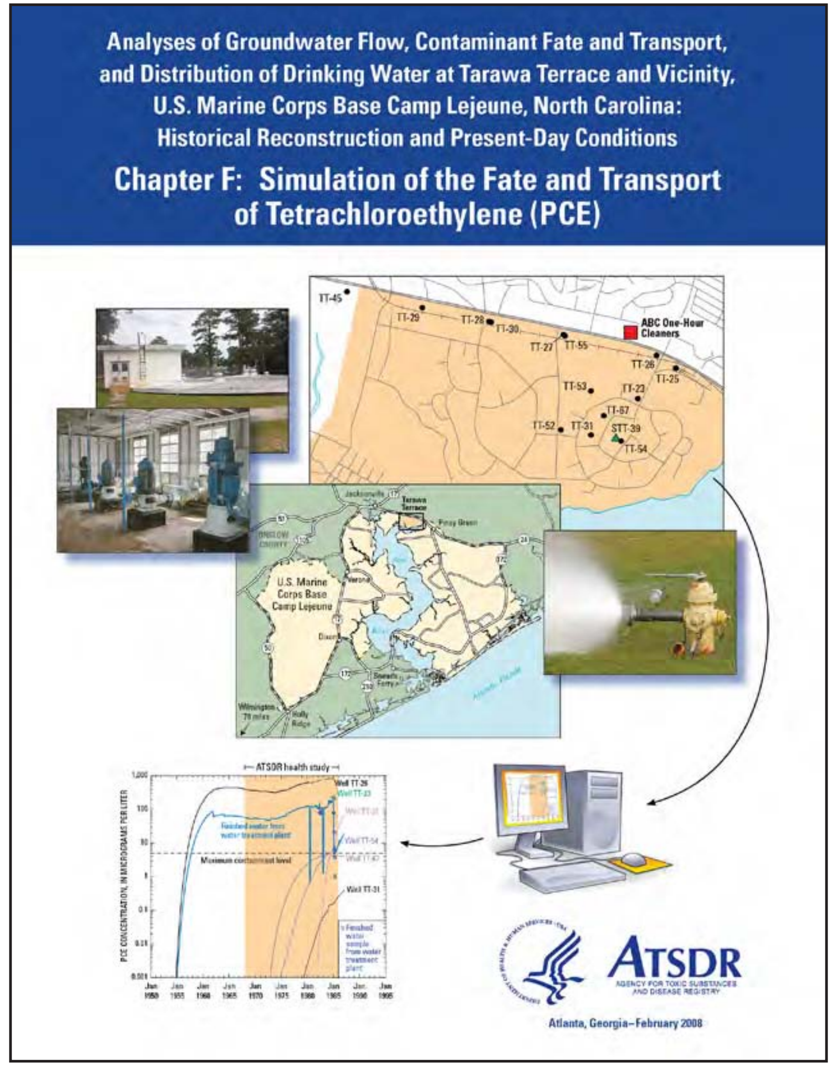




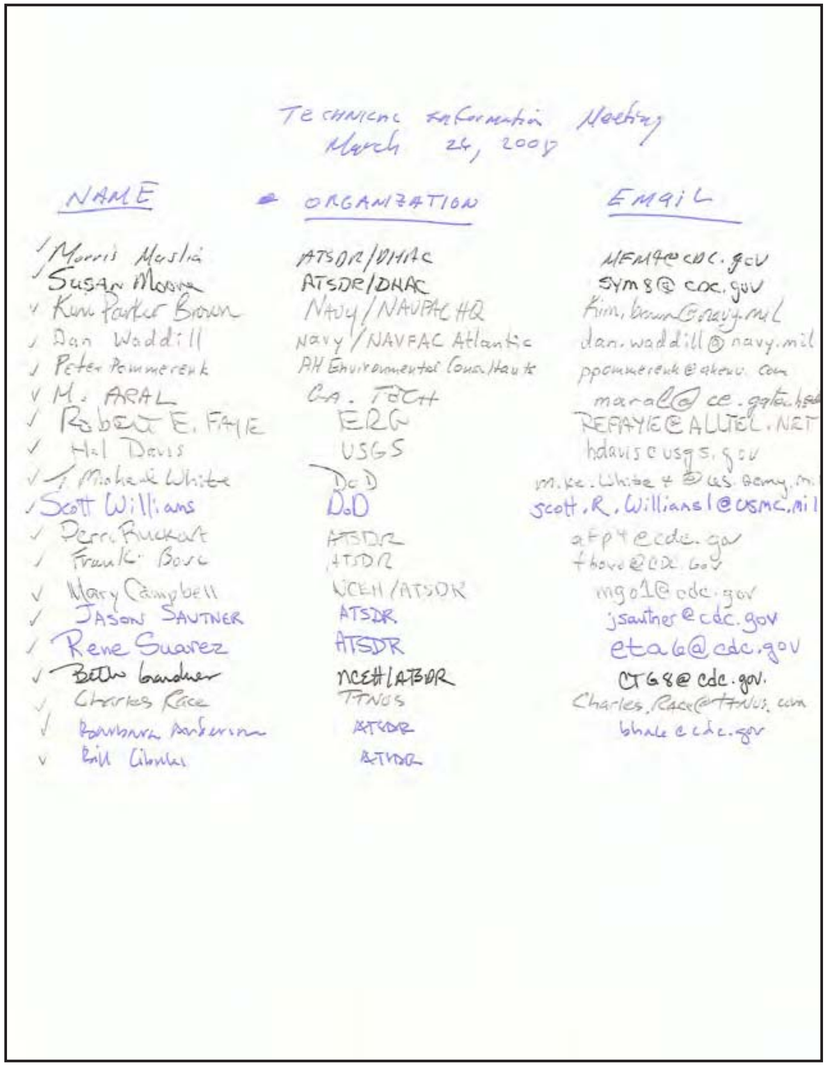
Release of Tarawa Terrace Chapter A Report (Summary of Findings), July 2007



Release of Tarawa Terrace Chapter F Report (Fate and Transport), February 2008



Technical Information Meeting with U.S. Navy and U.S. Marine Corps, 26 March 2008



Technical Information Meeting
March 24, 2008

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Bill Cibulas	ATSDR	

D R A F T — Subject to Change

WORK PLAN II

Historical Reconstruction Analysis of
Volatile Organic Compound Contamination of Drinking Water Supplies
United States Marine Corps Base
Camp Lejeune, North Carolina

by Morris L. Maslia, MSCE, P.E.

Exposure Investigations and Site Assessment Branch
Division of Health Assessment and Consultation
Agency for Toxic Substances and Disease Registry

March 20, 2008

Camp Lejeune, NC, Health Study Page 1

Technical Information Meeting with U.S. Navy and U.S. Marine Corps, 26 March 2008

Table 2. Schedule of proposed tasks, activities, and meetings, historical reconstruction analysis of contaminated drinking water, Hadnot Point and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Fiscal Year 2008: Quarter 2 (Jan, Feb, Mar), Quarter 3 (Apr, May, Jun), Quarter 4 (Jul, Aug, Sep). Fiscal Year 2009: Quarter 1 (Oct, Nov, Dec), Quarter 2 (Jan, Feb, Mar), Quarter 3 (Apr, May, Jun), Quarter 4 (Jul, Aug, Sep).

Task or activity	Duration	Start date
Data analysis (16 sites)	13 weeks	1/2/2008
Computation of mass ~6 sites)	12 weeks	3/17/2008
Well capacity histories (100 wells)	12 weeks	3/10/2008
Statistical analysis	21 weeks	4/2/2008
Fate analysis	8 weeks	6/9/2008
Model selection	8 weeks	2/4/2008
Grid design and data input	8 weeks	3/31/2008
Fate and transport analysis	13 months	5/26/2008
Water distribution system analysis	2 months	4/27/2008
Uncertainty analysis	6 months	4/20/2009
External progress meetings	—	6/26/2008
Citizens Advisory Panel meetings	—	4/17/2008
Reports	—	9/30/2008

Table 3. Comparison of data and information availability for Hadnot Point and Tarawa Terrace areas.

Descriptive data and information	Hadnot Point and vicinity[1]	Tarawa Terrace and vicinity
Active model domain	40 mi^2	2.1 mi^2
Number of wells and boreholes (includes hydropunch)	720	185
Number of water-level measurements	4,700	820
Number of groundwater samples analyzed for chlorinated solvents	2,200	192
Number of groundwater samples analyzed for Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX)	1,800	191

[1]Estimated values for Hadnot Point and vicinity

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 3: Comparison of contaminant fate and transport calibration statistics for the Naval Air Station, Jacksonville, Florida, and Tarawa Terrace, Camp Lejeune, North Carolina Sites

Attachment 3. Comparison of contaminant fate and transport analyses calibration statistics

Site[1]	Contaminant	Number of paired data points (excluding non-detects)[2]	Number of simulated data points within calibration target[3]	Number of simulated data points outside calibration target	Ratio (percentage) passing calibration target	Ratio (percentage) failing calibration target	Root-mean-square of concentration difference, in µg/L[4]
Naval Air Station, Jacksonville, FL	Trichloroethylene (TCE)	16	9	7	9/16 (56%)	7/16 (44%)	329
Tarawa Terrace, Camp Lejeune, NC	Tetrachloroethylene (PCE)	29	17	12	17/29 (59%)	12/29 (41%)	337

[1] Refer to the following references: **Jacksonville NAS**: Davis JH. Fate and Transport Modeling of Selected Chlorinated Organic Compounds at Hangar 1000, U.S. Naval Air Station, Jacksonville, Florida. Tallahassee, FL: U.S. Geological Survey Water-Resources Investigations Report 03-4089; 2003; **Tarawa Terrace, Camp Lejeune**: 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.

[2] Paired data point, a location with observed data (concentration) that is associated with a model location for the purpose of comparing observed data with model results; for Davis (2003), see Figure 34 (page 37); for Maslia et al. (2007), see Tables A9 and A10 (pages A27 and A28).

[3] No calibration target was described in Davis (2003) for contaminant fate and transport modeling. Therefore, the calibration target described in Maslia et al. (2007, Table A8) of ±1/2-order of magnitude of observed data is used for comparison purposes.

[4] The root-mean-square or RMS is defined as:

$$RMS = \left[\frac{\sum_{i=1}^{N_P} \left(C_i^{obs} - C_i^{sim} \right)^2}{N_p} \right]^{1/2}$$

, where N_p is the number of paired data points, C_i^{obs} is the observed or measured concentration of the ith paired data point, and C_i^{sim} is the corresponding model simulated concentration of the ith paired data point.

Attachment 3. Comparison of contaminant fate and transport analyses calibration statistics—continued

Fate and transport of trichloroethylene (TCE), Hangar 1000, Naval Air Station, Jacksonville, Florida[1]					
Sample location[3]	Measured concentration, in µg/L	Calibration target[4, 5]		Simulated concentration, in µg/L	Pass or fail calibration target
		+1/2-order of magnitude	-1/2-order of magnitude		
H10-MW01	7.8	25	3	19.8	Pass
H10-MW02	1.0	3	0	0.0	Pass
H10-MW03	3.1	10	1	0.0	Fail
H10-MW05	18.5	59	6	0.0	Fail
H10-MW06	36.2	115	11	231.6	Fail
H10-MW07	4.2	13	1	25.3	Fail
H10-MW08	8,608.5	27,223	2,722	8,710.0	Pass
H10-MW10	1.0	3	0	0.0	Pass
H10-MW12	94.5	299	30	596.4	Fail
H10-MW14	266.0	841	84	652.6	Pass
H10-MW15	578.0	1,828	183	356.5	Pass
H10-MW16	48.1	152	15	47.2	Pass
H10-MW17	16.3	52	5	29.5	Pass
H10-MW18	0.8	3	0	8.6	Fail
H10-MW19	1,077.8	3,409	341	229.0	Fail
H10-MW22	1,610.0	5,091	509	2,396.0	Pass

Fate and transport of tetrachloroethylene (PCE), Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina[2]					
Sample location and date	Measured concentration, in µg/L	Calibration target[5]		Simulated concentration, in µg/L	Pass or fail calibration target
		+1/2 order of magnitude	-1/2 order of magnitude		
TT-23:					
1/16/1985	132	42	417	254	Pass
2/12/1985	37	12	117	253	Fail
2/19/1985	26.2	8	83	253	Fail
3/11/1985	14.9	5	47	265	Fail
3/11/1985	16.6	5	53	265	Fail
3/121985	40.6	13	128	265	Fail
3/12/1985	48.8	15	154	265	Fail
9/251985	4	1	13	279	Fail
TT-25:					
9/25/1985	0.43	0	1	18.1	Fail
7/11/1991	23	7	73	72.7	Pass
TT-26:					
1/16/1985	1,580.0	500	4,996	804	Pass
2/12/1985	3.8	1	12	804	Fail
2/19/1985	64.0	20	202	798	Fail
2/19/1985	55.2	18	175	798	Fail
4/9/1985	630	199	1,992	801	Pass
6/24/1985	1,160.0	367	3,668	799	Pass
9/25/1985	1,100.0	348	3,468	788	Pass
7/11/1991	350.0	111	1,107	670	Pass
RW2:					
7/12/1991	760	240	2,403	879	Pass
TT-WTP:					
5/27/1992	80	25	253	148	Pass
7/28/1982	104	33	329	112	Pass
7/28/1982	76	24	240	112	Pass
7/28/1982	82	26	259	112	Pass
2/5/1985	80	25	253	176	Pass
2/11/1985	215	68	680	176	Pass
3/12/1985	6.6	2	21	8.7	Pass
3/12/1985	21.3	7	67	8.7	Pass
4/22/1985	1	0	3	8.1	Fail
4/29/1985	3.7	1	12	8.1	Pass

[1] Sample data and simulation results from Davis (2003, Figure 34).

[2] Sample data and simulation results from Maslia et al. (2007, Tables A9 and A10).

[3] All samples measured on January 17, 2001 (Davis 2003, Figures 16 and 34).

[4] No calibration target was provided in Davis (2003) for contaminant fate and transport modeling; the calibration targets ±1/2-order of magnitude of measured data suggested by Maslia et al. (2007) are applied to the measured data of Davis (2003, Figure 16) for comparison purposes.

[5] Calibration targets are rounded to nearest integer.

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 4: Simulated concentrations of tetrachloroethylene in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina (From Maslia et al. 2008, Appendix I5)

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

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 5: A Practical Method to Evaluate Ground water Plume Stability (Ricker 2008)

Ground Water Monitoring&Remediation

A Practical Method to Evaluate Ground Water Contaminant Plume Stability

by Joseph A. Ricker

Abstract

Evaluating plume stability is important for the evaluation of natural attenuation of dissolved chemicals in ground water. When characterizing ground water contaminant plumes, there are numerous methods for evaluating concentration data. Typically, the data are tabulated and ground water concentrations presented on a site figure. Contaminant concentration isopleth maps are typically developed to evaluate temporal changes in the plume boundaries, and plume stability is often assessed by conducting trend analyses for individual monitoring wells. However, it is becoming more important to understand and effectively communicate the nature of the entire plume in terms of its stability (i.e., is the plume growing, shrinking, or stable?). This article presents a method for evaluating plume stability using innovative techniques to calculate and assess historical trends in various plume characteristics, including area, average concentration, contaminant mass, and center of mass. Contaminant distribution isopleths are developed for several sampling events, and the characteristics mentioned previously are calculated for each event using numerical methods and engineering principles. A statistical trend analysis is then performed on the calculated values to assess the plume stability. The methodology presented here has been used at various contaminated sites to effectively evaluate the stability of contaminant plumes comprising tetrachloroethene, carbon tetrachloride, pentachlorophenol, creosote, naphthalene, benzene, and chlordane. Although other methods for assessing contaminant plume stability exist, this method has been shown to be efficient, reliable, and applicable to any site with an established monitoring well network and multiple years of analytical data.

Introduction

Evaluating plume stability is important for the evaluation of natural attenuation of dissolved chemicals in ground water. U.S. EPA (1998) states that the primary line of evidence in evaluating natural attenuation is historical ground water chemistry data that demonstrate a clear and meaningful trend of decreasing contaminant mass and/or concentration over time at appropriate monitoring or sampling points. When characterizing ground water contaminant plumes, there are numerous methods for evaluating concentration data.

Wiedemeier et al. (2000) discussed common approaches for evaluating plume stability using both graphical and statistical techniques. Graphical methods include the following: (1) the preparation of contaminant concentration isopleth maps; (2) plotting concentration data vs. time for individual monitoring wells; and (3) plotting concentration data vs. distance downgradient for several monitoring wells. Common statistical methods for evaluation of temporal and spatial trends include regression analysis (U.S. EPA 2006), the Mann-Whitney *U*-test (Mann and Whitney 1947), and the Mann-Kendall test (U.S. EPA 2006; Gilbert 1987).

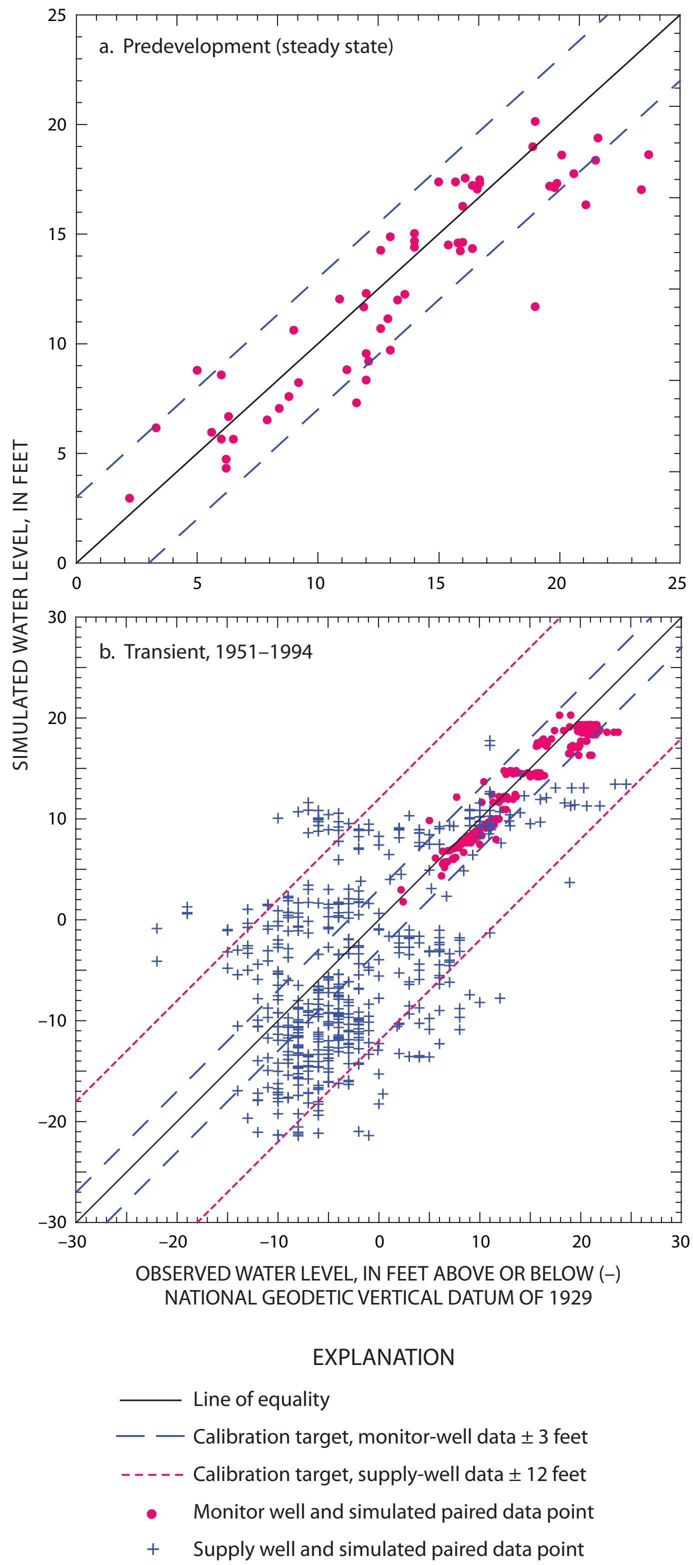
Graphical plume stability analysis by comparing isopleth maps over time can provide compelling visual evidence for natural attenuation. However, a comparison of apparent plume size over time does not always provide a complete analysis. Consider, for example, the case of a plume that discharges to a surface water body, or a plume geometry that is persistent over time. In this case, the plume area would remain relatively unchanged, whereas the overall plume average concentration and mass may be decreasing. The change in plume mass would not be necessarily reflected in the visual analysis of isopleth maps. However, a quantitative analysis of changes in overall plume concentration and mass would provide a better understanding of the plume stability.

A common approach for evaluating plume stability is the use of statistical analysis techniques for single-well data. However, chemical concentration trends at individual monitoring wells may show different trends. For example, at a given site, there may be wells exhibiting decreasing

Response to the Department of the Navy's Letter on Assessment of ATSDR Water Modeling for Tarawa Terrace

Attachment 6: Observed and simulated water levels, model layer 1, and calibration targets for (*a*) predevelopment (steady state) conditions and (*b*) transient conditions, 1951–1994, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2007b, Figure A10)

Attachment 6: ATSDR response to DON letter of June 19, 2008



Attachment 7: Summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2007b, Table A8)

Table A8. Summary of calibration targets and resulting calibration statistics for simulation models used to reconstruct historical contamination events at Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Calibration level[1, 2]	Analysis type	Calibration target[3]	Resulting calibration statistics[4]	[5]Number of paired data points (N)
1	Predevelopment (no pumping) groundwater flow	Magnitude of head difference: 3 feet	$\lvert\overline{\Delta h}\rvert$ = 1.9 ft σ = 1.5 ft *RMS* = 2.1 ft	59
2	Transient groundwater flow—monitor wells	Magnitude of head difference: 3 feet	$\lvert\overline{\Delta h}\rvert$ = 1.4 ft σ = 0.9 ft *RMS* = 1.7 ft	263
	Transient groundwater flow—supply wells	Magnitude of head difference: 12 feet	$\lvert\overline{\Delta h}\rvert$ = 7.1 ft σ = 4.6 ft *RMS* = 8.5 ft	526
3	Contaminant fate and transport—supply wells	Concentration difference: ± one-half order of magnitude or model bias (B_m) ranging from 0.3 to 3	Geometric bias [6]B_g = 5.8/3.9	[7]36
4	Mixing model—treated water at water treatment plant	Concentration difference: ± one-half order of magnitude or model bias (B_m) ranging from 0.3 to 3	Geometric bias B_g = 1.5	[8]25

[1]Refer to the Chapter C report (Faye and Valenzuela In press 2007) for calibration procedures and details on levels 1 and 2

[2]Refer to the Chapter F report (Faye In press 2007b) for calibration procedures and details on levels 3 and 4

[3]Head difference is defined as observed water level (h_{obs}) minus simulated water level (h_{sim}); Magnitude of head difference is defined as: $|\Delta h| = |h_{obs} - h_{sim}|$; a concentration difference of ± one-half order of magnitude equates to a model bias of 0.3 to 3, where, B_m = model bias and is defined as: $B_m = C_{sim}/C_{obs}$, where C_{sim} is the simulated concentration and C_{obs} is the observed concentration; when $B_m = 1$, the model exactly predicts the observed concentration, when $B_m > 1$, the model overpredicts the concentration, and when $B_m < 1$, the model underpredicts the concentration

[4]Average magnitude of head difference is defined as: $\left|\overline{\Delta h}\right| = \frac{1}{N}\sum_{i=1}^{N}\left|\Delta h_i\right|$; standard deviation of head difference is defined as: $\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(\Delta h_i - \overline{\Delta h}\right)^2}{N-1}}$, where $\overline{\Delta h}$ is the mean or average of head difference; root-mean-square of head difference is defined as: $RMS = \left[\frac{1}{N}\sum_{i=1}^{N}\Delta h_i^2\right]^{\frac{1}{2}}$; geometric bias, B_g, is defined as: $B_g = \exp\left[\frac{\sum_{i=1}^{N}\ln\left(B_{m,i}\right)}{N}\right]$, where ln ( ) is the Naperian logarithm

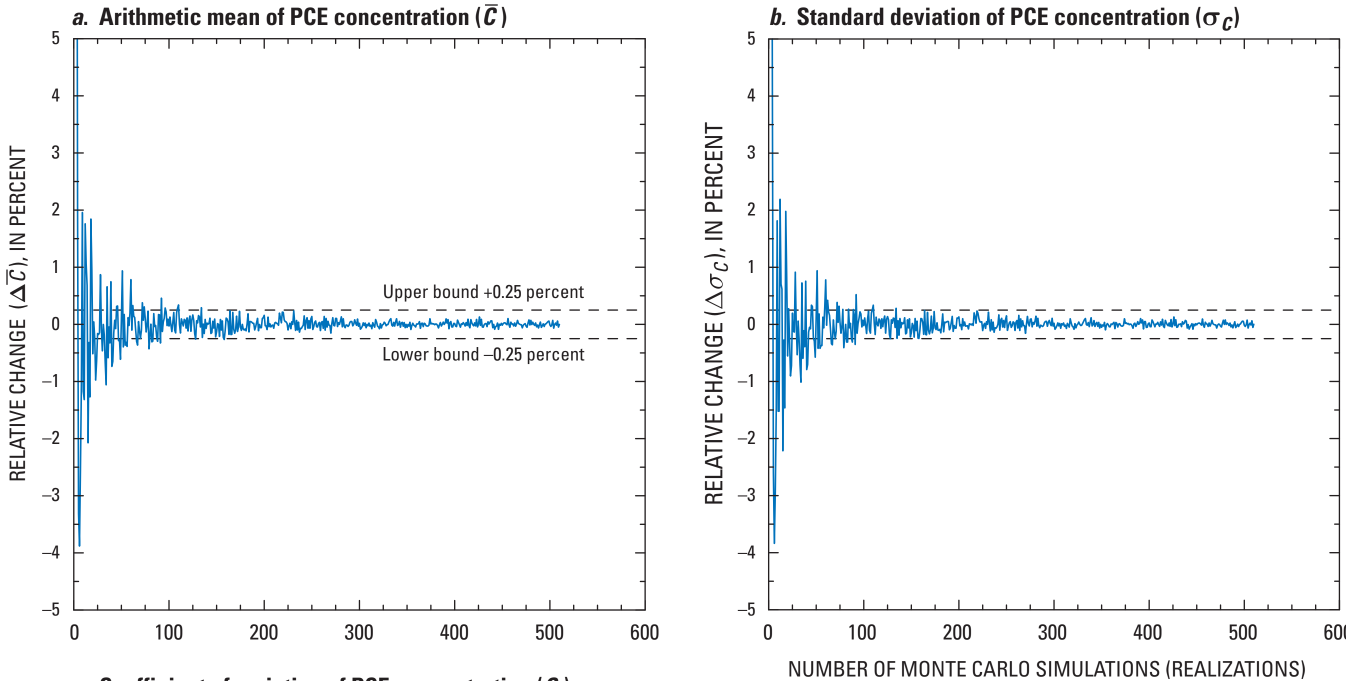
[5]A paired data point is defined as any location with observed data that is associated with a model location for the purpose of comparing observed data with model results for water level or concentration

[6]B_g = 5.8 computed using all water-supply wells listed in table A9; B_g = 3.9 computed without considering water-supply well TT-23—See text for explanation

[7]Observed concentration of 17 samples recorded as nondetect (see Table A9) and are not used in computation of geometric bias

[8]Observed concentration of 15 samples recorded as nondetect (see Table A10) and are not used in computation of geometric bias

Attachment 8: 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 (σC), and coefficient of variation of PCE concentration (C_v), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (from Maslia et al. 2008, Figure I26)



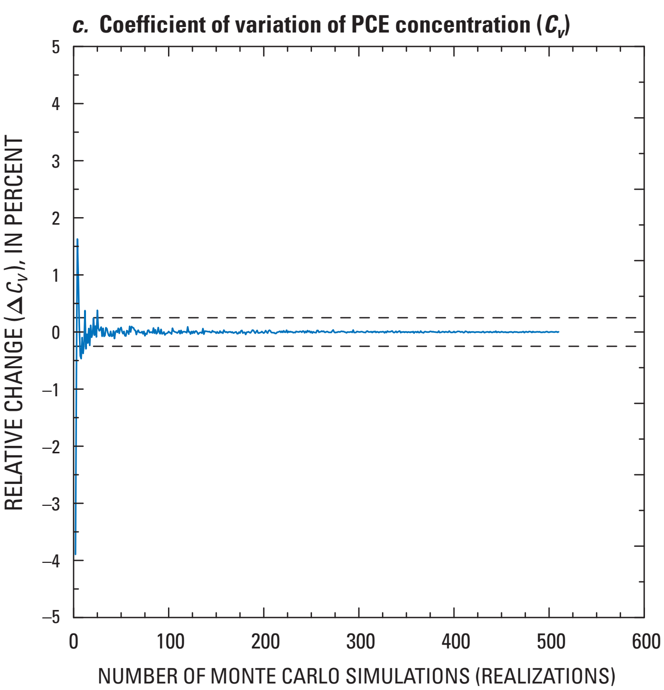


Figure I26. Stopping (convergence) criteria results for Monte Carlo simulations (scenario 1—pumping uncertainty excluded) shown as relative change in: *(a)* arithmetic mean of PCE concentration ($\overline{C}$), *(b)* standard deviation of PCE concentration (σ_C), and *(c)* coefficient of variation of 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]

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AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

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