Hydraulic and Solute-Transport Properties and Simulated Advective Transport of Contaminated Ground Water in a Fractured-Rock Aquifer at the Naval Air Warfare Center, West Trenton, New Jersey, 2003

By Jean C. Lewis-Brown, Glen B. Carleton, and Thomas E. Imbrigiotta

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
	Flow rate	
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Historical data collected and stored as National Geodetic Vertical Datum of 1929 (NGVD 29) have been converted to NAVD 88 for this publication.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAVD 83). Historical data collected and stored as North American Datum of 1927 (NAD 27) have been converted to NAD 83 for this publication.

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or in grams per liter (g/L).

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Abstract

Volatile organic compounds, predominantly trichloroethylene and its degradation products, have been detected in ground water at the Naval Air Warfare Center (NAWC), West Trenton, New Jersey. An air-stripping pump-and-treat system has been in operation at the NAWC since 1998. An existing ground-water-flow model was used to evaluate the effect of a change in the configuration of the network of recovery wells in the pump-and-treat system on flow paths of contaminated ground water.

The NAWC is underlain by a fractured-rock aquifer composed of dipping layers of sedimentary rocks of the Lockatong and Stockton Formations. Hydraulic and solute-transport properties of the part of the aquifer composed of the Lockatong Formation were measured using aquifer tests and tracer tests. The heterogeneity of the rocks causes a wide range of values of each parameter measured. Transmissivity ranges from 95 to 1,300 feet squared per day; the storage coefficient ranges from 9×10^{-5} to 5×10^{-3}; and the effective porosity ranges from 0.0003 to 0.002.

The average linear velocity of contaminated ground water was determined for ambient conditions (when no wells at the site are pumped) using an existing ground-water-flow model, particle-tracking techniques, and the porosity values determined in this study. The average linear velocity of flow paths beginning at each contaminated well and ending at the streams where the flow paths terminate ranges from 0.08 to 130 feet per day. As a result of a change in the pump-and-treat system (adding a 165-foot-deep well pumped at 5 gallons per minute and reducing the pumping rate at a nearby 41-foot-deep well by the same amount), water in the vicinity of three 100- to 165-foot-deep wells flows to the deep well rather than the shallower well.

Introduction

Volatile organic compounds (VOCs), predominantly trichloroethylene (TCE) and its degradation products *cis*-1,2-dichloroethylene (DCE) and vinyl chloride (VC), are the primary contaminants of concern detected in ground water in the fractured-rock aquifer at the Naval Air Warfare Center (NAWC), West Trenton, N.J. (International Technology Corporation, 1994) (fig. 1). In June 1997, the highest concentrations of TCE, DCE, and VC detected in wells at the NAWC were 88, 52, and 21 mg/L, respectively (Lacombe, 2000). A pump-and-treat system consisting of six recovery wells and an air-stripping treatment system has been operating at the NAWC since 1998. The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of the Navy, conducted an 11-year, multiphase hydrogeologic investigation of the NAWC. In earlier phases of the investigation, Lacombe (2000, 2002) determined the hydrogeologic framework, and Lewis-Brown and Rice (2002) developed a digital model to simulate, and evaluate the effects of various recovery-well networks on, ground-water flow at the NAWC.

The purpose of the current phase of the investigation was to (1) estimate values of hydraulic and solute-transport properties of the fractured-rock aquifer, (2) estimate the velocity and travel time of contaminated ground water if the existing pump-and-treat system at the NAWC were replaced by a non-pumping remediation technique, and (3) evaluate the effect on flow paths of contaminated ground water of a change in the configuration of the network of recovery wells in the pump-and-treat system.

Values of transmissivity, storage coefficient, effective porosity, longitudinal dispersivity, and average linear velocity presented in this report can be used to investigate the feasibility of alternative, non-pumping remediation techniques at the NAWC. These values also can be used in investigations conducted at the NAWC as part of the USGS Toxic Substances Hydrology Program (TSHP) to identify the geochemical and microbiological processes that affect migration and natural attenuation of chlorinated solvents in fractured sedimentary rocks. These processes are being studied as part of the TSHP's overall initiative to provide objective and reliable scientific information needed to develop policies and practices that help avoid exposure to toxic substances, mitigate environmental deterioration from contaminants, provide cost-effective cleanup and waste-disposal strategies, and reduce risk of future contamination.

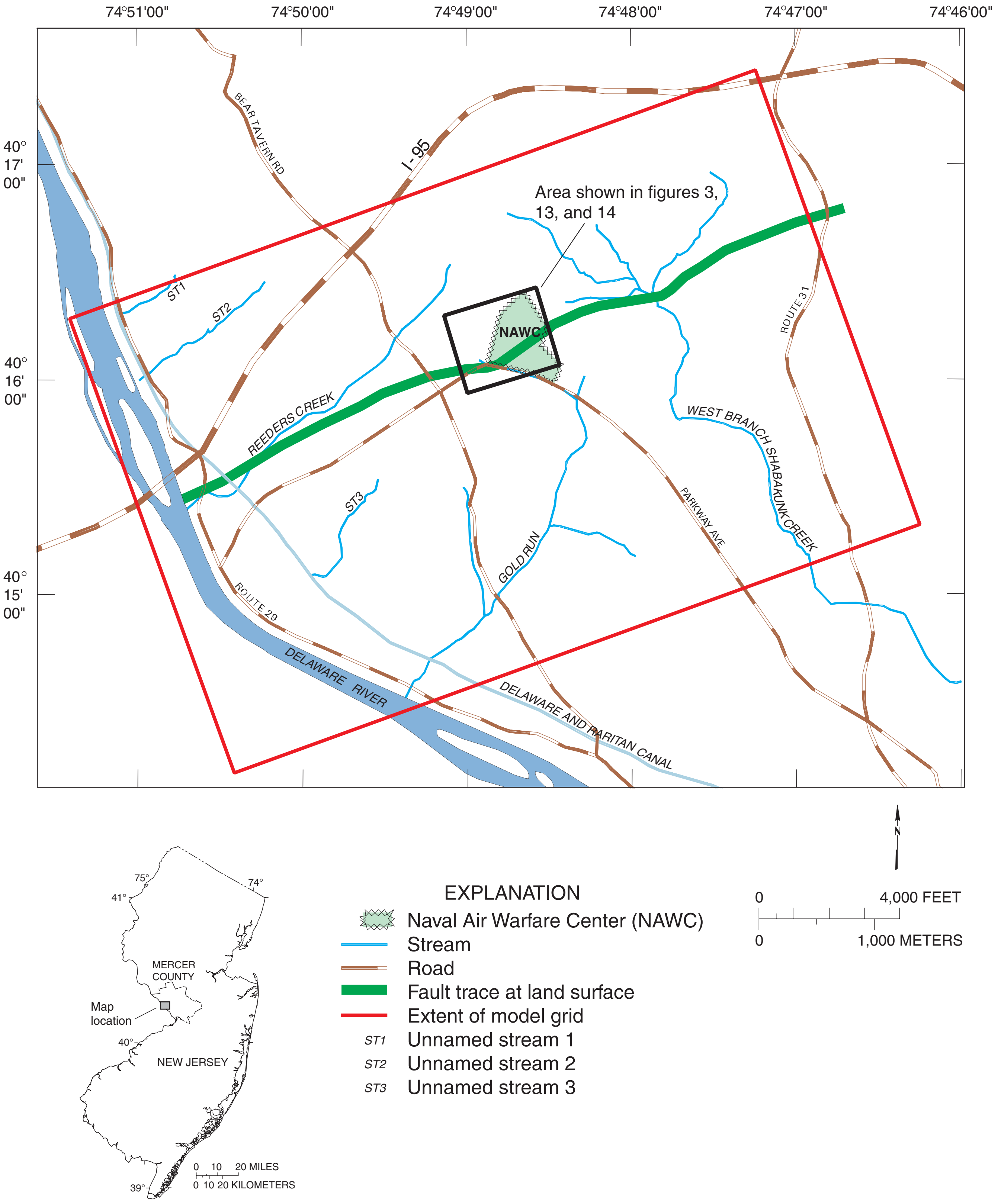

Figure 1. Location of the Naval Air Warfare Center and vicinity, West Trenton, New Jersey, and extent of the grid of the ground-water-flow model.

Purpose and Scope

This report presents estimates of the hydraulic and solute-transport properties of the fractured-rock aquifer at the NAWC. The velocity and travel time of contaminated ground water under the non-pumping conditions that would exist if the existing pump-and-treat system were replaced by a non-pumping remediation technique are estimated. The effect of a change in the configuration of the network of recovery wells in the pump-and-treat system on flow paths of contaminated ground water is evaluated. The estimates of velocity and travel time and the evaluation of effects on flow paths were made using an existing ground-water-flow model and effective-porosity values determined from the results of tracer tests.

This report documents the results of five aquifer tests and three tracer tests conducted at the NAWC during the summer of 2003. The transmissivity and storage coefficient determined from each aquifer test are reported, as are the effective porosity and longitudinal dispersivity from each tracer test. These tests were conducted in five small (less than 3,000 ft^2) areas at the NAWC.

Hydrogeologic Framework

The hydrogeologic framework underlying the NAWC (fig. 2) is described in detail by Lacombe (2000, 2002) and is summarized here. The NAWC is underlain by about 0 to 10 ft of unconsolidated sediments that are unsaturated much of the time. Dipping layers of fractured mudstone, siltstone, and sandstone of the Lockatong and Stockton Formations are beneath the unconsolidated sediments. Lacombe (2000) identified 16 bedding units (table 1) in the Lockatong and Stockton Formations at the NAWC. The units strike N. 60° E. to N. 70° E. and dip 15° to 20° NW. Each bedding unit consists of several water-bearing zones alternating with confining zones. These bedding units generally are 20 to 35 ft thick and are differentiated primarily on the basis of lithologic characteristics. The 16 bedding units comprise a fractured-rock aquifer. Water is transmitted primarily through fractures and joints in the rocks. Shallow rocks (less than about 40-70 ft deep) are more weathered and more fractured than deeper, more competent rocks.

A fault (fig. 2) cuts through the bedding units and acts as a nearly impermeable boundary to ground-water flow. The fault is at or near the contact between the Stockton and Lockatong Formations. The fault strikes about N. 70° E. and dips about 40° SE. In rock cores collected from the fault zone, the rocks are weathered extensively and fractured, and the fractures are completely filled with clay. Dry clay as much as 60 ft thick was found in rock cores from some parts of the fault zone. Abundant clay in the fault zone and the absence of drawdown in wells on the south side of the fault when wells on the north side were pumped indicate that the fault is a boundary to ground-water flow (Lacombe, 2000).

Table 1. Bedding units at the Naval Air Warfare Center, West Trenton, New Jersey.

[Modified from Lacombe, 2000]

Geologic unit	Bedding unit	Predominant lithology
Lockatong Formation	L23	Mudstone, light to dark gray, laminated, slightly calcareous
	L22	Mudstone, dark gray and green-gray
	L21	Mudstone, gray, platy, massive, interbedded, medium hard
	L20	Mudstone, gray
	L19	Mudstone, gray, hard to medium hard, with calcareous and soft brown mudstone seams
	L18	Siltstone and mudstone, light to dark olive green or black, massive, bioturbated; some strata finely laminated; strongly calcareous
	L17	Mudstone, red-brown to green-gray brown
	L16	Mudstone, argillite, and shale, light green to gray and black
	L15	Mudstone, red-brown and green-gray, soft, slightly broken, massively bedded, calcareous
	L14	Mudstone, dark gray to green-gray
	L13	Mudstone, dark gray
Stockton Formation	S15	Sandstone, brown, medium hard
	S14	Sandstone, gray-white, medium hard
	S13	Mudstone, red, hard, massive
	S12	Sandstone, gray-white
	S11	Mudstone, red

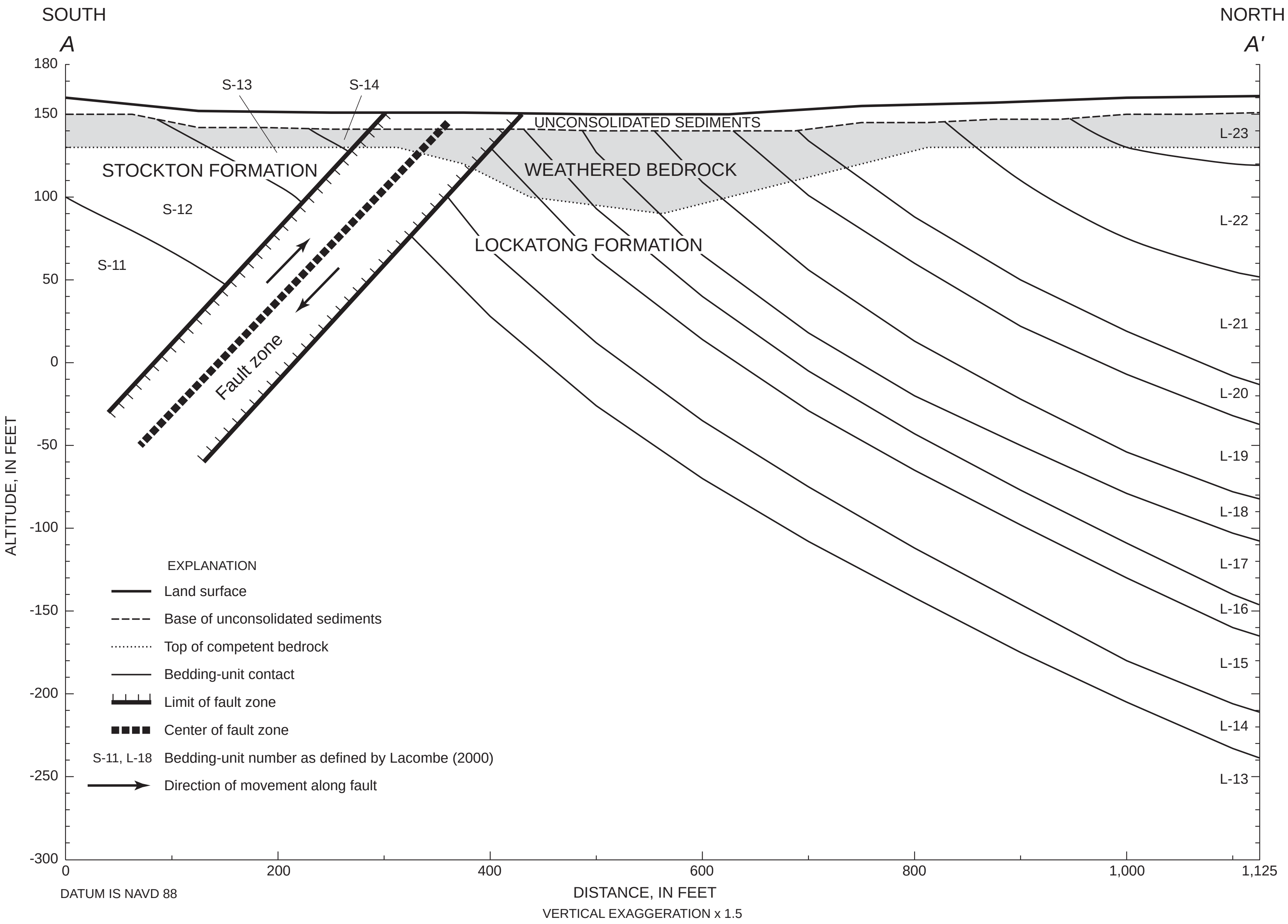

Figure 2. Geologic section A-A′ showing bedding units and fault zone at the Naval Warfare Center, West Trenton, New Jersey.

Site Selection

Pairs of existing wells were chosen for inclusion in the aquifer and tracer tests by using the following criteria: (1) The wells are open to the same bedding unit. (2) The wells are hydraulically connected--that is, the water level in one well decreases when the other well is pumped. (3) The distance between the wells is great enough to allow some measurable dispersion to occur, yet small enough to allow the tracer concentration to be measurable in the withdrawal well. (4) The injection well is hydraulically able to accept water, and the withdrawal well is able to withdraw water at a rate sufficient to allow injection of a mass of tracer large enough to result in detectable concentrations at the withdrawal well. (5) The withdrawal well is connected to the pump-and-treat system so the pumped water can be treated on site, as required by the N.J. Department of Environmental Protection (NJDEP). (6) The wells are open to the specific bedding units identified by Lacombe (2000) in which the highest concentrations of VOCs at the site have been detected (bedding units L17 and L19, fig. 2).

Thirteen recovery wells are connected to the pump-and-treat system and were available to be used as withdrawal wells in the aquifer and tracer tests. Most of these wells are in bedding units L17 and L19. On the basis of results of an evaluation of water-level data, the hydrogeologic framework, and the proximity of potential observation and injection wells to the available recovery wells, eight wells were selected for aquifer and tracer testing (table 2). Five pairs of wells were used for aquifer testing. Recovery wells BRP2, 15BR, 16BR, and 41BR were used as withdrawal wells in the aquifer tests. When well BRP2 was pumped, drawdown data in two observation wells, 20BR and 56BR, were analyzed. For purposes of this report, these two data sets are treated as separate aquifer tests, referred to as the BRP2-20BR aquifer test and the BRP2-56BR aquifer test, respectively. Similarly, the other three aquifer tests are referred to as the 15BR-BRP3 aquifer test, the 16BR-41BR aquifer test, and the 41BR-53BR aquifer test. Three pairs of wells were used for tracer testing. Recovery wells BRP2, 15BR, and 16BR were used as withdrawal wells in the tracer tests. For purposes of this report, the test in which well BRP2 was pumped while tracer was being injected into well 20BR is referred to as the BRP2-20BR tracer test. Similarly, the other two tracer tests are referred to as the 15BR-BRP3 tracer test and the 16BR-41BR tracer test, respectively. The locations of the wells are shown in figure 3.

Aquifer testing was planned at all five well pairs listed in table 2. Tracer testing also was planned at each of these well pairs except the BRP2-56BR pair. This well pair was included in aquifer testing because, at the time the tests were conducted, well 56BR was a potential candidate for addition to the network of wells pumped in the pump-and-treat system. This well pair was not suitable for tracer testing, however, because the distance between the wells was too great to ensure that the tracer concentrations at the withdrawal well would be measurable.

Hydraulic and Solute-Transport Properties

The transmissivity, storage coefficient, longitudinal dispersivity, and effective porosity of the fractured-rock aquifer at the NAWC were estimated from the results of aquifer tests and tracer tests. The tests were conducted in parts of the aquifer composed of the Lockatong Formation, in the two bedding units (L17 and L19) in which the highest concentrations of VOCs have been detected.

Table 2. Wells used in aquifer and tracer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

Well Pair		**Bedding unit (Lacombe, 2000)**	**Open interval of withdrawal well (feet below land surface**	**Open interval of observation/ injection well (feet below land surface)**	**Horizontal distance at land surface between wells (feet)**	**Distance between mid-point of open intervals of wells (feet)**
Withdrawal well	**Observation/ injection well**					
BRP2	20BR	L17	25 - 45	28 - 43	97	97
BRP2[1]	56BR[1]	L17	25 - 45	140 - 165	253	279
15BR	BRP3	L19	26 - 41	25 - 40	92	93
16BR	41BR	L19	40 - 65	85 - 110	84	94
41BR[2]	53BR[2]	L19	85 - 110	95 - 120	138	139

[1] No tracer test was planned at this well pair.

[2] A tracer test was planned but not conducted at this well pair because well 53BR overflowed when water was injected into it.

Figure 3. Locations of wells used in aquifer tests and tracer tests, 2003, and line of section A-A′ at the Naval Air Warfare Center, West Trenton, New Jersey.

Transmissivity and Storage Coefficient

Aquifer tests were conducted to estimate the transmissivity and storage coefficient of the fractured-rock aquifer in the area of each well pair for which subsequent tracer testing was planned. Three analytical methods were used to analyze data from each test.

Field Methods

Water levels in observation wells and withdrawal wells were recorded using down-hole pressure-transducer digital data recorders in six of the wells and float-type digital recorders in the other two wells. Generally, water levels were recorded at 5-second intervals during the first 1 to 2 hours after pumps were turned on or off and at 1-minute intervals thereafter. Selected recovery wells used in the pump-and-treat system were used as withdrawal wells in the aquifer tests, and submersible pumps previously installed in the wells for use in the pump-and-treat system were used in the aquifer tests. The pumping rates at the withdrawal wells during the aquifer tests are listed in table 3. The pumping rates were monitored using flow meters installed at each well, and flow was adjusted as needed to maintain constant rates.

To avoid the possibility of changes in stress to the ground-water-flow system caused by unexpected shutdowns of recovery wells (for example, as a result of system malfunction), it would have been beneficial to shut down all of the recovery wells except the one used as a withdrawal well in the test. This was not done, however, in order to keep the pump-and-treat system operating to the maximum extent practicable in accordance with NJDEP regulations. Consequently, pumps in some recovery wells in the pump-and-treat system continued operating during the tests, but pumps in wells less than 600 ft from and open to the same bedding unit as the aquifer-test withdrawal well were shut down at least 24 hours prior to each test and remained off during the test. Recovery wells pumped during each aquifer test are listed in table 4.

Analysis Methods

Three analytical solutions were used to analyze data from each aquifer test:

1. the Neuman (1974) solution for an aquifer test in an unconfined aquifer,
2. the Theis (1935) solution for an aquifer test in a confined aquifer, and
3. the Hantush (1962) solution for an aquifer test in a wedge-shaped confined aquifer.

All three of these methods involve matching observed drawdown data from the test to drawdown computed from analytical solutions. Matching was performed using the computer program AQTESOLV (Duffield, 2000). Although shallow parts of the aquifer generally are considered to be unconfined and deeper parts are considered to be confined, the depth at which the transition from unconfined to confined conditions occurs is not clear (Lacombe, 2000). Consequently, solutions for both confined and unconfined aquifers were attempted for each well pair. The Hantush solution for a wedge-shaped confined aquifer was used because the hydraulic properties of the bedding units at the NAWC are assumed to be similar to those of a wedge-shaped aquifer. In a wedge-shaped aquifer, the transmissivity decreases as the wedge becomes thinner. In the bedding units at the NAWC, the transmissivity in each bedding unit is assumed to decrease with depth below land surface because the hydraulic conductivity decreases with depth (Lewis-Brown and Rice, 2002). In well pairs in which the withdrawal well is open at a different depth than the observation well, the effect of decreasing hydraulic conductivity with depth is assumed to be similar to the effect of decreasing thickness in a wedge-shaped aquifer.

Table 3. Pumping rates and duration of pumping at withdrawal wells during aquifer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

Well pair				
Withdrawal well	**Observation well**	**Bedding unit to which well pair is open (Lacombe, 2000)**	**Pumping rate (gallons per minute)**	**Duration of pumping (minutes)**
BRP2	20BR	L17	6.6	1,690
BRP2	56BR	L17	6.6	1,690
15BR	BRP3	L19	14.9	5,570
16BR	41BR	L19	1.3	1,300
41BR	53BR	L19	10.2	690

Table 4. Pumping rates at recovery wells during aquifer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

[Pumping rates listed in this table are for additional wells being pumped during aquifer tests to maintain operation of the pump-and-treat system at the Naval Air Warfare Center; WW, well used as withdrawal well during the given aquifer test]

		Pumping rate at recovery well (gallons per minute)			
Recovery well	**Bedding unit to which recovery well is open (Lacombe, 2000)**	**BRP2-20BR aquifer test and BRP2-56BR aquifer test**	**15BR-BRP3 aquifer test**	**16BR-41BR aquifer test**	**41BR-53BR aquifer test**
BRP2	L17	WW	0	6.6	6.6
20BR	L17	0	0	8.5	8.5
48BR	L17	0	13.5	13.5	13.5
56BR	L17	0	0	0	0
15BR	L19	0	WW	0	0
45BR	L19	5.1	5.1	5.1	5.1
22BR	S13	4.4	4.4	4.4	4.4

Each of the solutions is based on assumptions and conditions regarding the aquifer, the wells, and the stress on the aquifer. These assumptions and conditions and their applicability to the tests conducted in this study are listed in table 5.

Water levels in observation wells were recorded for at least 24 hours prior to each test to determine whether ambient water-level trends needed to be considered in the analysis of test data. The water level in well 53BR decreased at a rate of about 0.00026 ft/min during the hour before the pump in well 41BR was turned on for the 41BR-53BR aquifer test. Although this rate is low, it is large enough to affect test results because total measured drawdown during the test was only 0.74 ft. During the 690-minute test, the decline in water level attributable to ambient conditions was 0.18 ft. Consequently, the observed water levels in well 53BR were adjusted by subtracting the ambient water-level decline from the drawdown.

The water level in well 56BR decreased at a rate of about 0.000017 ft/min during the 18-hour period before the pump was turned on in well BRP2 for the BRP2-56BR aquifer test. Although this rate is low, it is large enough to affect test results because total measured drawdown during the pumping phase of the test was only 0.60 ft. During the 1,690-minute pumping phase, the decline in water level attributable to ambient conditions was 0.029 ft. Consequently, the observed water levels in well 56BR were adjusted by subtracting the ambient water-level decline from the drawdown.

In the other three observation wells, water levels were stable for at least 1 hour prior to the start of the test. No adjustments were made to the drawdown data from these tests.

Some of the tests were affected by stress to ground-water flow caused by infiltration of precipitation after pumping began. During the 16BR-41BR aquifer test, precipitation began 320 minutes after the beginning of the recovery phase; therefore, no data collected after that time were used in the analysis. During the 41BR-53BR aquifer test, precipitation began 690 minutes after pumping began; therefore, no data collected after that time were used in the analysis and recovery data could not be analyzed. No precipitation occurred during the other three tests.

Estimated Values

The transmissivity and storage coefficient obtained from applying each analytical solution to each test are listed in table 6. Transmissivity ranges from 95 to 1,300 ft^2/d and storage coefficient ranges from 9×10^{-5} to 5×10^{-3}. These broad ranges are caused by the heterogeneity of the fractured-rock aquifer. For most of the tests, however, the transmissivity and storage coefficients agreed reasonably well among the three analytical solutions. Because all of the aquifer tests were conducted at the NAWC, these transmissivity and storage-coefficient values cannot be assumed to be representative of the fractured-rock aquifer in other areas underlain by the Lockatong Formation. Although a value of specific yield can be derived from the Neuman (1974) solution, these specific-yield values are not listed in table 6 because the determination of specific yield from this solution is considered a dubious procedure (Van der Kamp, 1985; Kruseman and deRidder, 1990). Values of specific yield and other parameters used in or derived from the aquifer-test analyses are presented in appendix 1. Plots of observed drawdown and drawdown computed using each of the three solutions are shown in figures 4 through 8.

The hydraulic conductivity of the fractured-rock aquifer formed by bedding units in the Lockatong Formation at the NAWC has been estimated previously from the results of slug testing individual wells and by calibration of a digital ground-water-flow model (Lewis-Brown and Rice, 2002). These two previous estimates and the estimates made on the basis of the small-scale aquifer testing described in this report (table 7)

Table 5. Assumptions and conditions inherent in solution methods used to analyze data from aquifer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

Assumption/condition (modified from Kruseman and deRidder, 1990)	Applicability to aquifer tests described in this report
Assumptions and conditions required for all solution methods used in this study	
Aquifer has an infinite areal extent.	The hydrogeologic framework described by Lacombe (2000) indicates that this assumption probably is valid over the small area influenced by each test.
Aquifer is homogeneous and isotropic.	The hydrogeologic framework described by Lacombe (2000) indicates that this assumption probably is valid over the small area influenced by each test.
Prior to pumping, the piezometric surface is horizontal (or nearly so) over the area influenced by the test.	This assumption is valid. In the area influenced by each test, the slope of the piezometric surface was less than 1 degree prior to pumping.
The aquifer is pumped at a constant discharge rate.	In four of the tests (BRP2-20BR, BRP2-56BR, 15BR-BRP3, and 41BR-53BR tests), the pumping rate varied by less than 3 percent of the average pumping rate (total gallons pumped divided by pumping duration). This is considered a near-constant rate. In one test (16BR-41BR test), the average pumping rate was relatively low (1.33 gallons per minute). During the first 5 minutes of the test, the pumping rate varied from 0.94 to 3.00 gallons per minute. During the remainder of the test, the rate varied from 1.27 to 1.46 gallons per minute, a variability of 14 percent. Because the pumping rate was low, it was difficult to maintain it at a constant level. Although drawdown data from the later parts of each test were weighted more heavily in curve-matching than data from early parts of the tests, the 14-percent variability in the later-time pumping rate is a concern. Consequently, the level of certainty associated with this test is lower than that associated with the other aquifer tests.
The withdrawal well penetrates the entire thickness of the aquifer.	This assumption probably is met. The reason for this requirement is to minimize the influence of parts of the aquifer that are above or below the well opening. The aquifer consists of many thin water-bearing zones alternating with thin confining zones. It is likely that one of the thin confining zones is at or near the top and bottom of each well opening and that the full-penetration assumption is adequately met.
The diameter of the withdrawal well is small so that storage in the well can be neglected.	The diameter of the open interval of the withdrawal wells is 6 inches. It is assumed that storage in the well can be neglected because of the small well diameter and because drawdown data from the later parts of each test were weighted more heavily in curve-matching than data from early parts of the tests, when well storage is more likely to affect drawdown.
Flow to the well is in unsteady state; that is, the drawdown differences with time are not negligible, nor is the hydraulic gradient constant with time.	This condition was met for all tests.
Additional assumptions and conditions required for the Theis solution method for a confined aquifer	
The aquifer is confined.	Whether the aquifer was unconfined or confined at each test location is unknown; therefore, solutions for both types of aquifers were attempted for each test.
The aquifer is of uniform thickness over the area influenced by the test.	The hydrogeologic framework described by Lacombe (2000) indicates that this assumption probably is valid.
The water removed from storage is discharged instantaneously with decline of water level.	It is assumed that this condition was met.

Table 5. Assumptions and conditions inherent in solution methods used to analyze data from aquifer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003--Continued.

Assumption/condition (modified from Kruseman and deRidder, 1990)	Applicability to aquifer tests described in this report
Additional assumptions and conditions required for the Hantush solution method for a wedge-shaped confined aquifer	
The aquifer is confined.	(See the above explanation of the first condition pertaining to the Theis solution method.)
The water removed from storage is discharged instantaneously with decline of water level.	It is assumed that this condition was met.
The thickness of the aquifer varies exponentially in the direction of flow.	The effect of decreasing transmissivity with depth may mimic the effect of decreasing thickness with depth. In tests in which the withdrawal well and observation well are open to different depths, this assumption is assumed to be valid.
The rate of change in aquifer thickness in the direction of flow does not exceed 0.20.	Because the transmissivity, rather than the thickness, of the aquifer decreases, it is not possible to know whether the intended effect of this assumption is met.
Additional assumptions and conditions required for the Neuman solution method for an unconfined aquifer	
The aquifer is unconfined.	(See the above explanation of the first condition pertaining to the Theis solution method.)
The influence of the unsaturated zone on drawdown in the aquifer is negligible.	It is assumed that this condition is met.
The ratio of specific yield to early-time storage coefficient is greater than 10.	It is assumed that this condition is met.
The diameter of the observation well is small; that is, storage in the well can be neglected.	The diameters of the open intervals of the observation wells are 4 to 6 inches. It is assumed that storage in the well can be neglected because of the small well diameters and because drawdown data from the later parts of each test were weighted more heavily in curve-matching than data from early parts of the tests, when well storage is more likely to affect drawdown.

represent conditions at three different scales within the heterogeneous aquifer. Hydraulic-conductivity estimates from slug testing represent the conditions in the small area around the tested well (probably less than 100 ft^2). Hydraulic-conductivity estimates from the aquifer testing described in this report represent the conditions in the area of aquifer extending from the area around the withdrawal well to the area around the observation well (probably less than 1,500 ft^2). Hydraulic-conductivity estimates from calibration of the digital model (table 7) represent mean conditions over the extent of the NAWC (about 0.15 mi^2).

The hydraulic-conductivity values estimated from aquifer tests, slug tests, and calibration of the digital model are consistent with each other and reflect the heterogeneous character of the aquifer. In the two instances in which the comparison can be made, the hydraulic-conductivity values estimated from aquifer testing are consistent with the values estimated from slug testing in that the conductivity value obtained from the aquifer test at a given pair of wells falls between the conductivity values obtained from the slug tests conducted at the two individual wells (table 7).

In many cases, the values of hydraulic conductivity derived from aquifer testing and slug testing are higher than the values obtained from calibration of the digital model (table 7). These higher values represent the hydraulic conductivity in several small areas, whereas the conductivity values used in the model represent the net effect of areas of high and low conductivity in the heterogeneous rocks. The aquifer tests all were conducted using recovery wells in the pump-and-treat system, which was designed to include wells from which the greatest amounts of water could be extracted--that is, wells for which slug testing had indicated high hydraulic conductivities. The median hydraulic conductivity (estimated from slug-test results) in areas near wells used in the aquifer tests is 47 ft/d, whereas the mean hydraulic conductivity in areas near all wells open to parts of the aquifer formed by rocks of the Lockatong Formation at the NAWC (also estimated from slug-test results) is 3.2 ft/d (Lewis-Brown and Rice, 2002). Consequently, conductivity values derived from aquifer and slug testing in areas near the pump-and-treat recovery wells are expected to be higher than those in the model and are consistent with previous results.

Table 6. Transmissivity and storage coefficient estimated from aquifer-test data, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

[T, transmissivity; S, storage coefficient; all transmissivity values are in units of feet squared per day]

Withdrawal well			Observation well				Solution method					
Well name	Depth of open interval (feet below land surface)		Well name	Depth of open interval (feet below land surface)		Bedding unit[1] (Lacombe, 2000)	Theis solution for confined aquifers		Hantush solution for wedge-shaped confined aquifers		Neuman solution for unconfined aquifers	
	Top	Bottom		Top	Bottom		T	S	T	S	T	S
BRP2	25	45	20BR	28	43	L17	990	2×10^{-4}	790	3×10^{-4}	540	2×10^{-4}
BRP2	25	45	56BR	140	165	L17	650	6×10^{-4}	[2]170	[2]3×10^{-4}	230	3×10^{-4}
15BR	26	41	BRP3	25	40	L19	1,300	5×10^{-3}	1,300	5×10^{-3}	1,300	2×10^{-3}
16BR	40	65	41BR	85	110	L19	210	9×10^{-5}	[2]100	[2]1×10^{-4}	95	1×10^{-4}
41BR	85	110	53BR	95	120	L19	420	4×10^{-3}	350	3×10^{-3}	240	3×10^{-3}

[1] All bedding units in which aquifer tests were conducted are in the Lockatong Formation.

[2] In tests in which the withdrawal and observation wells are open at substantially different depths, the transmissivity and storage coefficients derived from the Hantush solution are assumed to represent the values of these parameters at some point between the two wells.

Table 7. Values of hydraulic conductivity estimated from aquifer tests, slug tests, and calibration of a digital model, Naval Air Warfare Center, West Trenton, New Jersey.

[na, this well was not available for slug testing]

				Values from aquifer tests described in this report		Values from slug testing (Lewis-Brown and Rice, 2002)		Values from calibration of digital model (Lewis-Brown and Rice, 2002)	
Withdrawal well	Observation well	Geologic formation	Mean length of open intervals of withdrawal well and observation well (feet)	Transmissivity (median of values from three solution methods) (feet squared per day)	Hydraulic conductivity (transmissivity divided by mean length of open interval of withdrawal well and observation well) (feet per day)	Hydraulic conductivity near withdrawal well (feet per day)	Hydraulic conductivity near observation well (feet per day)	Hydraulic conductivity at location of withdrawal well (feet per day)[1]	Hydraulic conductivity at location of observation well (feet per day)[1]
BRP2	20BR	Lockatong	17.5	790	45	3.3	49	9.4	9.4
BRP2	56BR	Locaktong	22.5	230	10	3.3	na	9.4	0.4
15BR	BRP3	Lockatong	15	1,300	87	na	140	9.4	9.4
16BR	41BR	Lockatong	25	100	4.0	2.4	47	9.4 and 6.9	6.9 and 0.4
41BR	53BR	Locaktong	25	350	14	47	na	6.9 and 0.4	6.9 and 0.4

[1] Hydraulic-conductivity values used in the digital model are depth-dependent. In parts of the aquifer composed of rocks of the Lockatong Formation, a hydraulic conductivity of 11.3 feet per day was used for rocks at depths of 26 to 50 feet below land surface; 4.0 feet per day was used for rocks 51 to 100 feet below land surface; and 0.4 feet per day was used for rocks 101 to 300 feet below land surface.

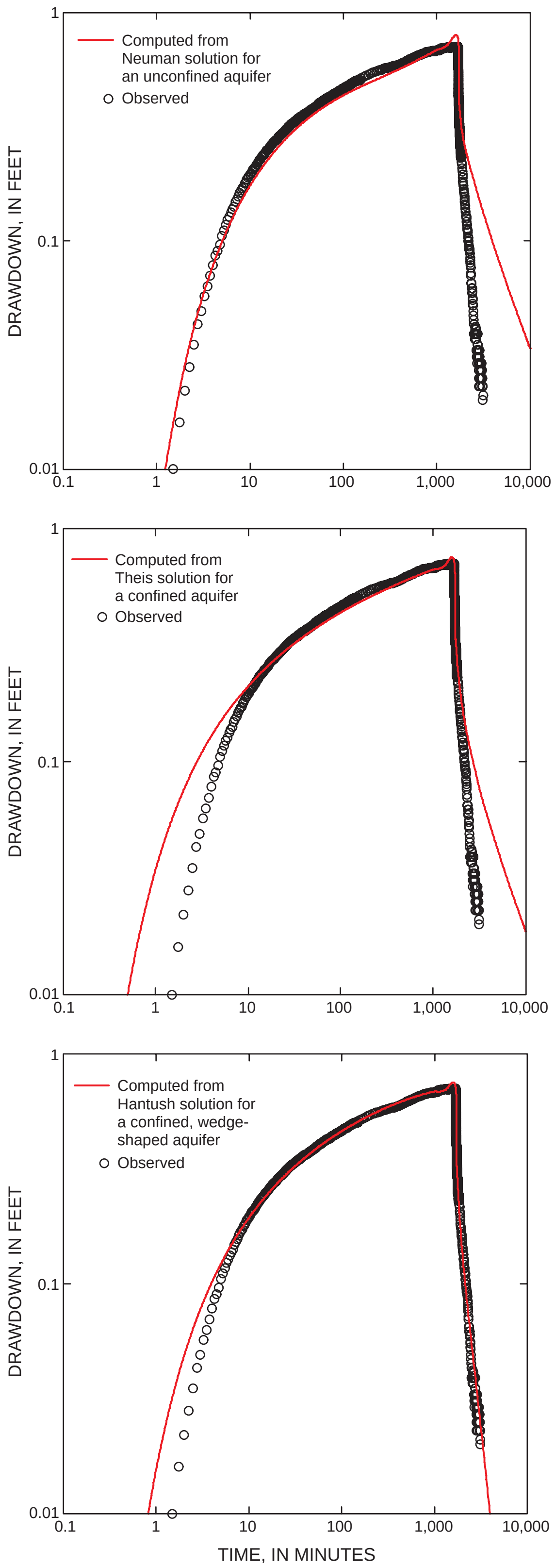

Figure 4.Observed drawdown in observation well 20BR during pumping of well BRP2, July 1-3, 2003, and drawdown computed from three analytical solutions, Naval Air Warfare Center, West Trenton, New Jersey.

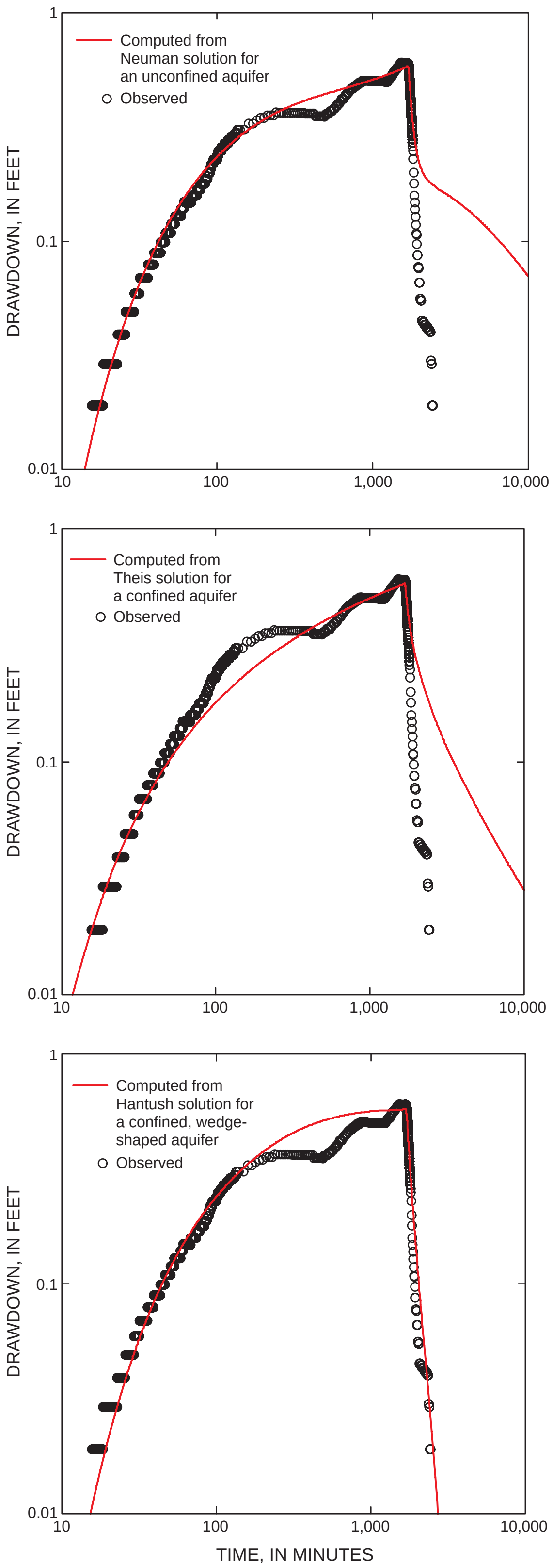

Figure 5. Observed drawdown in observation well 56BR during pumping of well BRP2, July 1-3, 2003, and drawdown computed from three analytical solutions, Naval Air Warfare Center, West Trenton, New Jersey.

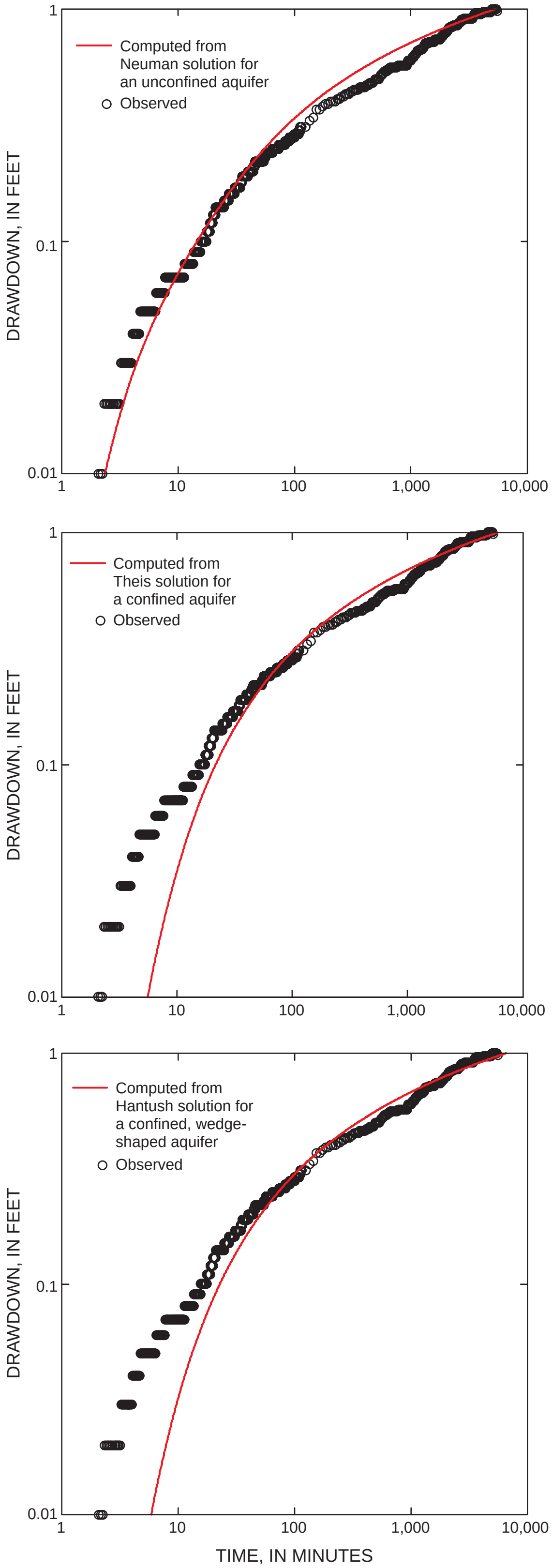

Figure 6. Observed drawdown in observation well BRP3 during pumping of well 15BR, June 26-30, 2003, and drawdown computed from three analytical solutions, Naval Air Warfare Center, West Trenton, New Jersey.

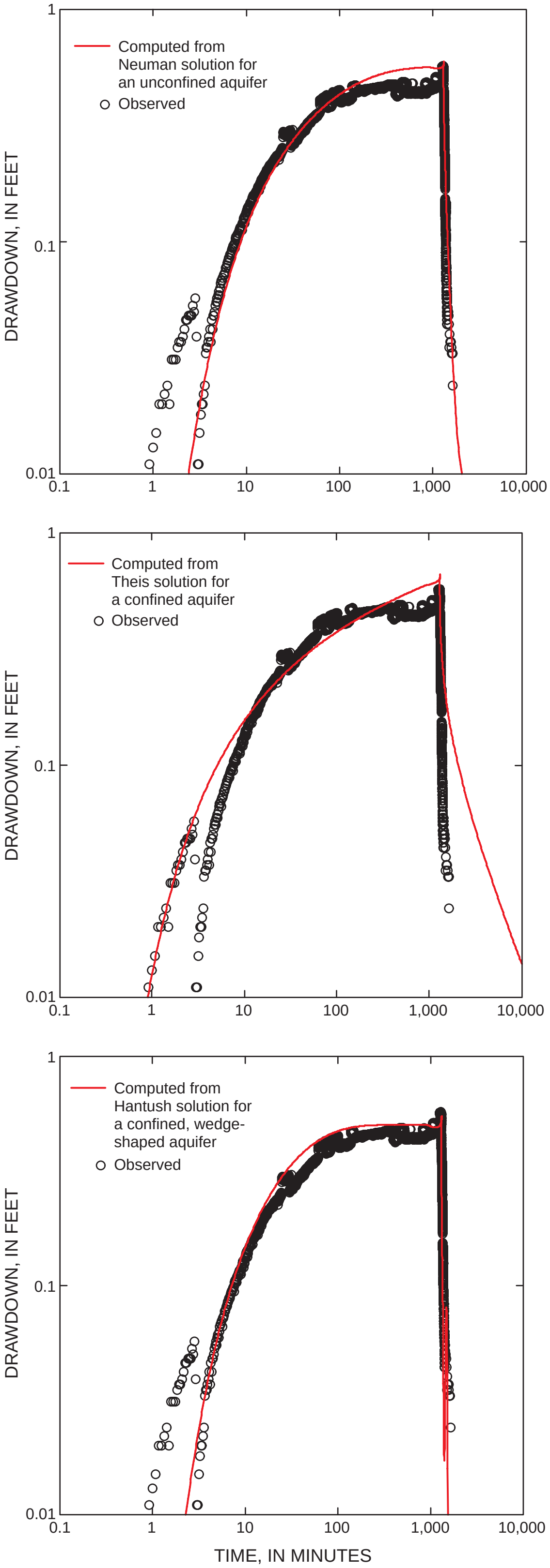

Figure 7. Observed drawdown in observation well 41BR during pumping of well 16BR, June 11-12, 2003, and drawdown computed from three analytical solutions, Naval Air Warfare Center, West Trenton, New Jersey.

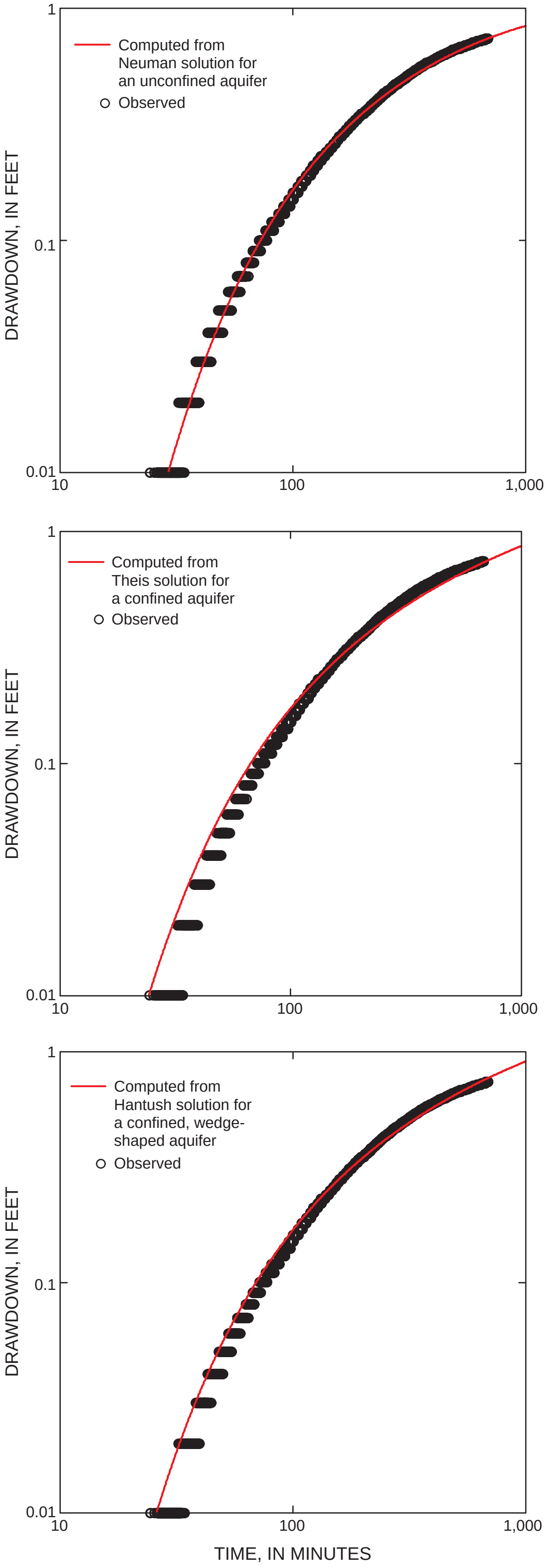

Figure 8. Observed drawdown in observation well 53BR during pumping of well 41BR, June 17, 2003, and drawdown computed from three analytical solutions, Naval Air Warfare Center, West Trenton, New Jersey.

Longitudinal Dispersivity and Effective Porosity

Tracer tests can be used to determine solute-transport properties (longitudinal dispersivity and effective porosity) of an aquifer. Velocity is inversely and linearly related to effective porosity; therefore, if the volumetric flux of water is held constant, and the effective porosity is doubled, velocity is halved.

Tracer tests were planned for four pairs of wells at the NAWC site. The 41BR/53BR pair was not tested, however, because well 53BR overflowed when water was injected, even at an extremely low rate (0.3 gal/min).

Field Methods

Doublet tracer tests were conducted at three well pairs. This type of tracer test involves creating a stable flow field with injection of water into one well and withdrawal of water from a second well at the same rate as the injection. The withdrawal and injection rate for each tracer test is listed in table 8. After a steady-state flow field is established, the tracer is injected as nearly instantaneously as possible and water samples are collected from the withdrawal well to monitor the arrival time and concentration of the tracer. Doublet tests were conducted rather than single-well tests because they take less time, allow more control of the tracer flow path and concentration, and allow for continuation of the pump-and-treat operation during the tracer testing. Bromide was used as the tracer because it is nontoxic, conservative (not biodegradable and does not sorb to aquifer material), present in very low concentrations (<0.35 mg/L) in the native ground water, easy to detect, and inexpensive to measure with an ion-selective electrode.

Before each tracer test was begun, injection of tap water was begun at the injection well and withdrawal of water was begun at the withdrawal well at a rate equal to the injection rate. After the water level in both wells had stabilized, water samples were collected from each withdrawal well to obtain background bromide concentrations in the water withdrawn from the aquifer (0.343, 0.279, and 0.174 mg/L at withdrawal wells BRP2, 15BR, and 16BR, respectively). The tracer test was then initiated by substituting water containing bromide at a concentration of about 1,000 mg/L for the tap water. The tracer was pumped into the injection well at a constant injection rate equal to the pumping rate from the withdrawal well (3.5 gal/min, 5.0 gal/min, and 1.4 gal/min from wells BRP2, 15BR, and 16BR, respectively). Injection and withdrawal rates were held constant during each test. The injection flow rate was monitored using a flow meter near the well head and controlled by means of an in-line valve.

During each tracer test, pumps in other recovery wells that are part of the pump-and-treat system at the site were either turned off or maintained at constant pumping rates for the duration of the test. Pumps in wells that could have interfered with flow paths at the test site were turned off; others were kept at a constant pumping rate. The pumping rates of all pumped wells were monitored during the tracer tests to ensure that they were constant. The pumping rate at each recovery well during each test is listed in table 9.

Table 8. Rates and duration of pumping at withdrawal wells and injection at injection wells during tracer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

Well pair		Bedding unit (Lacombe, 2000)	Withdrawal and injection rate (gallons per minute)	Duration of withdrawal and injection (minutes)
Withdrawal well	Injection well			
BRP2	20BR	L17	3.5	9,000
15BR	BRP3	L19	5.0	9,265
16BR	41BR	L19	1.4	9,665

Table 9. Pumping rates at recovery wells during tracer tests, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

[Pumping rates listed in this table are for additional wells being pumped during tracer tests to maintain operation of the pump-and-treat system at the Naval Air Warfare Center; WW, well used as withdrawal well during the given tracer test; IW, well used as injection well during the given tracer test]

Recovery well	Bedding unit (Lacombe, 2000)	Pumping rate (gallons per minute)		
		BRP2-20BR tracer test	15BR-BRP3 tracer test	16BR-41BR tracer test
BRP2	L17	WW	6.5	6.5
20BR	L17	IW	0	8.5
48BR	L17	0	13.5	0
56BR	L17	0	0	0
15BR	L19	0	WW	1.0
45BR	L19	0	0	0
22BR	S13	4.4	4.4	4.4

Water at the withdrawal wells was sampled at preset time intervals using two alternating automatic samplers connected to the discharge line by a pipe “T”. Preset time intervals ranged from 3 minutes near the beginning of a test to about 24 hours during the last days of each test. The samples were transferred in the field from the automatic-sampler bottles to polyethylene bottles. The automatic-sampler bottles were rinsed with deionized water in the field after they were emptied and before the next set of samples was collected. The samples were analyzed at the USGS New Jersey Water Science Center laboratory using a calibrated bromide-selective electrode.

The mass of bromide injected during each test was determined on the basis of four limiting factors: (1) Sufficient mass must be injected to yield measurable concentrations at the withdrawal well. This mass was estimated using the analytical solution of Welty and Gelhar (1994) for a doublet test in isotropic, homogeneous porous media. The analytical solution requires estimates of the very parameters measured with the tracer tests, longitudinal dispersivity and effective porosity. Therefore, values of these parameters determined at a nearby site (Carleton and others, 1999) were used for the calculations (effective porosity equal to 0.001 and a range of longitudinal-dispersivity values from 3 to 66 ft). A detailed description of techniques and equations used to estimate the mass required for input and to analyze the results is given by Carleton and others (1999). (2) Sufficient mass must be injected such that the peak concentration in the withdrawal well is at least 3 mg/L so as to provide adequate resolution on a graph of bromide concentration as a function of time. (3) The density of the injection solution must be low enough to prevent gravity-induced flow from significantly affecting the results; therefore, the concentration of the injection fluid was kept below 10 g/L, as suggested by Becker and Shapiro (2000). (4) The minimum possible mass that satisfied the above three requirements regarding the mass and concentration of bromide was used to minimize the injection time, because the theoretical injection time is instantaneous.

Carleton and others (1999) found that approximately a five-fold increase over the mass estimated from the analytical solution was required, probably because actual field conditions depart from the assumptions in the solution (including homogeneous porous media, no diffusion into the rock matrix, and instantaneous input of tracer). On the basis of the analytical solution and the five-fold increase, the appropriate mass of injected bromide for the first test, the BRP2-20BR well pair, was determined to be 300 g. Because the measured peak bromide concentration during the first test was still lower than ideal, the masses for the next two tests were increased to more than five times the calculated value. The masses injected for the 15BR-BRP3 and 16BR-41BR well pairs were 471 and 656 g, respectively.

Analysis Methods

The longitudinal dispersivity and effective porosity of the tested volumes of the fractured-rock aquifer were estimated using the observed bromide-concentration data from each of the three tracer tests and the analytical solution described by Welty and Gelhar (1994) and Carleton and others (1999). Background bromide concentrations (0.343, 0.279, and 0.174 mg/L at withdrawal wells BRP2, 15BR, and 16BR, respectively), as determined by analyzing water samples collected before the bromide was injected, were subtracted from the observed concentrations.

Observed data from each test were plotted as dimensionless bromide concentration (measured concentration divided by total mass injected) as a function of time and overlaid on multiple plots from the analytical solution. The plots from the analytical solution were generated with all parameters fixed except dispersivity. The analytical-solution plot whose rising limb best approximated the shape of the rising limb of the plots of observed concentration data indicated the estimated dispersivity of the aquifer in the areas around the injection and withdrawal wells. Observed bromide-concentration data and the analytical-solution plots for the three tests are shown in figures 9 through 11.

Although the match between the observed-data plots and the analytical-solution plots was good for the rising limb into the peak, the falling limbs were not well matched. In all cases, the falling limbs of the analytical-solution plots were substantially below those of the observed-data plots. The falling limbs of the observed-data plots probably match those of the analytical-solution plots poorly because the analytical solution is based on assumptions that are not strictly valid for the fractured-rock aquifer: that the aquifer is homogeneous and isotropic and that the tracer is not retarded by the formation. The processes of heterogeneous flow and matrix diffusion, both of which contradict the assumptions and affect solute transport, probably occur in the aquifer. For purposes of analyzing the small-scale aquifer tests described earlier, however, in which solute-transport properties are not measured, the aquifer can be assumed to be homogeneous and isotropic over the small volumes of aquifer affected by those tests.

It is unknown which process (heterogeneous flow or matrix diffusion) is dominant in causing the offset of the observed-data plots from the analytical-solution plots. If diffusion of the bromide into and out of dead-end fractures and pores in the rock matrix is the dominant process causing the tailing of the falling limb, then the dispersivity estimates would produce reliable results when used in simulations of advective flow. If variable advective transport of the bromide in the heterogeneous fractured rock is the dominant process, as described by Becker and Shapiro (2003), the dispersivity estimates are questionable. Because the process causing the departure from the homogeneous, isotropic model has not been identified, the dispersivity estimates obtained from the tracer tests conducted in this study are questionable and cannot be used reliably in models simulating advective flow.

The effective porosity of the aquifer was estimated from the observed bromide-concentration data by solving the equation from Welty and Gelhar (1994):

$$n = \frac{Qt}{t_d H L^2}$$

where n is effective porosity,
Q is equal pumping and injection rates [L^3t^{-1}],
t is time (obtained by finding the time on the observed-data plot corresponding to the dimensionless time chosen from the analytical-solution plot),
t_d is dimensionless time (obtained by choosing a dimensionless time on the analytical-solution plot),
H is aquifer thickness (assumed to be the length of the open interval of the withdrawal well) [L], and
L is the distance between the wells [L].

The effective-porosity estimates obtained from the tracer tests conducted in this study are considered to be more reliable than the dispersivity estimates. Effective porosity is determined from the time of arrival of peak bromide concentration, which is not affected substantially by diffusion into the rock matrix or the variable advective transport of the bromide in the heterogeneous fractured rocks.

Estimated Values

The estimates of longitudinal dispersivity and effective porosity obtained from analysis of the data from the three tracer tests conducted at the NAWC are presented in table 10. Because all three tests were conducted at the NAWC, they cannot be assumed to be representative of the fractured-rock aquifer in other areas underlain by the Lockatong Formation.

The tracer-test data indicate that both the longitudinal dispersivity and the effective porosity of shallow rocks (less than about 45 ft below land surface) are greater than those of deeper rocks. The estimated longitudinal dispersivities of the shallow and deep rocks are 7 and 4 ft, respectively; the estimated porosities of the shallow and deep rocks are 0.002 and 0.0003, respectively (table 10). The shallow rocks are more porous than the deeper rocks, probably because the degree of weathering and fracturing is greater in the shallow rocks.

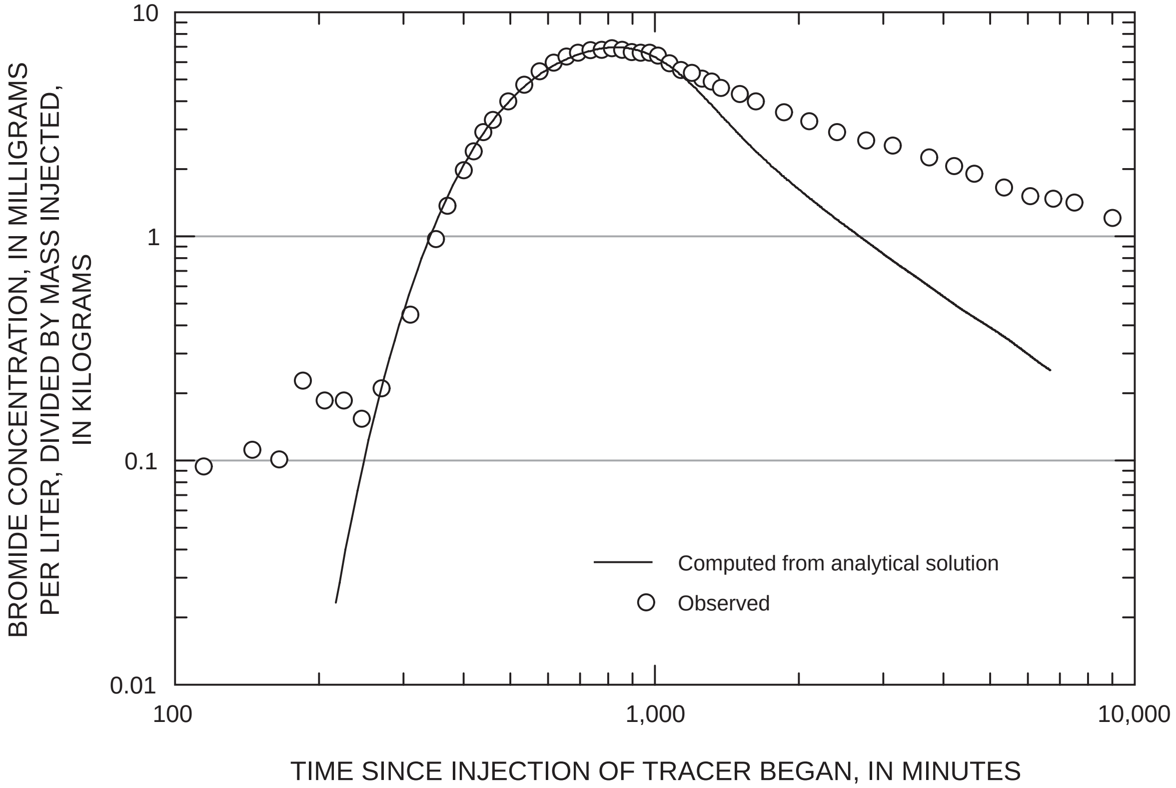

Figure 9. Observed bromide concentration in withdrawal well BRP2 resulting from injection of bromide tracer at well 20BR at the Naval Air Warfare Center, West Trenton, New Jersey, and the dimensionless concentration computed from the analytical solution of Welty and Gelhar (1994) for a doublet tracer test with longitudinal dispersivity (α_L) divided by distance between wells (L) of 0.07.

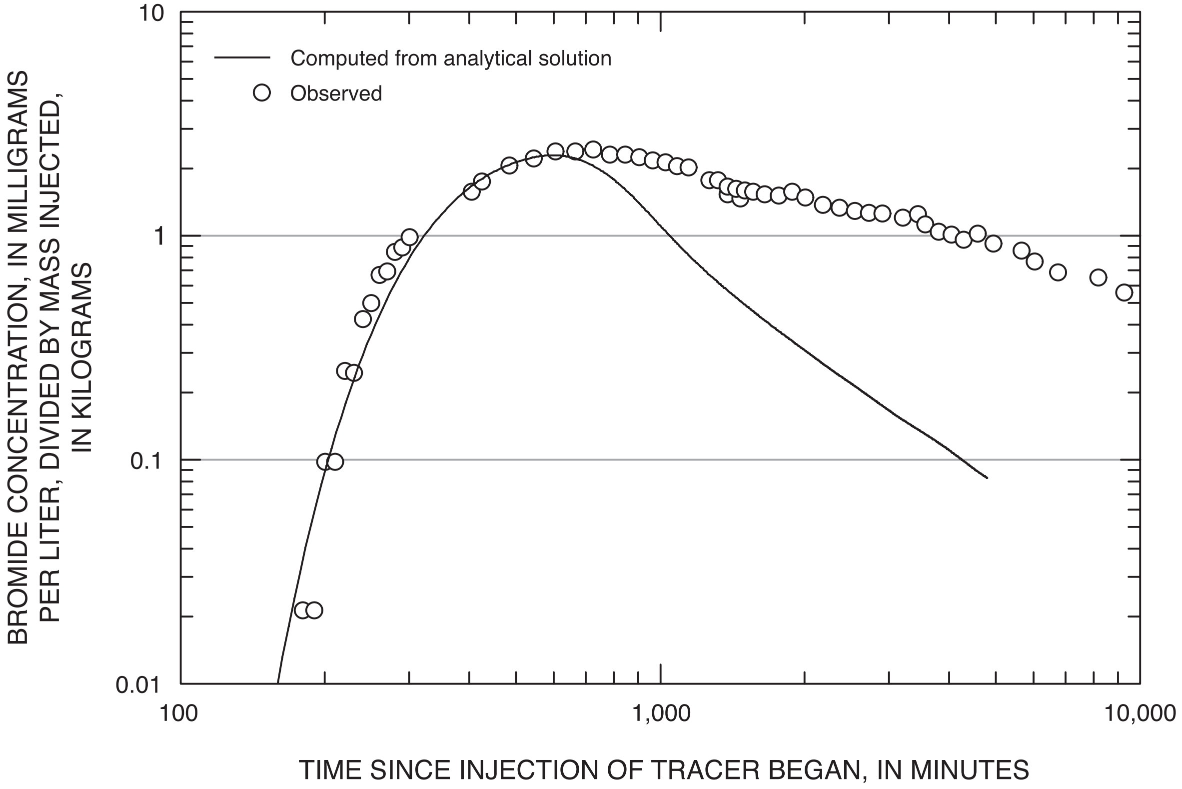

Figure 10. Observed bromide concentration in withdrawal well 15BR resulting from injection of bromide tracer at well BRP3 at the Naval Air Warfare Center, West Trenton, New Jersey, and the dimensionless concentration computed from the analytical solution of Welty and Gelhar (1994) for a doublet tracer test with longitudinal dispersivity (α_L) divided by distance between wells (L) of 0.07.

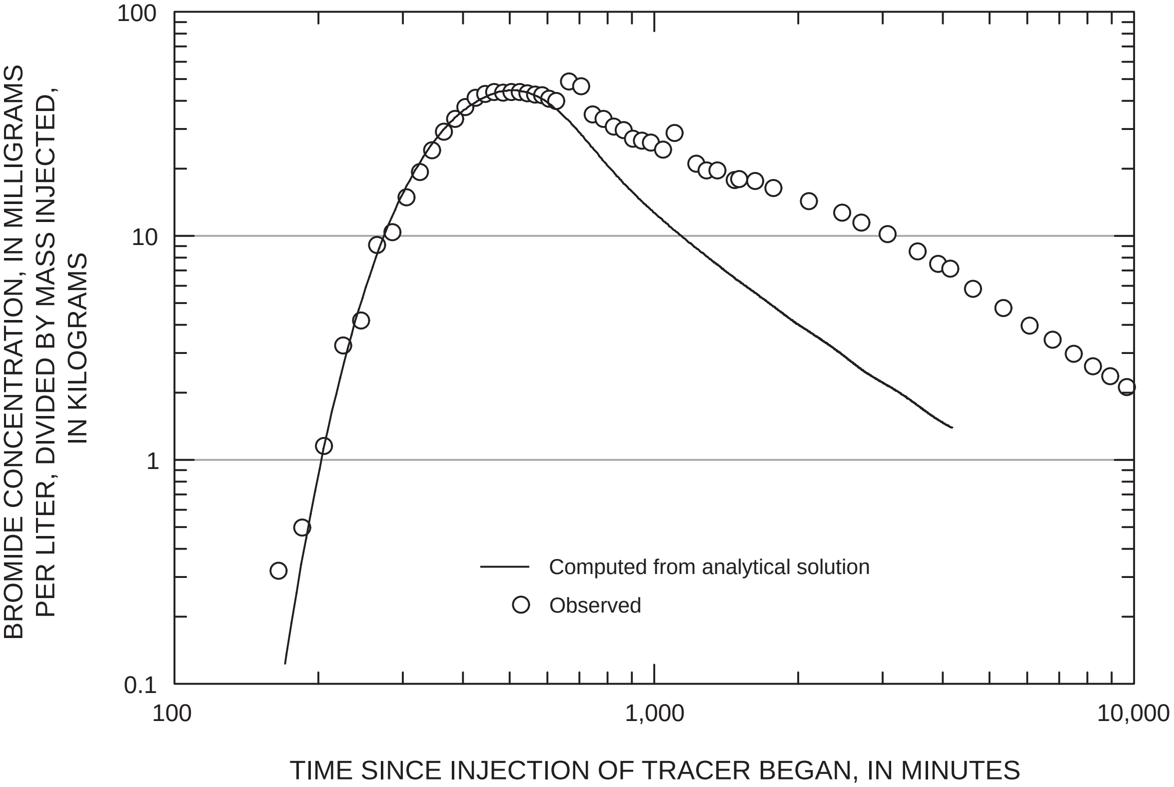

Figure 11. Observed bromide concentration in withdrawal well 16BR resulting from injection of bromide tracer at well 41BR at the Naval Air Warfare Center, West Trenton, New Jersey, and the dimensionless concentration computed from the analytical solution of Welty and Gelhar (1994) for a doublet tracer test with longitudinal dispersivity (α_L) divided by distance between wells (L) of 0.04.

Table 10. Longitudinal dispersivity and effective porosity estimated from tracer-test data, Naval Air Warfare Center, West Trenton, New Jersey, 2003.

Injection well	Withdrawal well	Bedding unit[1] (Lacombe, 2000)	Depth of open interval of well (feet below land surface): Injection well	Depth of open interval of well (feet below land surface): Withdrawal well	Longitudinal dispersivity[2] (feet)	Effective porosity
20BR	BRP2	L17	28 - 43	25 - 45	7	.002
BRP3	15BR	L19	25 - 40	26 - 41	7	.002
41BR	16BR	L19	85 - 110	40 - 65	4	.0003

[1] All bedding units in which tracer tests were conducted are in the Lockatong Formation.

[2] These longitudinal dispersivity values are questionable because some assumptions in the model used to determine the values are not met in this aquifer.

Simulated Advective Transport of Contaminated Ground Water

Ground-water flow at the NAWC under conditions in which no wells are pumped at the NAWC and in two different pumping scenarios was simulated using an existing model of steady-state ground-water flow at the site (Lewis-Brown and Rice, 2002). The modeled area extends beyond the NAWC to include streams to which ground water from the NAWC may flow (fig. 1). The model grid is variably spaced, with small (25- to 50-ft-wide) cells in the area representing the NAWC and larger cells near the model borders (fig. 12). The MODFLOW code (Harbaugh and others, 2000) was used for the simulation. Travel time, velocity, and discharge points of contaminated ground water were computed using the particle-tracking post-processor MODPATH (Pollock, 1994) and the effective-porosity values determined in this study.

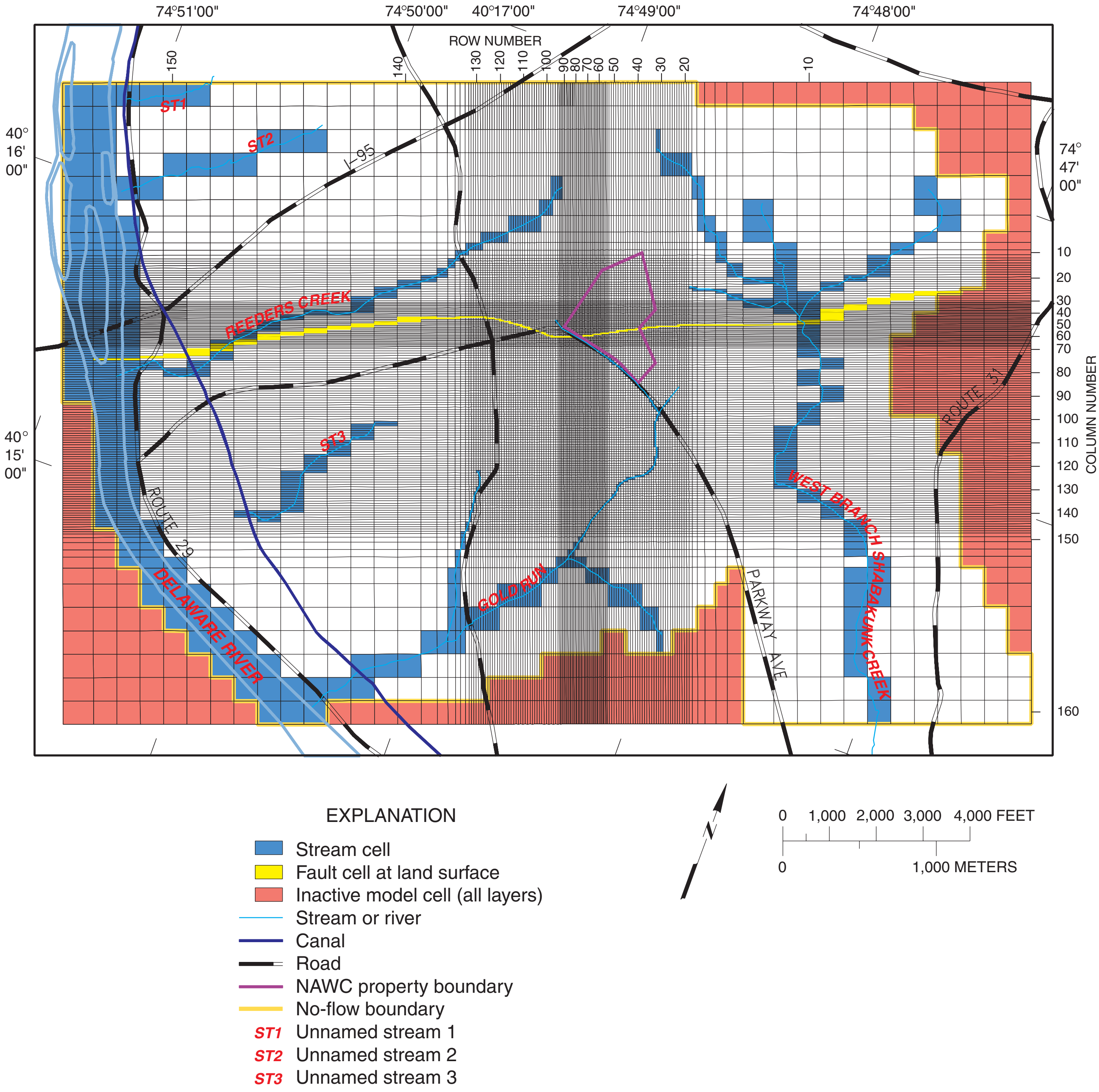

Figure 12. Finite-difference grid for the ground-water-flow model, Naval Air Warfare Center, West Trenton, New Jersey, and vicinity.

Travel Time and Velocity under Ambient Conditions

Travel time and velocity of contaminated ground water under ambient conditions (with no wells being pumped at the NAWC) were estimated by computing ground-water flow paths from each contaminated well to the stream where the water exits the ground-water system. Only advective flow is simulated with the model; the effects of density, dispersion, diffusion, dilution, and degradation of contaminants are not simulated. Therefore, it is not possible to determine with the model whether water from each contaminated well remains contaminated along its entire flow path. One particle was placed in the center of each model cell containing a contaminated well. Most (40) of the 58 model cells containing contaminated wells are 25 x 25 ft in area; 17 are 25 x 50 ft; and 1 is 50 x 50 ft. One point at the center of these small cells was considered to be an adequate representation of the volume of water at and near the well location. For purposes of this report, a well is contaminated if any sample collected from the well contained TCE, DCE, or VC in concentrations greater than the New Jersey maximum contaminant level (1, 70, and 2 μg/L, respectively (N.J. Department of Environmental Protection, 2002)). Construction and location data for contaminated wells and wells used in aquifer and tracer tests are listed in table 11. The travel time, velocity, and discharge point of each flow path are listed in table 12. The receiving stream for the flow path from each contaminated well is illustrated in figure 13.

The value of the effective porosity of the aquifer is a necessary component of the computation of travel time and velocity. In this study, the effective porosity was determined in three discrete parts of the aquifer. To rigorously determine travel times throughout the heterogeneous aquifer at the NAWC, it would be necessary to determine the effective porosity throughout the site by conducting at least two tracer tests in each of the 16 bedding units at the NAWC. Because conducting that many tests was beyond the scope of this phase of the investigation, tests were conducted in the areas of greatest concern, which were the two bedding units in which the highest levels of contamination have been detected. For purposes of estimating travel time using the MODPATH particle tracker, the effective porosity of the aquifer was assumed to be 0.002 in rocks less than 45 ft below land surface and 0.0003 in deeper rocks, on the basis of the findings listed in table 10, with a margin of uncertainty of about one order of magnitude. The estimates of travel time and velocity presented in table 12 include this margin of uncertainty.

If values of effective porosity are assumed to be low, the travel time of contaminated ground water from a contaminated well to the receiving stream is shorter than if values of effective porosity are assumed to be high (table 12). Shorter travel times would result in a worst-case scenario for non-pumping remediation methods because less time would be available for processes such as dispersion, dilution, and degradation of contaminants to occur before the contaminated water reaches the stream. Short travel times would result in a best-case scenario, however, for the pump-and-treat remediation method currently being used at the NAWC, because the overall time required for clean-up would be shorter. Estimates of travel time computed from the ground-water-flow model, however, do not include the effects of density, dispersion, dilution, degradation, and, perhaps most importantly, diffusion of contaminants into and out of dead-end fractures in the rock matrix, a factor that may be at least as important as the velocity of the water in determining the effectiveness of remediation techniques.

Table 11. Well-construction and location data for selected wells at the Naval Air Warfare Center, West Trenton, New Jersey.

[USGS, U.S. Geological Survey; WZ, weathered zone; --, not determined; latitude and longitude, in degrees, minutes, and seconds, are referenced to the North American Datum of 1983; altitude is referenced to the North American Vertical Datum of 1988]

Well name	USGS well number	New Jersey permit number	Latitude	Longitude	Altitude of land surface (feet)	Depth of open interval (feet below land surface)		Bedding unit (Lacombe, 2000)	Geologic formation
						Top	Bottom		
2S	210493	27-09895-8	401607	744848	148.83	3	8	WZ	Lockatong
6S	210495	27-09893-1	401604	744846	146.89	4	10	WZ	Stockton
11S	210496	27-09888-5	401612	744834	158.83	8	23	WZ	Lockatong
12S	210497	27-09889-3	401612	744832	157.83	10.5	20.5	WZ	Lockatong
13S	210498	27-09890-7	401613	744831	158.36	10	20	WZ	Lockatong
14S	210499	27-09891-5	401614	744830	162.90	14.5	24.5	WZ	Lockatong
15S	210500	27-09918-1	401608	744847	148.73	3	13	WZ	Lockatong
24S	210507	27-09927-0	401615	744849	168.39	5.5	15.5	WZ	Lockatong
25S	210508	27-09925-3	401614	744848	167.81	3.5	18.5	WZ	Lockatong
28S	210511	27-10962	401611	744833	156.31	10	25	WZ	Lockatong
31S	210601	27-10963	401609.45	744834.97	149.73	10	20	WZ	Lockatong
37S	210528	27-12681	401605	744836	147.35	6	16	WZ	Stockton
39S	210529	27-12683	401605	744845	149.06	3	13	WZ	Stockton
41S	210531	27-12685	401606	744849	149.49	3	13	WZ	Lockatong
11MW1	210570	27-14458	401607.28	744834.37	152.16	8	22	WZ	Stockton

Table 11. Well-construction and location data for selected wells at the Naval Air Warfare Center, West Trenton, New Jersey--Continued.

[USGS, U.S. Geological Survey; WZ, weathered zone; --, not determined; latitude and longitude, in degrees, minutes, and seconds, are referenced to the North American Datum of 1983; altitude is referenced to the North American Vertical Datum of 1988]

Well name	USGS well number	New Jersey permit number	Latitude	Longitude	Altitude of land surface (feet)	Depth of open interval (feet below land surface)		Bedding unit (Lacombe, 2000)	Geologic formation
						Top	Bottom		
12MW1	210580	27-15414	401608.99	744833.24	155.53	5	15	WZ	Stockton
35MW1	210572	27-14459	401616.28	744847.56	168.92	7	25	WZ	Lockatong
BRP1	210537	27-09937-7	401609	744844	149.73	20	60	L20	Lockatong
BRP2	210422	27-12419	401605	744849	149.37	25	45	L17	Lockatong
BRP3	210423	27-12420	401607	744850	149.53	25	40	L19	Lockatong
2BR	210545	27-10961-5	401612	744833	157.24	40	60	L20	Lockatong
4BR	210530	27-11938	401606	744844	149.97	24	39	L17	Lockatong
5BR	210424	27-11939	401605	744848	148.84	69	84	L15	Lockatong
7BR	210514	27-11941	401606	744847	148.65	38	53	L18	Lockatong
8BR	210515	27-11942	401610	744848	150.98	32	57	L22	Lockatong
9BR	210516	27-11948	401612	744848	152.13	19	44	L23	Lockatong
11BR	210427	27-11950	401614	744830	163.61	55	75	L21	Lockatong
12BR	210517	27-11951	401614	744833	161.78	56.5	71.5	L22	Lockatong
15BR	210520	27-11943	401607	744849	148.73	26	41	L19	Lockatong
16BR	210521	27-11954	401609	744842	149.42	40	65	L19	Lockatong
17BR	210522	27-11944	401608	744843	149.64	19	44	L19	Lockatong
20BR	210525	27-11945	401605	744850	149.77	28	43	L17	Lockatong
21BR	210526	27-11957	401614	744849	167.94	50	65	L23	Lockatong
22BR	210527	27-11946	401604	744844	147.37	24	49	S13	Stockton
23BR	210428	27-11947	401606	744844	149.90	65	90	L16	Lockatong
24BR	210429	27-12408	401606	744847	149.18	80	95	L16	Lockatong
25BR	210430	27-12409	401607	744849	148.61	75	100	L18	Lockatong
27BR	210432	27-12412	401604	744846	146.91	65	80	L13	Lockatong
29BR	210417	27-12427	401609	744848	149.81	85	100	L21	Lockatong
30BR	210434	27-12428	401608	744844	149.41	85	110	L18	Lockatong
31BR	210435	27-12429	401609	744835	150.66	35	45	L15	Lockatong
36BR	210440	27-12417	401608	744850	154.34	102	125	L19	Lockatong
37BR	210441	27-12418	401605	744833	142.76	60	75	S11	Stockton
38BR	210442	27-12411	401609	744845	149.61	100	115	L19	Lockatong
40BR	210533	27-13977	401606	744852	153.05	95	120	L18	Lockatong
41BR	210541	27-13978	401610	744842	149.30	85	110	L19	Lockatong
45BR	210542	27-13982	401610	744850	158.51	185	210	L19	Lockatong
46BR	210543	27-13983	401611	744846	149.73	196	221	L19	Lockatong
47BR	210538	27-14146	401609	744844	149.85	3	18	WZ	Lockatong
48BR	210540	27-14149	401610	744835	159.84	82	100	L17	Lockatong
49BR	210536	27-14148	401609	744838	149.16	42	60	L17	Lockatong
50BR	210544	27-14147	401612	744829	157.28	60	80	L17	Lockatong
51BR	210548	27-14150	401613	744832	158.48	86	96	L20	Lockatong
53BR	210581	27-15279	401610.31	744839.55	147.43	95	120	L19	Lockatong
54BR	210575	27-15278	401608.13	744834.46	152.95	175	200	--	Lockatong
56BR	210579	27-15276	401608.05	744848.52	149.37	140	165	L17	Lockatong
60BR	210624	27-16879	401606.56	744851.19	153.39	70	85	L19	Lockatong
61BR	210627	27-16880	401609.24	744849.89	156.96	70	100	L19	Lockatong
65BR	210622	27-16883	401605.04	744844.45	149.36	15	40	L14	Lockatong

Table 12. Travel time and average linear velocity of flow paths from contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey, under ambient flow conditions.

[WZ, weathered zone; L, Lockatong Formation; S, Stockton Formation; --, not determined]

							Travel time and average linear velocity of flow paths					
									Incorporating a margin of uncertainty into porosity values obtained from tracer-test results			
	Depth of open interval (feet below land surface)						Assuming porosity equal to tracer-test results (0.002 in rocks less than 45 feet below land surface and 0.0003 in deeper rocks)		Assuming porosity lower than tracer-test results (0.0006 in rocks less than 45 feet below land surface and 0.0001 in deeper rocks)		Assuming porosity greater than tracer-test results (0.006 in rocks less than 45 feet below land surface and 0.001 in deeper rocks)	
Well name	Top	Bottom	Bedding unit (Lacombe, 2000)	Geologic formation	Stream to which water discharges from the ground-water system	Length of flow path from well to stream (feet)	Travel time (days)	Average linear velocity (feet per day)	Travel time (days)	Average linear velocity (feet per day)	Travel time (days)	Average linear velocity (feet per day)
2S	3	8	WZ	L	Gold Run (west branch)	263	16	16	4.8	55	48	5.5
6S	4	10	WZ	S	Gold Run (west branch)	37.7	470	.080	140	.27	1,400	.027
11S	8	23	WZ	L	Delaware River	12,000	220	55	71	170	710	17
12S	10.5	20.5	WZ	L	Gold Run (west branch)	2,270	280	8.0	93	24	930	2.4
13S	10	20	WZ	L	Gold Run (main stem)	3,660	980	3.8	320	11	3,200	1.1
14S	14.5	24.5	WZ	L	West Branch Shabakunk Creek	3,840	390	10	130	30	1,300	3.0
15S	3	13	WZ	L	Gold Run (west branch)	480	41	12	12	40	120	4.0
24S	5.5	15.5	WZ	L	Reeders Creek	5,210	54	96	17	310	170	31
25S	3.5	18.5	WZ	L	Reeders Creek	5,400	65	83	20	270	200	27
28S	10	25	WZ	L	Gold Run (west branch)	1,430	260	5.6	81	18	810	1.8
31S	10	20	WZ	L	Gold Run (west branch)	839	1,600	.54	470	1.8	4,700	.18
37S	6	16	WZ	S	Gold Run (west branch)	363	35	11	10	35	100	3.5
39S	3	13	WZ	S	Gold Run (west branch)	175	460	.38	140	1.3	1,400	.13
41S	3	13	WZ	L	Gold Run (west branch)	149	5.7	26	1.7	87	17	8.7
11MW1	8	22	WZ	S	Gold Run (west branch)	611	57	1	17	35	170	3.5
12MW1	5	15	WZ	S	Gold Run (west branch)	906	93	9.7	28	32	280	3.2
35MW1	7	25	WZ	L	Reeders Creek	5,230	78	66	24	220	240	22
BRP1	20	60	L20	L	Gold Run (west branch)	725	18	40	5.4	130	54	13
BRP2	25	45	L17	L	Gold Run (west branch)	108	2.5	44	.74	150	7.4	15
BRP3	25	40	L19	L	Gold Run (west branch)	300	6.0	50	1.8	170	18	17

Table 12. Travel time and average linear velocity of flow paths from contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey, under ambient flow conditions--Continued.

[WZ, weathered zone; L, Lockatong Formation; S, Stockton Formation; --, not determined]

							Travel time and average linear velocity of flow paths					
									Incorporating a margin of uncertainty into porosity values obtained from tracer-test results			
	Depth of open interval (feet below land surface)						Assuming porosity equal to tracer-test results (0.002 in rocks less than 45 feet below land surface and 0.0003 in deeper rocks)		Assuming porosity lower than tracer-test results (0.0006 in rocks less than 45 feet below land surface and 0.0001 in deeper rocks)		Assuming porosity greater than tracer-test results (0.006 in rocks less than 45 feet below land surface and 0.001 in deeper rocks)	
Well name	Top	Bottom	Bedding unit (Lacombe, 2000)	Geologic formation	Stream to which water discharges from the ground-water system	Length of flow path from well to stream (feet)	Travel time (days)	Average linear velocity (feet per day)	Travel time (days)	Average linear velocity (feet per day)	Travel time (days)	Average linear velocity (feet per day)
2BR	40	60	L20	L	Delaware River	12,300	700	18	230	53	2,300	5.3
4BR	24	39	L17	L	Gold Run (west branch)	419	12	34	3.7	110	37	11
5BR	69	84	L15	L	Gold Run (west branch)	130	1.8	71	.57	230	5.7	23
7BR	38	53	L18	L	Gold Run (west branch)	382	7.4	52	2.2	170	22	17
8BR	32	57	L22	L	Gold Run (west branch)	735	12	63	3.6	200	36	20
9BR	19	44	L23	L	Reeders Creek	7,630	59	130	19	410	190	41
11BR	55	75	L21	L	West Branch Shabakunk Creek	3,850	410	9.4	140	28	1,400	2.8
12BR	56.5	71.5	L22	L	Delaware River	12,200	260	47	87	140	870	14
15BR	26	41	L19	L	Gold Run (west branch)	319	8.6	37	2.6	120	26	12
16BR	40	65	L19	L	Gold Run (west branch)	823	10	82	3.1	260	31	26
17BR	19	44	L19	L	Gold Run (west branch)	658	18	37	5.4	120	54	12
20BR	28	43	L17	L	Gold Run (west branch)	61.6	1.4	43	.43	140	4.3	14
21BR	50	65	L23	L	Reeders Creek	5,570	101	55	34	170	340	17
22BR	24	49	S13	S	Gold Run (west branch)	45.3	27	1.7	8.1	5.6	81	.56
23BR	65	90	L16	L	Gold Run (west branch)	455	6.2	73	1.9	230	19	23
24BR	80	95	L16	L	Gold Run (west branch)	406	3.2	130	1.0	400	10	40
25BR	75	100	L18	L	Gold Run (west branch)	389	3.9	100	1.2	320	12	32
27BR	65	80	L13	L	Gold Run (west branch)	122	130	.91	44	2.8	440	.28
29BR	85	100	L21	L	Gold Run (west branch)	753	8.0	95	2.5	300	25	30
30BR	85	110	L18	L	Gold Run (west branch)	660	15	43	4.6	140	46	14
31BR	35	45	L15	L	Gold Run (west branch)	2,060	320	6.5	100	20	1,000	2.0
36BR	102	125	L19	L	Gold Run (west branch)	541	7.5	70	2.3	230	23	23
37BR	60	75	S11	S	Gold Run (west branch)	391	52	75	16	25	160	2.5
38BR	100	115	L19	L	Gold Run (west branch)	882	8.4	100	2.7	330	27	33
40BR	95	120	L18	L	Gold Run (west branch)	262	4.3	61	1.3	200	13	20

Table 12. Travel time and average linear velocity of flow paths from contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey, under ambient flow conditions--Continued.

[WZ, weathered zone; L, Lockatong Formation; S, Stockton Formation; --, not determined]

	Depth of open interval (feet below land surface)						Travel time and average linear velocity of flow paths					
							Assuming porosity equal to tracer-test results (0.002 in rocks less than 45 feet below land surface and 0.0003 in deeper rocks)		Incorporating a margin of uncertainty into porosity values obtained from tracer-test results			
									Assuming porosity lower than tracer-test results (0.0006 in rocks less than 45 feet below land surface and 0.0001 in deeper rocks)		Assuming porosity greater than tracer-test results (0.006 in rocks less than 45 feet below land surface and 0.001 in deeper rocks)	
Well name	Top	Bottom	Bedding unit (Lacombe, 2000)	Geologic formation	Stream to which water discharges from the ground-water system	Length of flow path from well to stream (feet)	Travel time (days)	Average linear velocity (feet per day)	Travel time (days)	Average linear velocity (feet per day)	Travel time (days)	Average linear velocity (feet per day)
41BR	85	110	L19	L	Gold Run (west branch)	951	9.1	100	2.9	320	29	32
45BR	185	210	L19	L	Delaware River	10,600	460	23	150	71	1,500	7.1
46BR	196	221	L19	L	Delaware River	11,000	510	21	170	64	1,700	6.4
47BR	3	18	WZ	L	Gold Run (west branch)	675	34	20	10	66	100	6.6
48BR	82	100	L17	L	Gold Run (west branch)	1,050	440	2.3	130	7.9	1,300	.79
49BR	42	60	L17	L	Delaware River	11,300	210	55	68	170	680	17
50BR	60	80	L17	L	West Branch Shabakunk Creek	4,310	1,300	3.5	430	10	4,300	1.0
51BR	86	96	L20	L	Gold Run (main stem)	6,920	2,300	2.1	770	9.0	7,700	.90
54BR	175	200	--	L	Gold Run (west branch)	2,450	260	11	83	30	830	3.0
56BR	140	165	L17	L	Reeders Creek	7,300	96	79	30	240	300	24
60BR	70	85	L19	L	Gold Run (west branch)	192	4.2	46	1.3	150	13	15
61BR	70	100	L19	L	Delaware River	10,500	120	73	41	260	410	26
65BR	15	40	L14	L	Gold Run (west branch)	115	100	1.1	31	3.8	310	.38

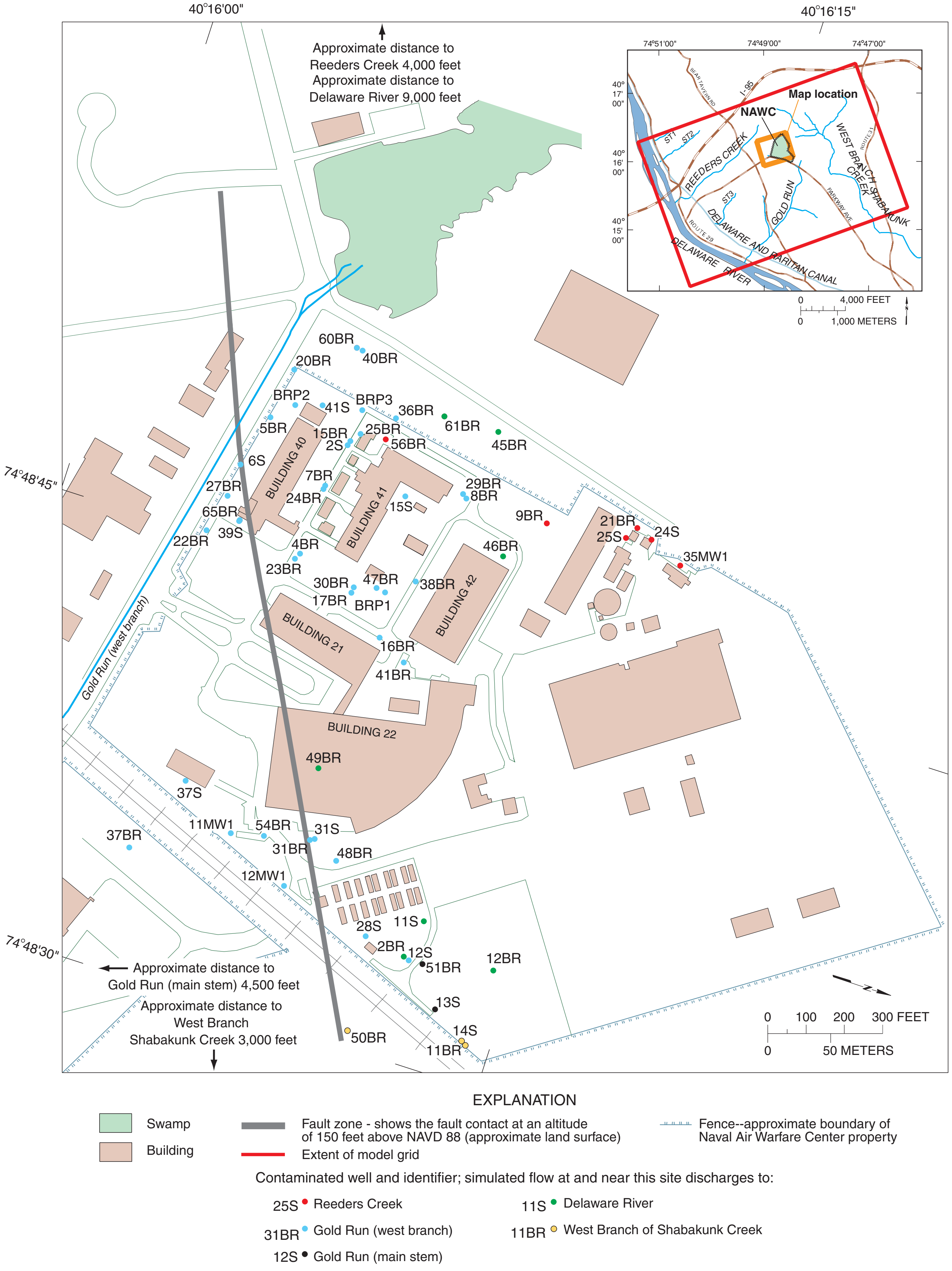

Figure 13. Simulated discharge locations of ground water at and near contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey (with no recovery wells pumped).

The wide range of velocities listed in table 12 (0.080 to 130 ft/d if porosities of 0.002 and 0.0003 in the shallow and deep rocks, respectively, are used to calculate velocities) is a result of the heterogeneity of the aquifer. Hydraulic conductivity in the aquifer varies widely between the Lockatong and Stockton Formations, between faulted and nonfaulted rocks, and with depth (Lewis-Brown and Rice, 2002). Overall, the horizontal hydraulic conductivity used in the model varies from 0.001 to 11.3 ft/d, and the vertical hydraulic conductivity varies from 0.0001 to 1.13 ft/d (Lewis-Brown and Rice, 2002).

Discharge Points during Operation of Pump-and-Treat System

The effect on ground-water flow of a recent (July 2004) change to the configuration of recovery wells in the pump-and-treat system at the NAWC was evaluated using the existing ground-water-flow model. The wells pumped in the former and current networks (networks II and III) are listed in table 13.

Network II was changed to network III by adding well 56BR with a pumpage rate of 5 gal/min, and decreasing pumpage from well 15BR by the same amount. Well 56BR is near well 15BR but is deeper. The change was made to increase the amount of water pumped directly from the deeper, more contaminated part of the aquifer. Simulation results indicate that the change caused water in the areas of three deep wells (25BR, 38BR, and 56BR) to be captured by well 56BR instead of flowing upward to well 15BR. The simulated discharge point of ground water at and near each contaminated well when each of these networks is operating is shown in figure 14 and listed in table 14.

Simulation results also indicate that the change from recovery-well network II to network III resulted in the additional, unexpected effect that water in the vicinity of well 49BR is captured by well 22BR instead of well BRP2. In the area near well 49BR, the model apparently is very sensitive to changes in the pumpage scheme. Consequently, it is uncertain which recovery well captures flow from this area, although it is nearly certain that the flow is captured by one of the wells.

Suggestions for Additional Work

To determine more definitively the effectiveness of various configurations of recovery wells in the pump-and-treat system, it would be helpful to compute and illustrate the system's capture area in each bedding unit. To compute the capture areas accurately, the current ground-water-flow model could be refined to represent the distribution of hydraulic conductivity at the site with greater precision. The hydraulic conductivity of wells determined from slug testing (Lewis-Brown and Rice, 2002) could be used as a starting point in defining the distribution of conductivity; wells that have been installed since that testing and wells not available at that time also could be slug tested to obtain additional data points needed to improve the current understanding of the distribution of hydraulic conductivity.

A solute-transport model could be developed and used to obtain information about the transport and fate of contaminants under both pump-and-treat and non-pumping remediation methods. The model could be used to compute the decrease in contaminant concentrations resulting from dispersion, dilution, degradation, and diffusion along flow paths originating at the NAWC. Additional tracer tests aimed at defining more rigorously the distribution of effective porosity and longitudinal dispersivity at the NAWC would be helpful in developing the solute-transport model.

Table 13. Recovery wells in pump-and-treat system, Naval Air Warfare Center, West Trenton, New Jersey.

Recovery well	Bedding unit (Lacombe, 2000)	Depth of well opening (feet below land surface)	Pumping rate (gallons per minute)	
			Network II	Network III
BRP2	L17	25 - 45	10.0	10.0
15BR	L19	26 - 41	15.0	10.0
20BR	L17	28 - 43	8.5	8.5
22BR	S13	24 - 49	4.4	4.4
45BR	L19	185 - 210	5.1	5.1
48BR	L17	82 - 100	13.5	13.5
56BR	L17	140 - 165	0	5.0

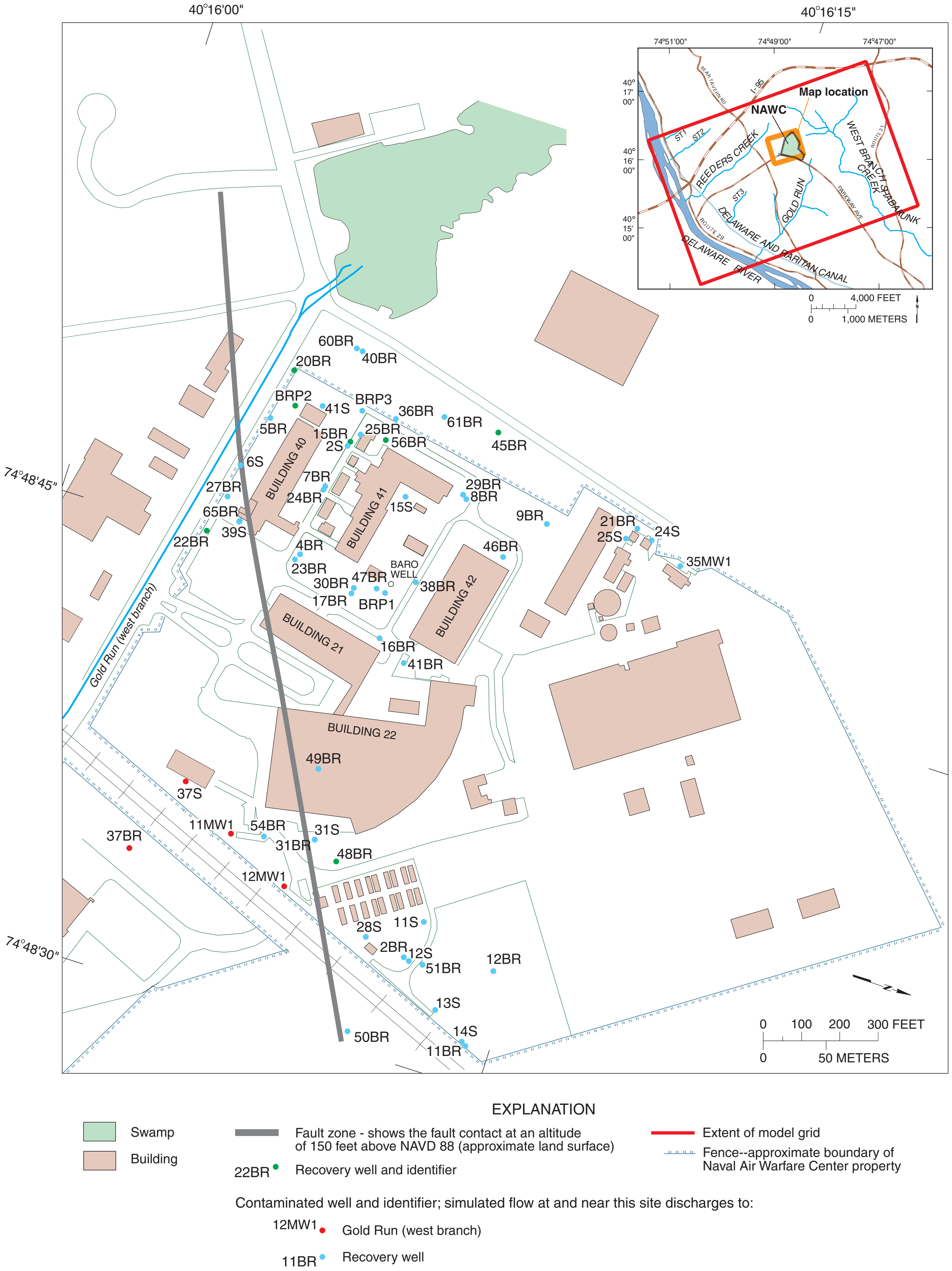

Figure 14. Simulated discharge locations of ground water at and near contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey (with recovery-well network II or III in operation).

Table 14. Simulated discharge points of ground-water flow paths from contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey, during operation of pump-and-treat system.

[WZ, weathered zone; gal/min, gallons per minute; --, not determined]

Well name (flow path starting point)	Bedding unit (Lacombe, 2000)	Geologic formation	Recovery-well network II[1]	Recovery-well network III[2]
2S	WZ	Lockatong	Well 15BR	Well 15BR
6S	WZ	Stockton	Well 22BR	Well 22BR
11S	WZ	Lockatong	Well 48BR	Well 48BR
12S	WZ	Lockatong	Well 48BR	Well 48BR
13S	WZ	Lockatong	Well 48BR	Well 48BR
14S	WZ	Lockatong	Well 48BR	Well 48BR
15S	WZ	Lockatong	Well 15BR	Well 15BR
24S	WZ	Lockatong	Well 15BR	Well 15BR
25S	WZ	Lockatong	Well 15BR	Well 15BR
28S	WZ	Lockatong	Well 48BR	Well 48BR
31S	WZ	Lockatong	Well 48BR	Well 48BR
37S	WZ	Stockton	Gold Run (west branch)	Gold Run (west branch)
39S	WZ	Stockton	Well 22BR	Well 22BR
41S	WZ	Lockatong	Well BRP2	Well BRP2
11MW1	WZ	Stockton	Gold Run (west branch)	Gold Run (west branch)
12MW1	WZ	Stockton	Gold Run (west branch)	Gold Run (west branch)
35MW1	WZ	Lockatong	Well 15BR	Well 15BR
BRP1	L20	Lockatong	Well 15BR	Well 15BR
BRP2	L17	Lockatong	Well BRP2	Well BRP2
BRP3	L19	Lockatong	Well 15BR	Well 15BR
2BR	L20	Lockatong	Well 48BR	Well 48BR
4BR	L17	Lockatong	Well BRP2	Well BRP2
5BR	L15	Lockatong	Well BRP2	Well BRP2
7BR	L18	Lockatong	Well 15BR	Well 15BR
8BR	L22	Lockatong	Well 15BR	Well 15BR
9BR	L23	Lockatong	Well 15BR	Well 15BR
11BR	L21	Lockatong	Well 48BR	Well 48BR
12BR	L22	Lockatong	Well 48BR	Well 48BR
15BR	L19	Lockatong	Well 15BR	Well 15BR
16BR	L19	Lockatong	Well BRP2	Well BRP2
17BR	L19	Lockatong	Well BRP2	Well BRP2
20BR	L17	Lockatong	Well 20BR	Well 20BR
21BR	L23	Lockatong	Well 45BR	Well 45BR
22BR	S13	Stockton	Well 22BR	Well 22BR
23BR	L16	Lockatong	Well BRP2	Well BRP2
24BR	L16	Lockatong	Well BRP2	Well BRP2
25BR	L18	Lockatong	Well 15BR	Well 56BR
27BR	L13	Lockatong	Well 22BR	Well 22BR
29BR	L21	Lockatong	Well 15BR	Well 15BR
30BR	L18	Lockatong	Well BRP2	Well BRP2
31BR	L15	Lockatong	Well 48BR	Well 48BR
36BR	L19	Lockatong	Well 15BR	Well 15BR
37BR	S11	Stockton	Gold Run (west branch)	Gold Run (west branch)
38BR	L19	Lockatong	Well 15BR	Well 56BR
40BR	L18	Lockatong	Well 20BR	Well 20BR
41BR	L19	Lockatong	Well BRP2	Well BRP2
45BR	L19	Lockatong	Well 45BR	Well 45BR
46BR	L19	Lockatong	Well 45BR	Well 45BR
47BR	WZ	Lockatong	Well BRP2	Well BRP2
48BR	L17	Lockatong	Well 48BR	Well 48BR

Table 14. Simulated discharge points of ground-water flow paths from contaminated wells at the Naval Air Warfare Center, West Trenton, New Jersey, during operation of pump-and-treat system--Continued.

[WZ, weathered zone; gal/min, gallons per minute; --, not determined]

Well name (flow path starting point)	Bedding unit (Lacombe, 2000)	Geologic formation	Recovery-well network II[1]	Recovery-well network III[2]
49BR	L17	Lockatong	Well BRP2	Well 22BR
50BR	L17	Lockatong	Well 48BR	Well 48BR
51BR	L20	Lockatong	Well 48BR	Well 48BR
54BR	--	Lockatong	Well 22BR	Well 22BR
56BR	L17	Lockatong	Well 15BR	Well 56BR
60BR	L19	Lockatong	Well 20BR	Well 20BR
61BR	L19	Lockatong	Well 45BR	Well 45BR
65BR	L14	Lockatong	Well 22BR	Well 22BR

[1] Well 15BR pumped at 15 gal/min, 20BR at 8.5 gal/min, 22BR at 4.4 gal/min, 45 BR at 5.1 gal/min, 48BR at 13.5 gal/min, and BRP2 at 10 gal/min

[2] Well 15BR pumped at 10 gal/min, 20BR at 8.5 gal/min, 22BR at 4.4 gal/min, 45 BR at 5.1 gal/min, 48BR at 13.5 gal/min, 56BR at 5 gal/min, and BRP2 at 10 gal/min

Summary and Conclusions

Volatile organic compounds, predominantly trichloroethylene and its degradation products, have been detected in ground water in the fractured-rock aquifer at the Naval Air Warfare Center (NAWC), West Trenton, N.J. The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of the Navy, has conducted an 11-year multiphase hydrogeologic investigation of the NAWC. The purpose of this phase of the investigation was to (1) estimate hydraulic and solute-transport properties of the aquifer, (2) estimate the velocity and travel time of contaminated ground water if the existing pump-and-treat system were replaced by a non-pumping remediation technique, and (3) evaluate the effect on ground-water flow of a change to the configuration of the network of recovery wells in the pump-and-treat system at the NAWC.

Hydraulic properties of the fractured-rock aquifer in the Lockatong Formation at the NAWC were measured using five aquifer tests and three tracer tests. The heterogeneous nature of the formation causes a wide range in values of each parameter. Transmissivity ranges from 95 to 1,300 ft^2/d, storage coefficient from 9×10^{-5} to 5×10^{-3}, effective porosity from 0.0003 to 0.002, and longitudinal dispersivity from 4 to 7 ft. All of these values represent conditions at the NAWC and are not necessarily representative of other areas underlain by the Lockatong Formation. In addition, the validity of the longitudinal-dispersivity values is uncertain because the analytical-solution method used to determine them is based partly on the assumption that the tested aquifer is homogeneous and isotropic--an assumption that is not strictly valid for solute transport in the fractured-rock aquifer.

The velocity and travel time of ground water along flow paths from each contaminated well to the stream where the water eventually discharges under non-pumping conditions were computed using the effective-porosity values obtained from the tracer tests, an existing ground-water-flow model, and particle-tracking techniques. The wide range of estimated velocities (0.08 to 130 ft/d) is a result of the heterogeneity of the aquifer.

A pump-and-treat system consisting of a network of six recovery wells and an air-stripping treatment system has been in operation at the NAWC since 1998. The existing ground-water-flow model and particle-tracking techniques were used to estimate the effect on ground-water flow of changing the network by pumping an additional deep (165 ft deep) well at a rate of 5 gal/min while decreasing pumpage from a nearby shallower (41 ft deep) well by the same amount. Simulation results indicate that the change caused water in the areas around three deep contaminated wells to be captured by the new deep recovery well rather than flowing upward to the shallower well.

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Appendix 1

Appendix 1. Aquifer-test solution parameters.

		Neuman solution for an unconfined aquifer				Theis solution for a confined aquifer		Hantush solution for a confined, wedge-shaped aquifer		
Withdrawal well	**Observation well**	**b (feet)**	**K_z/K_r**	**Sy**	**β**	**b (feet)**	**K_z/K_r**	**b at withdrawal well (feet)**	**r/a**	**K_z/K_r**
BRP2	20BR	20	0.0007	0.001	0.03	20	0.001	20	-0.06	0.001
BRP2	56BR	22.5	.002	.004	.2	22.5	.001	22.5	.6	.001
15BR	BRP3	15	.01	.002	.8	15	.01	15	.01	.01
16BR	41BR	25	.002	.04	.03	25	.002	25	-.5	.002
41BR	53BR	25	.003	.04	.1	25	.001	25	.08	.01

Definition of terms:

b	thickness of the saturated aquifer
K_z/K_r	ratio of hydraulic conductivity in the vertical direction to hydraulic conductivity in the horizontal direction
Sy	specific yield: ratio of the volume of water that drains under the influence of gravity to the volume of saturated rock (Heath, 1983)
β	r^2K_z/b^2K_r, where r is the radial distance from the withdrawal well to the observation well, K_z is the hydraulic conductivity in the vertical direction, b is the thickness of the saturated aquifer, and K_r is the hydraulic conductivity in the horizontal direction (Kruseman and deRidder, 1990).
r/a	radial distance (r) from the withdrawal well to the observation well divided by a constant defining the exponential variation of the aquifer thickness (a) (Kruseman and deRidder, 1990)