Hydrogeologic Framework and Simulation of Ground-Water Flow and Travel Time in the Shallow Aquifer System in the Area of Naval Support Activity Memphis, Millington, Tennessee

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CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/day)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
mile (mi)	1.609	kilometer
acre	0.4047	square hectometer
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.59	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meters per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallons per minute (gal/min)	0.06308	liter per second

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius as follows: °C = 5/9 x (°F - 32)

Transmissivity: In this report transmissivity is expressed as foot squared per day (ft^2/d)—The standard unit for transmissivity (T) is cubic foot per day per square foot times foot of aquifer thickness "$[(ft^3/d)/ft^2]ft$" or cubic meters per day per square meter times meter of aquifer thickness "$[(m^3/d)/m^2]m$." These mathematical expressions reduce to foot squared per day "ft^2/d" or meter squared per day "m^2/d."

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Tennessee District well-numbering system: Wells in Tennessee are identified according to the numbering system that is used by the U.S. Geological Survey, Water Resources Division. The well number consists of three parts:
(1) an abbreviation of the name of the county in which the well is located;
(2) a letter designating the 7 1/2-minute topographic quadrangle on which the well is plotted; quadrangles are lettered from left to right across the county beginning in the southwest corner of the county; and
(3) a number generally indicating the numerical order in which the well was inventoried.
For example, Sh:U-99 indicates that the well is located in Shelby County on the "U" quadrangle and is identified as well 99 in the numerical sequence.

ACRONYMS AND DEFINITIONS

AOC	Area of Concern
BRAC	Base Closure and Realignment
GWSI	Ground Water Site Inventory data base
MODFLOW	U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model
MODPATH	A computer program to compute ground-water-flow paths using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model
MODPLOT	A computer program to display ground-water-flow paths computed by the computer program MODPATH
NSA	Naval Support Activity
RCRA	Resource Conservation and Recovery Act
RMSE	Root mean square error
SSE	Sum of squares error
SWMU	Solid Waste Management Unit
USGS	U.S. Geological Survey

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Abstract

Naval Support Activity (NSA) Memphis is a Department of the Navy facility located at the City of Millington, Tennessee, about 5 miles north of Memphis. Contaminants have been detected in surface-water, sediment, and ground-water samples collected at the facility. As part of the Installation Restoration Program, the Navy is considering remedial-action options to prevent or lessen the effect of ground-water contamination at the facility and to control the movement and discharge of contaminants. A numerical model of the ground-water-flow system in the area of NSA Memphis was constructed and calibrated so that quantifiable estimates could be made of ground-water-flow rates, direction, and time-of-travel.

The sediments beneath NSA Memphis, to a depth of about 200 feet, form a shallow aquifer system. From youngest to oldest, the stratigraphic units that form the shallow aquifer system are alluvium, loess, fluvial deposits, and the Cockfield and Cook Mountain Formations. The shallow aquifer system is organized into five hydrogeologic units: (1) a confining unit composed of the relatively low permeability sediments of the upper alluvium and the loess; (2) the A1 aquifer comprising sand and gravel of the lower alluvium and the fluvial deposits, and sand lenses in the upper part of the preserved section of the Cockfield Formation; (3) a confining unit composed of clay and silt within the upper part of the Cockfield Formation; (4) the Cockfield aquifer comprising sand lenses within the lower part of the preserved section of the Cockfield Formation; and (5) a confining unit formed by low permeability sediments of the Cook Mountain Formation that composes the upper confining unit for the Memphis aquifer. Thicknesses of individual units vary considerably across the facility. Structural and depositional features that affect the occurrence of ground water in the shallow aquifer system include faulting, an erosional scarp, and "windows" in the confining units. Underlying the shallow aquifer system is the Memphis aquifer, the primary source of water for NSA Memphis and the City of Memphis, Tennessee.

Analyses of sediment cores, aquifer and well specific-capacity tests, and numerical modeling were used to estimate the hydraulic characteristics of units of the shallow aquifer system. The vertical hydraulic conductivity of core samples of the alluvium-loess confining unit ranged from about 8.5×10^{-5} to 1.6×10^{-2} feet per day, and the total porosity of the samples ranged from about 35 to 48 percent. The results of the aquifer test were used to estimate a horizontal hydraulic conductivity of about 5 feet per day for the alluvial-fluvial deposits aquifer. The total porosity of core samples of the alluvial-fluvial deposits aquifer ranged from about 22 to 39 percent. The vertical hydraulic conductivity of core samples of the Cockfield confining unit ranged from about 4.5×10^{-5} to 2.5×10^{-3} feet per day, and the total porosity ranged from about 41 to 55 percent. Well specific-capacity tests indicate that the horizontal hydraulic conductivity of sand units that compose the Cockfield aquifer range from about 0.5 to 3 feet per day. The vertical hydraulic conductivity of core samples of the Cook Mountain confining unit ranged from about 5.0×10^{-6} to 9.9×10^{-4} feet per day. Total porosity of core samples of the Cook Mountain confining unit ranged from about 30 to 42 percent.

Ground-water flow and time-of-travel in the shallow aquifer system were simulated using the MODFLOW finite-difference model and the particle-tracking program MODPATH. A three-layer, steady-state model of the shallow aquifer system was constructed and calibrated to the potentiometric surface of the A1 aquifer. Results of numerical modeling support the proposed conceptual hydrogeologic model of the shallow aquifer system. Ground-water time-of-travel in the A1 aquifer was simulated using an assumed effective porosity of 25 percent. Typical ground-water-flow velocities were on the order of 15 to 25 feet per year in the layer representing the A1 aquifer in the model. The average residence time of particles seeded in this layer was about 800 years.

Ground-water travel times were simulated at three sites within the A1 aquifer: (1) the former N-6 hangar location, (2) the "grassy" area near Solid Waste Management Unit 7, and (3) at Solid Waste Management Unit 2. Results indicate close agreement between the particle-tracking simulations and the measured extent of contaminant plumes at the former N-6 hangar area and the grassy area near Solid Waste Management Unit 7. Based on the results of particle-tracking analyses of ground-water flow and the estimated locations of contaminant plumes at these two sites, the potential for contaminants to reach the Memphis aquifer in the next 100 years is negligible. However, particle-tracking analysis of ground-water flow at Solid Waste Management Unit 2 suggests that the time-of-travel of contaminants to Big Creek Drainage Canal could be less than 30 years.

INTRODUCTION

Naval Support Activity (NSA) Memphis, formerly Naval Air Station Memphis, is a Department of the Navy (Navy) facility located at Millington, Tennessee (fig. 1). NSA Memphis encompasses about 3,490 acres (Kingsbury and Carmichael, 1995) and is divided into northern and southern complexes by Navy Road (fig. 2). Major operational areas include an airfield, former training facilities, and a hospital in the "Northside" area, and former housing and training facilities in the "Southside" area. The Northside area is undergoing transfer to the city of Millington, and the Southside is being realigned to become the site of the Navy's Bureau of Personnel under the Base Closure and Realignment Act (BRAC) of 1990.

Past operations at NSA Memphis have contaminated the soil, shallow ground water, and surface water locally. Sixty-seven Solid Waste Management Units (SWMU's) and one Area of Concern (AOC) have been identified at the facility. The SWMU's and AOC are under investigation as part of the Resource Conservation and Recovery Act (RCRA) Corrective Action Program. The objective of the Corrective Action Program is to obtain information to fully characterize the nature and extent of the contaminants and determine appropriate corrective measures. As part of a cooperative investigation with the Navy at NSA Memphis, the U.S. Geological Survey (USGS) and EnSafe (formerly EnSafe/Allen and Hoshall), Memphis, Tennessee, have collected environmental data at many of the SWMU's and the AOC, including 13 SWMU's (fig. 2), requiring RCRA Facility Investigations under the Corrective Action Program (Carmichael and others, 1997).

The Navy seeks to determine if contaminants in the shallow ground-water system may move through the subsurface or into nearby creeks, reaching other parts of NSA Memphis or to off-base property. As part of the U.S. Department of Defense Installation Restoration Program, the Navy is considering remedial-action options to control the movement of contaminants at NSA Memphis. Numerical simulation of ground-water-flow systems is a quick and cost effective way to evaluate the potential for migration of contaminants through the subsurface, into surface-water drainages, or into sources of public water supply. Thus, in 1995, the USGS began constructing a numerical ground-water-flow model of the shallow aquifer system beneath NSA Memphis and the surrounding area as part of the cooperative hydrogeological investigation with the Navy.

Purpose and Scope

This report presents the results of a study conducted from 1995 through 1997 to simulate ground-water flow over an area of about 30 square miles (mi^2) that includes all of the Southside and most of the Northside areas of NSA Memphis (fig. 3). Data presented in this report include ground-water level measurements, the results of test drilling, borehole geophysical surveys, sediment-core analyses, and an aquifer and well specific-capacity test. A description of the development and calibration of a numerical model used to simulate the flow of ground water at NSA Memphis is presented. The calibrated numerical model and an advective-flow particle-tracking program were used to estimate ground-water-flow direction, time-of-travel, and to evaluate the potential for migration of contaminants.

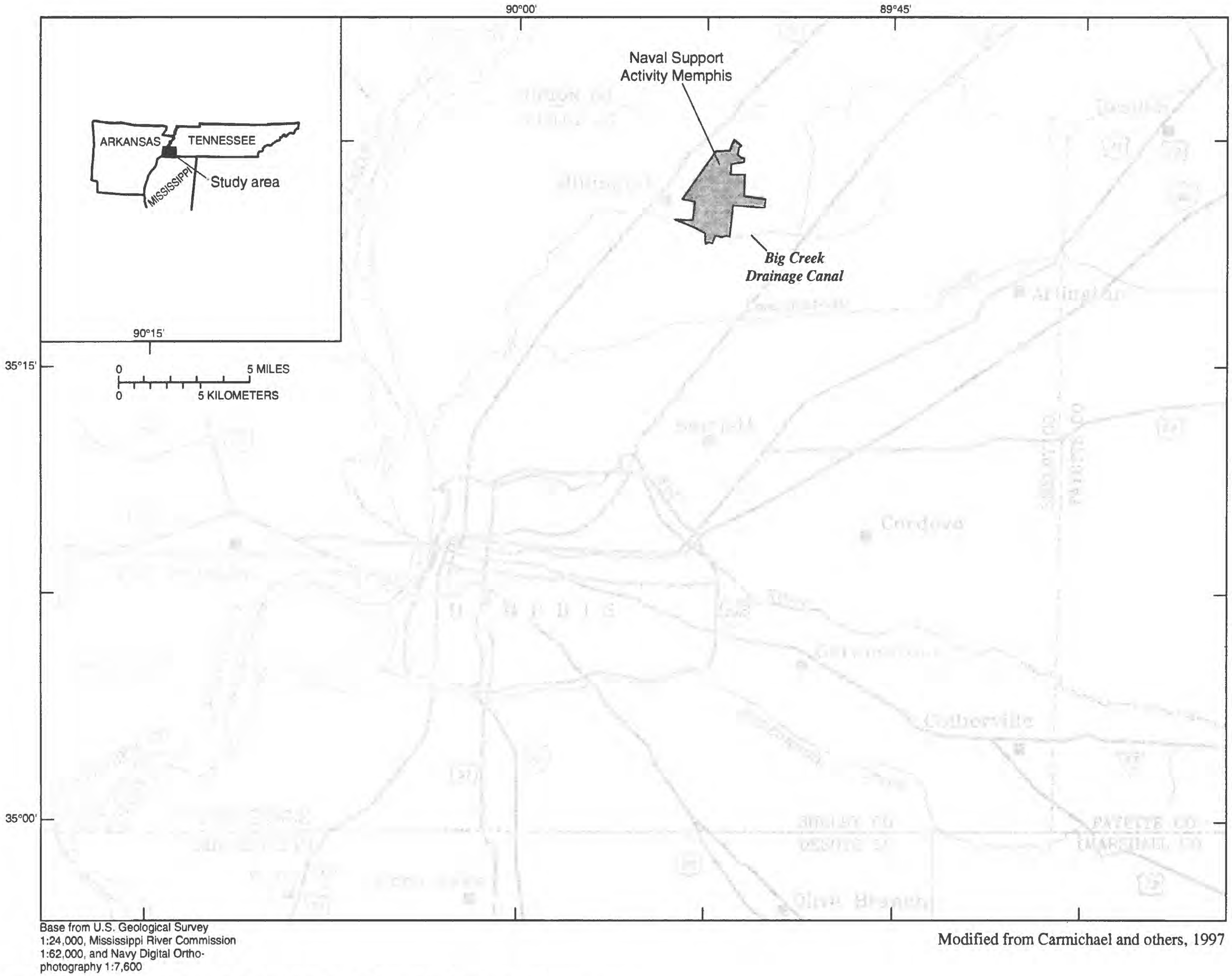


Figure 1. Location of Naval Support Activity Memphis, Millington, Tennessee.

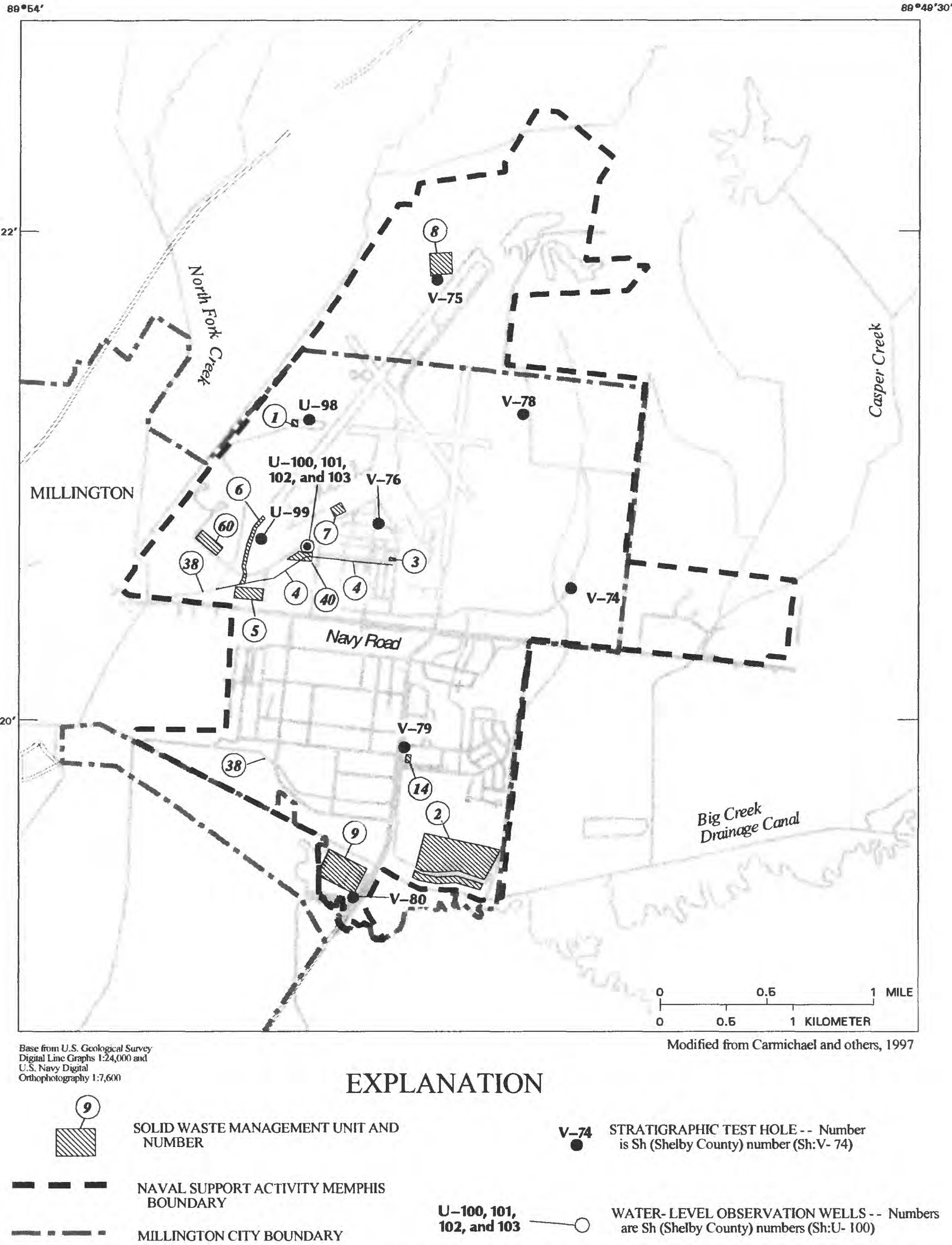


Figure 2. Locations of 13 Solid Waste Management Units, 9 stratigraphic test holes, and 4 water-level observation wells at Naval Support Activity Memphis, Millington, Tennessee.

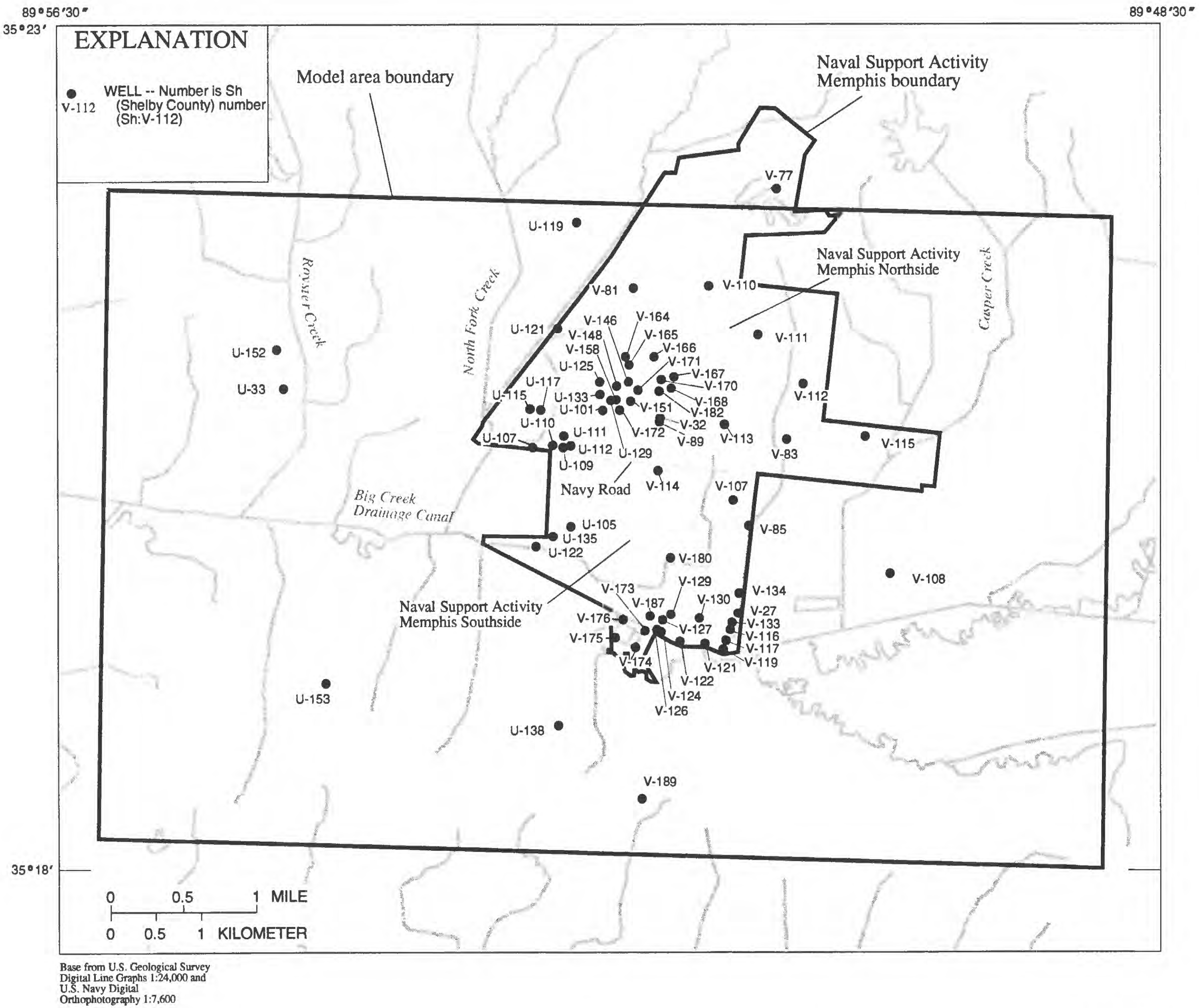


Figure 3. Location of model area, principal surface-water drainages, and wells in which water-level measurements were made in April and October 1996 near Naval Support Activity Memphis, Millington, Tennessee.

Approach

The study was organized into three phases: (1) development of a conceptual model of the ground-water system, (2) development and calibration of a numerical model of flow in the shallow ground-water system, and (3) particle-tracking analyses. Borehole geophysical surveys, lithologic logs, and sediment cores were used to correlate hydrogeologic units across the study area. Two synoptic water-level measurement surveys were used to determine seasonal high, low, and mean water levels in the shallow aquifers. The results of sediment-core analyses, the aquifer and well specific-capacity tests, and a parameter-estimation program were used to estimate the hydraulic characteristics of the hydrogeologic units. A steady-state, numerical model of the shallow ground-water-flow system was calibrated to mean ground-water levels based on the data collected during the two synoptic water-level measurement surveys. The calibrated numerical model and an advective-flow particle-tracking program were used to simulate ground-water-flow direction and time-of-travel. The potential for contaminants in the ground-water system to migrate to sources of public water supply or to surface-water drainages was evaluated with the calibrated numerical model and the particle-tracking program.

Previous Studies

The geology and hydrology of the study area and surroundings have been described in numerous reports, including those by Graham and Parks (1986), Brahana and others (1987), Parks (1990), Parks and Carmichael (1990a, b), Kingsbury and Carmichael (1995), and Carmichael and others (1997). Extensive lists of other selected references are given by Graham and Parks (1986) and Brahana and others (1987). Carmichael and others (1997) present the hydrogeology and ground-water quality at NSA Memphis and summarize the post-Midway Group geologic units underlying the facility and their hydrologic significance. Maps showing the potentiometric surfaces of the Memphis and Fort Pillow aquifers in 1995 were published by Kingsbury (1996). A constant-withdrawal aquifer test referenced in this study was analyzed using the computer model VS2DT (Lappala and others, 1987; Healy, 1990). The U.S. Army Corps of Engineers (1989a, b) published the results of a study to alleviate urban flooding in the Millington area. McDonald and Harbaugh (1988) document the USGS modular ground-water-flow model (MODFLOW) used to simulate the shallow ground-water-flow system at NSA Memphis. Halford (1992) documented the parameter-estimation program used to facilitate model calibration. The USGS particle-tracking program used to delineate ground-water-flow paths is described by Pollock (1989, 1994).

Description of the Study Area

The NSA Memphis study area is located in northern Shelby County, Tennessee (fig. 1). The major surface-water drainages in the NSA Memphis area, Big Creek Drainage Canal and its tributaries, Royster, North Fork, and Casper Creeks (fig. 3), have been channelized. Most soils in the Big Creek Drainage Canal basin are silt, clay, and sand. Land-surface altitudes in the area range from about 250 to 370 feet above sea level. Topographic relief varies from relatively flat alluvial plains to gently undulating upland areas. Most of the area has been cleared for agricultural, institutional, or recreational use.

The climate of Shelby County is temperate to subtropical. Average precipitation over the study area is about 50 inches per year (in/yr), and is uniformly distributed throughout the year (Owenby and Ezell, 1992). The long-term potential evaporation rate in the study area has been estimated to be 43 in/yr (Farnsworth and others, 1982, map 3). The mean annual temperature is about 62 degrees Fahrenheit (°F). Summer temperatures typically range from 75 °F to 95 °F, and winter temperatures range from 35 °F to 60 °F (Owenby and Ezell, 1992).

HYDROGEOLOGIC FRAMEWORK

The NSA Memphis study area is located in the north-central part of the Mississippi embayment, a broad syncline that plunges southward along an axis that approximates the Mississippi River (Cushing and others, 1964). In the NSA Memphis area, the embayment contains more than 2,500 feet of unconsolidated to semiconsolidated sediments of Cretaceous, Tertiary, and Quaternary age.

Post-Wilcox Group geologic units important to this study are, from youngest to oldest, the alluvium and loess of Quaternary age; the fluvial deposits of Quaternary and Tertiary(?) age; and the Cockfield and Cook Mountain Formations and Memphis Sand of Tertiary age (table 1). Kingsbury and Parks (1993)

Table 1. Post-Wilcox Group geologic units underlying Naval Support Activity Memphis, Millington, Tennessee, and their hydrologic significance
[Modified from Carmichael and others, 1997]

System	Series	Group	Stratigraphic unit (and local name)	Thickness (in feet)	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium (alluvial deposits)	0 - 70	Silt, clay, sand, and gravel. Underlies the alluvial plains of Big Creek Drainage Canal and tributary streams. A lower sand and gravel is connected to the fluvial deposits and constitutes part of the alluvial-fluvial deposits aquifer.
	Pleistocene		Loess	15 - 45	Silt, clay, and sand. Principal unit at the surface in upland areas. Generally forms the upper confining unit for the alluvial-fluvial deposits aquifer. Locally contains perched water tables.
Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)		Fluvial deposits (terrace deposits)	5 - 70	Sand and gravel; minor clay and ferruginous sandstone. Thickness varies greatly because of erosional surfaces at top and base. Constitutes part of the alluvial-fluvial deposits aquifer.
Tertiary	Eocene	Claiborne	Cockfield Formation	0 - 185	Sand, silt, clay, and lignite. Complexly interbedded and interlensed. Preserved thickness varies greatly because of erosional surfaces at top and base. Locally contains sand lenses in which domestic and farm wells are completed.
			Cook Mountain Formation	10 - 60	Clay, silt, and sand. Generally consists of clay and silt. Locally serves as part of the lower confining unit for the Cockfield aquifer, and is the principal upper confining unit for the Memphis aquifer.
			Memphis Sand	865 - 880	Sand, silt, clay, and minor lignite. Constitutes the Memphis aquifer—the principal aquifer providing water for most domestic, commercial, industrial, and municipal supplies in the Memphis area.

show normal faults in the Memphis area with displacements of the Memphis Sand ranging from about 50 to 150 feet. Displacements along the faults decrease upward (Kingsbury and Parks, 1993). Geologic sections (figs. 4a and b) by Carmichael and others (1997) illustrate the geologic units identified in the shallow subsurface at NSA Memphis. Geologic sections *A-A′* and *B-B′* (fig. 4b), oriented north-south, show a prominent step-up in the Cockfield Formation which is interpreted as an erosional scarp. The strata are relatively flatlying above and below this scarp (fig. 4b). Faults displacing the Cockfield and Cook Mountain Formations and the Memphis Sand also are illustrated (fig. 4b).

The shallow aquifers in the NSA Memphis area were recently described by Carmichael and others (1997) and are, in descending order, the alluvial-fluvial deposits aquifer and the Cockfield aquifer. Silt and clay in the upper alluvium and the loess overlie and confine the alluvial-fluvial deposits aquifer which is separated from the Cockfield aquifer by strata of low permeability in the upper part of the preserved section (table 1) of the Cockfield Formation. Silt and clay of the Cook Mountain Formation comprise a confining unit and separate the Cockfield aquifer from the underlying Memphis aquifer. The Memphis aquifer is the principal aquifer used for water supply by NSA Memphis and the city of Memphis.

Hydrologic and Hydrogeologic Data

A variety of geologic and hydrologic data was collected from wells and test borings completed in the post-Wilcox Group geologic units (table 1) that underlie the NSA Memphis area (fig. 5). The altitudes of the tops and bottoms and the thicknesses of stratigraphic

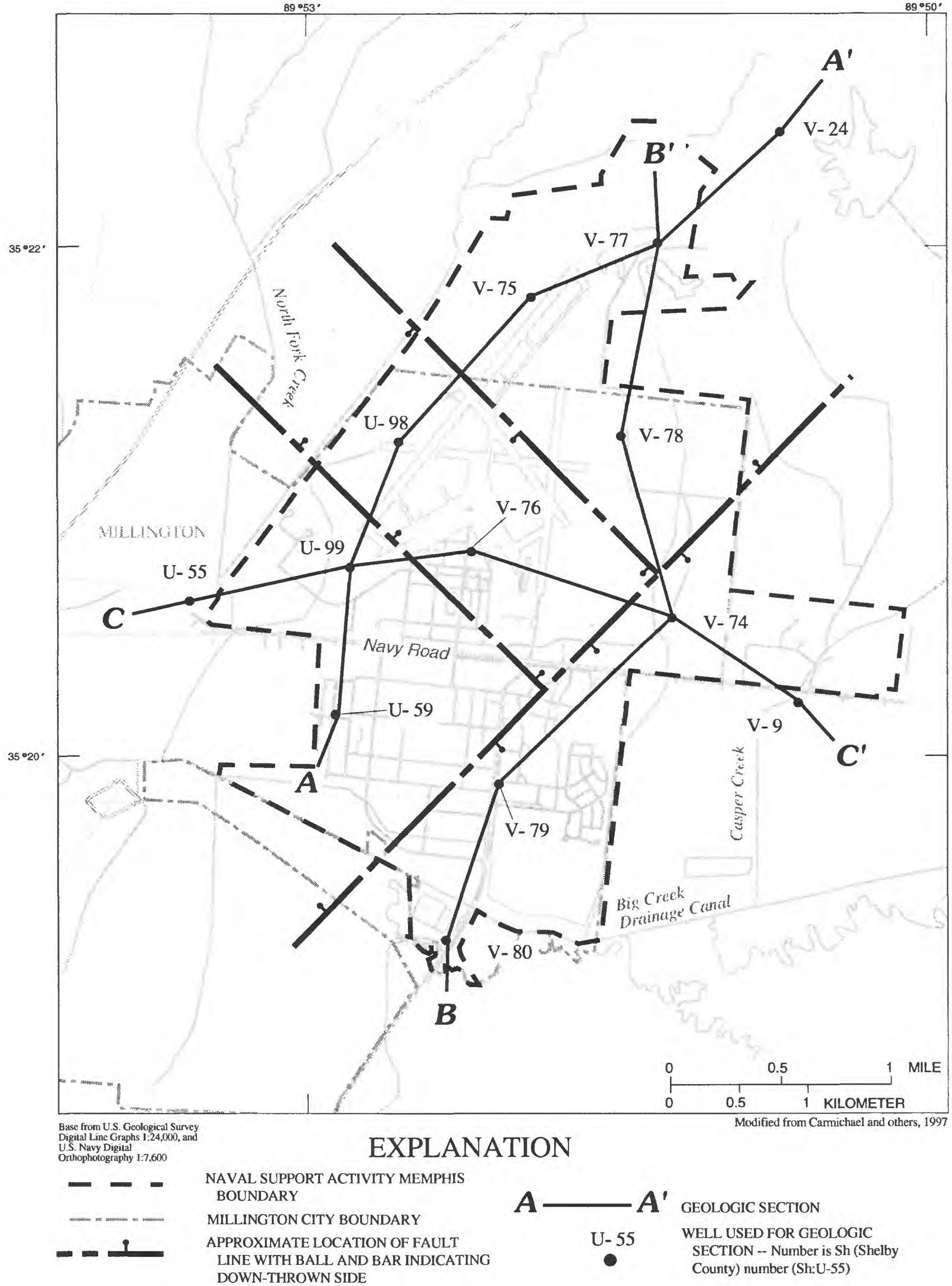
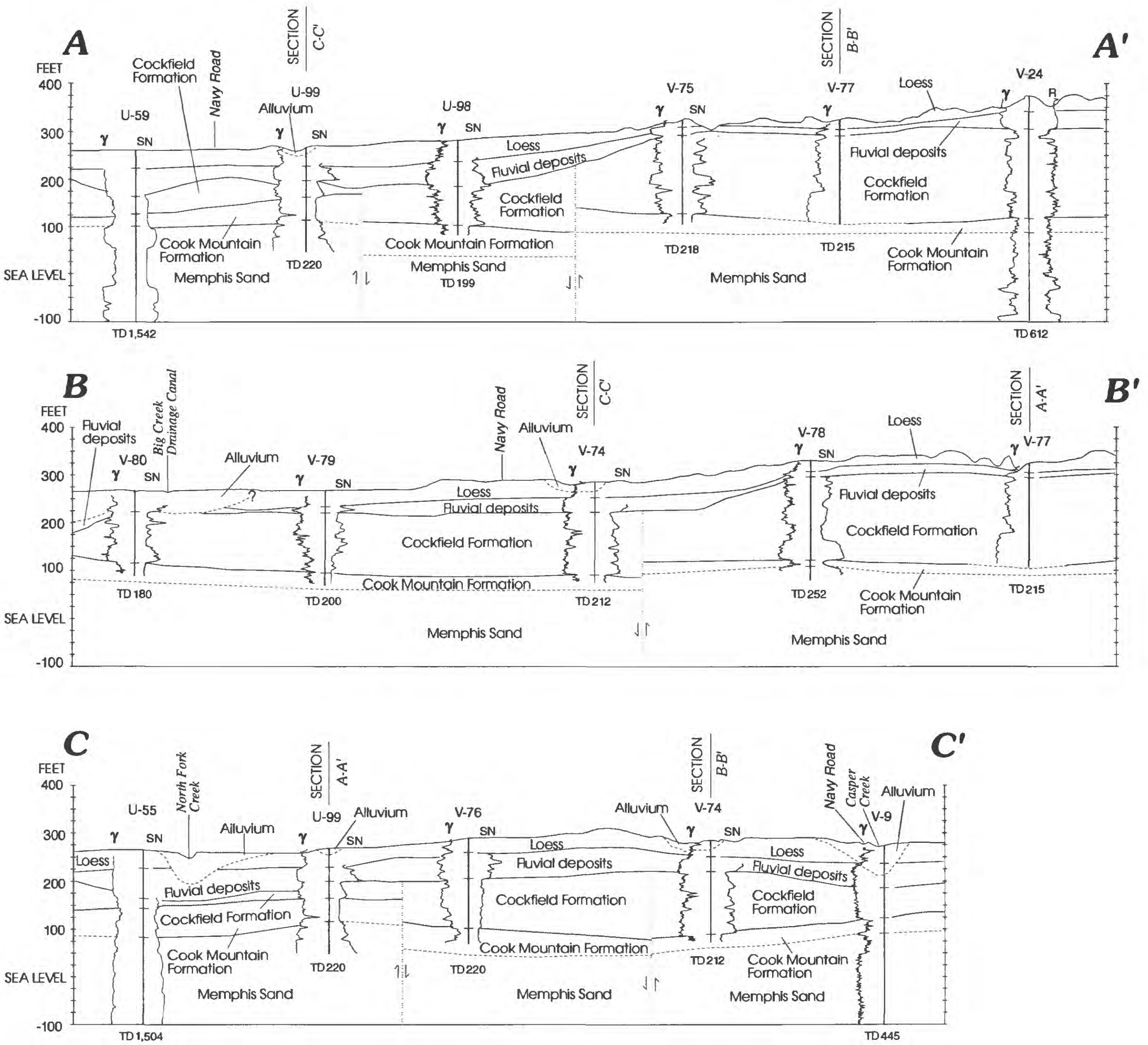


Figure 4a. Locations of geologic sections *A-A′*, *B-B′*, and *C-C′*, and faults that displace the Cockfield and Cook Mountain Formations and Memphis Sand at Naval Support Activity Memphis, Millington, Tennessee.



Modified from Carmichael and others, 1997

VERTICAL EXAGGERATION X 10

0 0.5 1 MILE

0 0.5 1 KILOMETER

EXPLANATION

A——A' GEOLOGIC SECTION

FORMATION CONTACT. DASHED WHERE APPROXIMATE

APPROXIMATE LOCATION OF FAULT, AND RELATIVE DIRECTION OF DISPLACEMENT

V-79 TEST HOLE OR WELL — Number is Sh (Shelby County) number (Sh:V-79). Tick marks indicate formation contacts

TD200 TOTAL DEPTH OF WELL OR TEST HOLE

GEOPHYSICAL LOGS

γ GAMMA-RAY LOG

SN SHORT-NORMAL RESISTIVITY LOG

R RESISTANCE LOG

Figure 4b. Geologic sections *A-A´*, *B-B´*, and *C-C´*, and geophysical logs of test holes or wells in the area of Naval Support Activity Memphis, Millington, Tennessee.

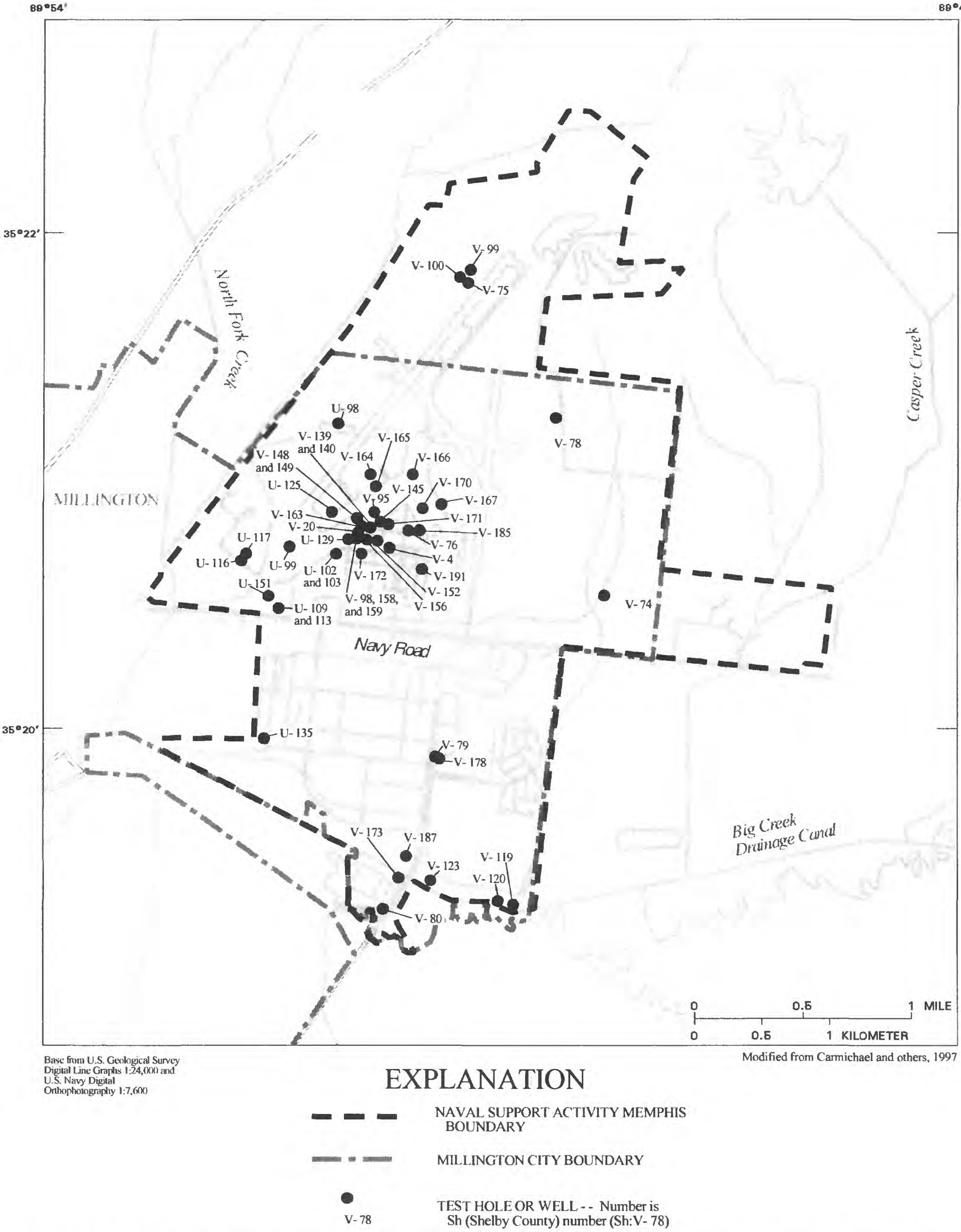


Figure 5. Locations of test holes or wells for which analyses of core samples, aquifer or specific-capacity tests, or water-quality samples are available for stratigraphic units beneath Naval Support Activity Memphis, Millington, Tennessee.

units at NSA Memphis were determined by Carmichael and others (1997). Analyses of 45 sediment cores retrieved during well installation and test boring provided information on the stratigraphic and lithologic characteristics (table 2) of the sediments underlying NSA Memphis. One constant-withdrawal aquifer test and 23 well specific-capacity tests were performed in 18 wells at NSA Memphis to determine the hydraulic characteristics of aquifers and confining units (table 3). Water levels were measured in 67 wells (fig. 3) during synoptic surveys in April and October 1996 (table 4), and continuous water-level measurements were obtained in 3 wells from May 1995 through September 1996 (fig. 6).

Alluvium-Loess Confining Unit

In the NSA Memphis area, alluvium underlies the alluvial plains of streams, and loess is the near surface unit in upland areas (Carmichael and others, 1997). The alluvium generally consists of 10 to 30 feet of silt and clay in the valleys of the minor streams. In the valleys of the principal streams, the alluvium is generally thicker and consists of 10 to 30 feet of silt and clay in the upper part and 15 to 40 feet of sand and gravel in the lower part. The vertical hydraulic conductivity of six samples of silt and clay from the upper part of the alluvium (table 2) ranged from about 1.5×10^{-3} to 1.4×10^{-2} feet per day (ft/d), and the total porosity of the samples ranged from 38 to 48 percent. The loess consists of 15 to 45 feet of silt and clay. The vertical hydraulic conductivity of 12 loess samples ranged from 8.5×10^{-5} to 1.6×10^{-2} ft/d (table 2). Total porosity of the loess samples ranged from 35 to 45 percent. Together, these sediments overlie and confine the alluvial-fluvial deposits aquifer (Carmichael and others, 1997).

Alluvial-Fluvial Deposits Aquifer

The alluvial-fluvial deposits aquifer consists of sand and gravel in the lower part of the alluvium beneath the flood plains of the principal streams, and sand and gravel of the fluvial deposits in upland areas. The sand and gravel of the lower part of the alluvium is about 10 feet thick on the south side of the Big Creek Drainage Canal, but the alluvium may have a thicker section of sand and gravel in the area where Big Creek flowed before channelization (Carmichael and others, 1997). Sand and gravel in the lower part of the alluvium locally is in hydraulic connection with the fluvial deposits and is part of the alluvial-fluvial deposits aquifer. Permeable sands and gravels at the base of the alluvium generally are semiconfined to confined by fine-grained sediments of the overlying upper alluvium. Measurements of water levels in well pairs completed in the upper and lower alluvium show no consistent upward or downward vertical gradient between the units (Carmichael and others, 1997).

A map of the altitude of the base of the sand and gravel in the lower alluvium or fluvial deposits at NSA Memphis was prepared by Carmichael and others (1997) (fig. 7). Beneath the NSA Memphis Southside, the basal altitude of the sand and gravel deposits is about 220 feet above sea level (fig. 7), with lower altitudes indicated in areas where Big Creek and its tributaries flowed before being channelized. The basal altitude of the fluvial deposits in the northern part of NSA Memphis is about 300 feet above sea level. The sand in the fluvial deposits is described as fine to very coarse and generally poorly sorted (Carmichael and others, 1997). The thickness of the sand and gravel in the lower alluvium or fluvial deposits is irregular and varies greatly over short distances (fig. 8), with thicker deposits indicated generally southwest of the erosional scarp (30 to 70 feet) and particularly in the flood plains of Big Creek Drainage Canal and its tributaries. Thickness of the fluvial deposits that overlie the Cockfield Formation north of the erosional scarp ranges from about 10 to 20 feet (fig. 8).

The fluvial deposits south of the erosional scarp generally are saturated, and the ground water is confined (Carmichael and others, 1997). The fluvial deposits north of the scarp generally are dry or contain only a few feet of saturated thickness. The fluvial deposits on either side of the scarp may be hydraulically connected along the scarp boundary (Carmichael and others, 1997). Potentiometric-surface maps (figs. 9 and 10) were prepared for the alluvial-fluvial deposits aquifer by Carmichael and others (1997). These potentiometric maps show a ground-water mound centered over the NSA Memphis Southside, with lower water levels centered over Casper Creek and the original drainage area of Big Creek before channelization. Ground-water levels also decrease to the west towards the channelized drainages of North Fork Creek and Royster Creek. An area of lower ground-water levels, oriented northwest-southeast, is indicated in the area of the erosional scarp and the northeasternmost of the two northwest trending faults (fig. 4b).

Table 2. Selected geotechnical properties of stratigraphic units at Naval Support Activity Memphis, Millington, Tennessee

[Modified from Carmichael and others, 1997; °, degrees; ′, minutes; ″, seconds; a, analyses conducted by Inberg-Miller Engineers, Cheyenne, Wyoming, under contract to the U.S. Geological Survey; b, analyses conducted by TRI State Testing Services, Inc., Memphis, Tennessee, under contract to EnSafe]

USGS local well number	Latitude	Longitude	Sample depth, in feet	Sample description	Total porosity, in percent	Vertical hydraulic conductivity, in feet per day
			Upper Alluvium			
Sh:U-99	35°20′44″	89°52′48″	13-15	Clayey silt	38 a	$1.5x10^{-3}$ a
Sh:V-80	35°19′16″	89°52′20″	17-19	Clayey silt	48 a	$6.8x10^{-3}$ a
Sh:V-120	35°19′18″	89°51′46″	17-19	Clayey silt	40 b	$1.9x10^{-3}$ b
Sh:V-123	35°19′23″	89°52′06″	17-19	Clayey silt	44 b	$6.5x10^{-3}$ b
Sh:V-173	35°19′24″	89°52′16″	16-18	Silty clay	44 b	$2.7x10^{-3}$ b
Sh:V-187	35°19′29″	89°52′13″	14-16	Clayey silt	42 b	$1.4x10^{-2}$ b
			Lower Alluvium			
Sh:V-119	35°19′17″	89°51′41″	41-43	Sand, small gravel	30 b	$2.4x10^{0}$ b
Sh:V-123	35°19′23″	89°52′06″	41-43	Coarse sand, gravel, clay	34 b	$9.6x10^{-1}$ b
Sh:V-187	35°19′29″	89°52′13″	38-40	Sand, gravel, silt	22 b	$5.1x10^{-1}$ b
			Loess			
Sh:U-102	35°20′42″	89°52′34″	12-14	Silty clay	43 a	$7.7x10^{-3}$ a
Sh:U-116	35°20′41″	89°53′02″	20-22	Silty Clay	36 b	$4.8x10^{-4}$ b
Sh:U-135	35°19′57″	89°52′55″	13-15	Clayey silt	35 b	$1.6x10^{-3}$ b
Sh:U-151	35°20′32″	89°52′54″	18-20	Silty clay	38 b	$4.0x10^{-4}$ b
Sh:V-75	35°21′48″	89°51′55″	11-13	Silty clay	39 a	$3.4x10^{-4}$ a
Sh:V-76	35°20′48″	89°52′13″	11-13	Silty clay	45 a	$4.5x10^{-4}$ a
Sh:V-78	35°21′15″	89°51′29″	18-20	Silty clay	43 a	$1.6x10^{-2}$ a
Sh:V-79	35°19′53″	89°52′05″	10-12	Clayey silt	41 a	$8.0x10^{-4}$ a
Sh:V-100	35°21′49″	89°51′57″	3-5	Silty clay	39 b	$8.5x10^{-5}$ b
Sh:V-163	35°20′49″	89°52′26″	20-22	Silty clay	42 b	$2.7x10^{-3}$ b
Sh:V-178	35°19′52″	89°52′03″	8-10	Clayey silt	44 b	$1.2x10^{-3}$ b
Sh:V-188	35°20′39″	89°52′09″	18-20	Silty clay	41 b	$4.0x10^{-4}$ b
			Fluvial deposits			
Sh:U-125	35°20′52″	89°52′35″	47-49	Silty sand, clay	35 b	$4.2x10^{-3}$ b
Sh:U-129	35°20′46″	89°52′30″	40-42	Sand	33 b	$4.8x10^{-1}$ b
Sh:U-135	35°19′57″	89°52′55″	41-43	Sandy gravel	26 b	$7.4x10^{-1}$ b
Sh:V-140	35°20′49″	89°52′24″	75-77	Silt, fine sand	39 b	$1.9x10^{-1}$ b
Sh:V-171	35°20′49″	89°52′18″	41-43	Silty sand	37 b	$1.0x10^{-1}$ b
Sh:V-164	35°21′01″	89°52′24″	47-49	Clayey, silty sand	31 b	$9.3x10^{-3}$ b
Sh:V-165	35°20′59″	89°52′22″	47-49	Sand	26 b	$2.3x10^{-1}$ b
Sh:V-166	35°21′01″	89°52′11″	41-43	Silty sand, clay	36 b	$7.1x10^{-2}$ b
Sh:V-167	35°20′54″	89°52′03″	47-49	Clayey, silty, fine sand	32 b	$3.1x10^{-3}$ b
Sh:V-170	35°20′53″	89°52′08″	46-48	Silty sand	34 b	$5.9x10^{-1}$ b

Table 2. Selected geotechnical properties of stratigraphic units at Naval Support Activity Memphis, Millington, Tennessee—Continued

USGS local well number	Latitude	Longitude	Sample depth, in feet	Sample description	Total porosity, in percent	Vertical hydraulic conductivity, in feet per day
			Fluvial deposits—Continued			
Sh:V-172	35°20'42"	89°52'27"	47-49	Silty sand	34 b	$6.2x10^{-1}$ b
Sh:V-181	35°19'52"	89°52'03"	41-43	Silty clay, sand, gravel	29 b	$1.1x10^{-3}$ b
Sh:V-185	35°20'48"	89°52'09"	44-46	Fine sand	38 b	$4.2x10^{-1}$ b
			Cockfield Formation			
Sh:U-102	35°20'42"	89°52'34"	120-122	Silty clay	44 a	$2.2x10^{-3}$ a
Sh:V-79	35°19'53"	89°52'05"	160-162	Silty clay	41 a	$2.9x10^{-4}$ a
Sh:V-140	35°20'49"	89°52'24"	110-112	Clay, silt and sand lenses	51 b	$1.2x10^{-4}$ b
Sh:V-145	35°20'50"	89°52'21"	115-117	Clay, silt and sand lenses	55 b	$4.5x10^{-5}$ b
Sh:V-159	35°20'46"	89°52'28"	125-127	Clay, silt and sand lenses	50 b	$2.5x10^{-3}$ b
			Cook Mountain Formation			
Sh:U-98	35°21'14"	89°52'33"	199-200	Silty clay	37 a	$4.5x10^{-5}$ a
Sh:V-74	35°20'32"	89°51'14"	209-211	Silty clay	31 a	$8.1x10^{-6}$ a
Sh:V-75	35°21'48"	89°51'55"	218-220	Sandy clay	42 a	$1.6x10^{-4}$ a
Sh:V-76	35°20'48"	89°52'13"	195-197	Clay	30 a	$4.0x10^{-5}$ a
Sh:V-79	35°19'53"	89°52'05"	200-201	Silty clay	36 a	$9.9x10^{-4}$ a
Sh:V-80	35°19'16"	89°52'20"	180-182	Clay	40 a	$5.0x10^{-6}$ a

The hydraulic properties of the sand and gravel in the lower alluvium and the fluvial deposits have been estimated using analyses of core samples, an aquifer test, and well specific-capacity tests. The vertical hydraulic conductivity of three samples of the lower alluvium ranged from about 5.1×10^{-1} to 2.4×10^{0} ft/d, and the total porosity ranged from about 22 to 34 percent (table 2). The vertical hydraulic conductivity of 13 samples of the fluvial deposits ranged from about 1.1×10^{-3} to 7.4×10^{-1} ft/d, and the total porosity of the samples ranged from about 26 to 39 percent (table 2). Estimates of the horizontal hydraulic conductivity within the fluvial deposits, determined from nine specific capacity tests (table 3), ranged from about 8 to 150 ft/d. A constant-withdrawal aquifer test was conducted to determine the hydraulic properties of the alluvial-fluvial deposits aquifer at the location of water-level observation wells Sh:U-100, Sh:U-101, Sh:U-102, and Sh:U-103 (fig. 2). The aquifer was tested over a 3-day period beginning August 22, 1995. The results calculated from the test came from calibrating VS2DT, a variably saturated, radial-flow model (Lappala and others, 1987; Healy, 1990) to the measured drawdowns in the observation wells during the test. Horizontal hydraulic conductivity for the alluvial-fluvial deposits aquifer was estimated to be about 5 ft/d (table 3).

Surface-water drainages at NSA Memphis may not be major discharge areas for the alluvial-fluvial deposits aquifer. A comparison of streambed altitudes of the major drainages in the NSA Memphis area (U.S. Army Corps of Engineers, 1989a, b) to the altitude of the potentiometric surface of the alluvial-fluvial deposits aquifer indicates that the potentiometric surface of the aquifer is lower than most streambed altitudes, except for limited reaches of Big Creek Drainage Canal, Casper Creek, and North Fork Creek along the southern boundary of NSA Memphis and near SWMU 2 (fig. 2). The alluvial-fluvial deposits aquifer rests unconformably upon the Cockfield Formation in these areas.

Cockfield Confining Unit

The Cockfield Formation of late Eocene age consists of sand, silt, clay, and lignite (Parks and Carmichael, 1990a). Individual beds are lenticular and

Table 3. Results of aquifer and specific-capacity tests for selected wells at Naval Support Activity Memphis, Millington, Tennessee

[USGS, U.S. Geological Survey; constant-withdrawal test data analyzed using VS2DT model (Lappala and others, 1987; Healy, 1990); specific-capacity tests analyzed using method of Bradbury and others (1985)]

USGS local number	Type of test	Length of test, in minutes	Horizontal hydraulic conductivity, in feet per day	Test performer
		Alluvial-fluvial deposits aquifer		
Sh:U-103	Constant withdrawal	1,440	5	USGS
Sh:U-109	Specific capacity	2	12	EnSafe
Sh:U-113	Specific capacity	1	30	EnSafe
Sh:U-117	Specific capacity	50	15	EnSafe
Sh:V-98	Specific capacity	5	10	EnSafe
Sh:V-99	Specific capacity	5	8	EnSafe
Sh:V-139	Specific capacity	2	50	EnSafe
Sh:V-148	Specific capacity	5	10	EnSafe
Sh:V-158	Specific capacity	5	40	EnSafe
Sh:V-191	Specific capacity	1	150	EnSafe
		Sand unit in upper part of the Cockfield Formation		
Sh:V-95	Specific capacity	5	.6	EnSafe
	Specific capacity	20	.5	EnSafe
Sh:V-140	Specific capacity	8	1	EnSafe
	Specific capacity	16	.7	EnSafe
Sh:V-145	Specific capacity	10	2	EnSafe
Sh:V-149	Specific capacity	4	1	EnSafe
	Specific capacity	14	3	EnSafe
Sh:V-152	Specific capacity	11	2	EnSafe
Sh:V-156	Specific capacity	6	.6	EnSafe
Sh:V-159	Specific capacity	10	.8	EnSafe
Sh:V-163	Specific capacity	4	1	EnSafe
	Specific capacity	7	1	EnSafe
	Specific capacity	8	1	EnSafe
	Specific capacity	12	2	EnSafe

Table 4. Water levels measured in 67 wells screened in the alluvium, fluvial deposits, and Cockfield Formation in the area of Naval Support Activity Memphis, Millington, Tennessee, April 8-26, and October 22-24, 1996

[Modified from Carmichael and others, 1997; °, degrees; ′, minutes; ″, seconds]

USGS local well number	Latitude	Longitude	Altitude of land surface, in feet above sea level	Screened interval, in feet below land surface	Depth to water on April 8-26, 1996	Depth to water on October 22-24, 1996
			Alluvium			
Sh:U-122	35°19′54″	89°53′03″	262	38-48	14.39	17.15
Sh:V-116	35°19′24″	89°51′38″	267	48-58	3.84	10.96
Sh:V-117	35°19′20″	89°51′40″	267	41-51	7.27	13.51
Sh:V-119	35°19′17″	89°51′41″	267	38-48	8.45	14.37
Sh:V-121	35°19′19″	89°51′49″	267	40-50	10.82	14.48
Sh:V-122	35°19′20″	89°52′00″	268	44-54	14.69	18.02
Sh:V-124	35°19′23″	89°52′08″	267	35-45	15.31	20.62
Sh:V-126	35°19′24″	89°52′10″	266	36-46	14.70	18.67
Sh:V-127	35°19′28″	89°52′08″	270	40-50	9.55	17.12
Sh:V-129	35°19′29″	89°52′04″	265	32-42	2.57	10.46
Sh:V-130	35°19′28″	89°51′52″	267	38-48	3.95	10.96
Sh:V-133	35°19′27″	89°51′38″	267	55-65	3.29	9.51
Sh:V-134	35°19′37″	89°51′35″	269	40-50	4.90	10.28
Sh:V-173	35°19′24″	89°52′16″	270	46-56	17.94	21.26
Sh:V-174	35°19′18″	89°52′20″	269	36-46	9.70	13.72
Sh:V-175	35°19′21″	89°52′29″	267	45-55	13.92	17.50
Sh:V-176	35°19′28″	89°52′25″	268	62-72	17.95	20.84
Sh:V-187	35°19′29″	89°52′13″	264	32-42	7.68	12.50
			Fluvial deposits			
Sh:U-33	35°20′50″	89°54′52″	263	[a]70	47.98	49.55
Sh:U-101	35°20′42″	89°52′34″	275	59-69	17.64	21.20
Sh:U-105	35°20′01″	89°52′48″	262	40-50	11.69	14.41
Sh:U-107	35°20′29″	89°53′04″	266	43-53	12.90	16.18
Sh:U-109	35°20′29″	89°52′51″	269	42-52	11.86	15.12
Sh:U-110	35°20′30″	89°52′55″	268	40-50	11.55	14.96
Sh:U-111	35°20′33″	89°52′51″	265	40-50	8.81	12.10
Sh:U-112	35°20′30″	89°52′48″	267	40-50	9.73	12.95
Sh:U-115	35°20′43″	89°53′05″	269	84-94	17.96	21.43
Sh:U-117	35°20′42″	89°53′01″	270	87-97	18.75	21.32
Sh:U-119	35°21′49″	89°52′45″	282	[a]95	53.08	54.35
Sh:U-121	35°21′11″	89°52′53″	274	56-66	28.66	30.46

Table 4. Water levels measured in 67 wells screened in the alluvium, fluvial deposits, and Cockfield Formation in the area of Naval Support Activity Memphis, Millington, Tennessee, April 8-26, and October 22-24, 1996—Continued

USGS local well number	Latitude	Longitude	Altitude of land surface, in feet above sea level	Screened interval, in feet below land surface	Depth to water on April 8-26, 1996	Depth to water on October 22-24, 1996
			Fluvial deposits—Continued			
Sh:U-125	35°20′52″	89°52′35″	278	90-100	23.72	26.12
Sh:U-129	35°20′46″	89°52′30″	283	75-85	26.97	29.51
Sh:U-133	35°20′48″	89°52′35″	278	86-96	23.17	25.64
Sh:U-135	35°19′57″	89°52′55″	264	44-54	14.82	17.69
Sh:U-138	35°18′50″	89°52′53″	291	[a]70	46.18	46.73
Sh:U-152	35°21′04″	89°54′55″	265	Unknown	46.42	Not measured
Sh:U-153	35°19′05″	89°54′34″	292	[a]81	41.88	43.84
Sh:V-27	35°19′30″	89°51′35″	267	44-49	3.40	7.95
Sh:V-32	35°20′40″	89°52′09″	286	46-51	26.92	29.95
Sh:V-81	35°21′26″	89°52′20″	294	[a]79	48.20	49.43
Sh:V-83	35°20′32″	89°51′14″	284	36-46	28.31	31.20
Sh:V-85	35°20′01″	89°51′30″	272	35-45	9.06	13.18
Sh:V-89	35°20′38″	89°52′09″	284	55-65	24.90	27.81
Sh:V-107	35°20′10″	89°51′37″	296	[a]70	34.34	38.36
Sh:V-112	35°20′52″	89°51′07″	300	50-60	46.02	48.24
Sh:V-113	35°20′37″	89°51′41″	313	62-72	53.48	56.08
Sh:V-114	35°20′21″	89°52′10″	269	36-46	9.28	12.03
Sh:V-115	35°20′33″	89°50′40″	290	45-55	34.33	36.48
Sh:V-146	35°20′52″	89°52′23″	284	60-70	25.64	28.04
Sh:V-148	35°20′51″	89°52′28″	283	66-76	26.22	28.66
Sh:V-151	35°20′45″	89°52′22″	284	67-77	26.00	28.58
Sh:V-158	35°20′46″	89°52′28″	281	66-76	23.63	26.17
Sh:V-164	35°21′01″	89°52′24″	282	68-78	33.68	35.07
Sh:V-165	35°20′59″	89°52′22″	283	60-70	30.97	32.36
Sh:V-166	35°21′01″	89°52′11″	289	80-90	36.00	37.23
Sh:V-167	35°20′54″	89°52′03″	293	66-76	35.09	37.54
Sh:V-168	35°20′50″	89°20′04″	297	84-94	38.21	40.81
Sh:V-170	35°20′53″	89°52′08″	294	90-100	35.95	38.29
Sh:V-171	35°20′49″	89°52′18″	285	70-80	26.94	29.45
Sh:V-172	35°20′42″	89°52′27″	281	62-72	22.88	25.53
Sh:V-180	35°19′50″	89°52′04″	269	39-49	8.37	9.87

Table 4. Water levels measured in 67 wells screened in the alluvium, fluvial deposits, and Cockfield Formation in the area of Naval Support Activity Memphis, Millington, Tennessee, April 8-26, and October 22-24, 1996—Continued

USGS local well number	Latitude	Longitude	Altitude of land surface, in feet above sea level	Screened interval, in feet below land surface	Depth to water on April 8-26, 1996	Depth to water on October 22-24, 1996
			Fluvial deposits—Continued			
Sh:V-182	35°20′49″	89°52′09″	294	80-90	35.27	37.83
Sh:V-189	35°18′24″	89°52′17″	320	[a]92	63.47	63.92
			Cockfield Formation			
Sh:V-77	35°22′01″	89°51′18″	323	195-215	83.24	83.78
Sh:V-108	35°19′44″	89°50′29″	289	[a]120	23.46	28.68
Sh:V-110	35°21′26″	89°51′48″	320	52-62	36.69	38.63
Sh:V-111	35°21′09″	89°51′26″	321	50-60	34.90	35.80

[a]Depth to bottom of well screens estimated.

locally can be discontinuous over short distances. At NSA Memphis, the Cockfield Formation consists of clay, silt, and sand. Thickness of the preserved Cockfield Formation section at NSA Memphis (fig. 11) ranges from 0 to greater than 185 feet and is highly variable because both the top and base of the formation are erosional surfaces.

Clay and silt lenses in the Cockfield Formation slow downward movement of ground water from the alluvial-fluvial deposits aquifer (Carmichael and others, 1997) and form the Cockfield confining unit. Vertical hydraulic conductivities of five clay samples from the Cockfield Formation ranged from about 4.5×10^{-5} to 2.5×10^{-3} ft/d, and the total porosity ranged from about 41 to 55 percent (table 2).

Cockfield Aquifer

At NSA Memphis, sand lenses present in the Cockfield Formation comprise the Cockfield aquifer. Lenses of fine- to medium-grained sand as much as 50 feet thick are present (Carmichael and others, 1997). Well Sh:V-77 (fig. 3), screened in a sand lens in the Cockfield Formation, once supplied water for a small park at Navy Lake in the northern part of the NSA Memphis Northside. In general, small capacity domestic wells will produce as much as 10 gallons per minute from this aquifer (Carmichael and others, 1997). The horizontal hydraulic conductivity of sand units in the Cockfield aquifer, estimated from 14 specific-capacity tests (table 3), ranged from about 0.5 to 3 ft/d. The Cockfield Formation rests unconformably upon the Cook Mountain Formation.

Cook Mountain Confining Unit

The Cook Mountain Formation of middle to late Eocene age consists predominantly of clay and silt (table 1). Minor lenses of silty, fine sand may be present. Thickness of the Cook Mountain Formation at NSA Memphis ranges from about 10 to 60 feet (Carmichael and others, 1997). The vertical hydraulic conductivity of six clay samples from the Cook Mountain Formation ranged from about 5×10^{-6} to 9.9×10^{-4} ft/d, and the total porosity ranged from about 30 to 42 percent (table 2). The clay and silt lenses in the Cook Mountain Formation slow downward movement of ground water from the alluvial-fluvial deposits and Cockfield aquifers, and form the lower confining unit for the Cockfield aquifer and the upper confining unit for the Memphis aquifer at NSA Memphis (Kingsbury and Carmichael, 1995). The altitude of the base of the Cockfield Formation (top of the Cook Mountain Formation) and the locations of faults that displace these units are shown in figure 12.

Memphis Aquifer

The Memphis aquifer consists of fine to very coarse sand with lenses of clay and silt at various

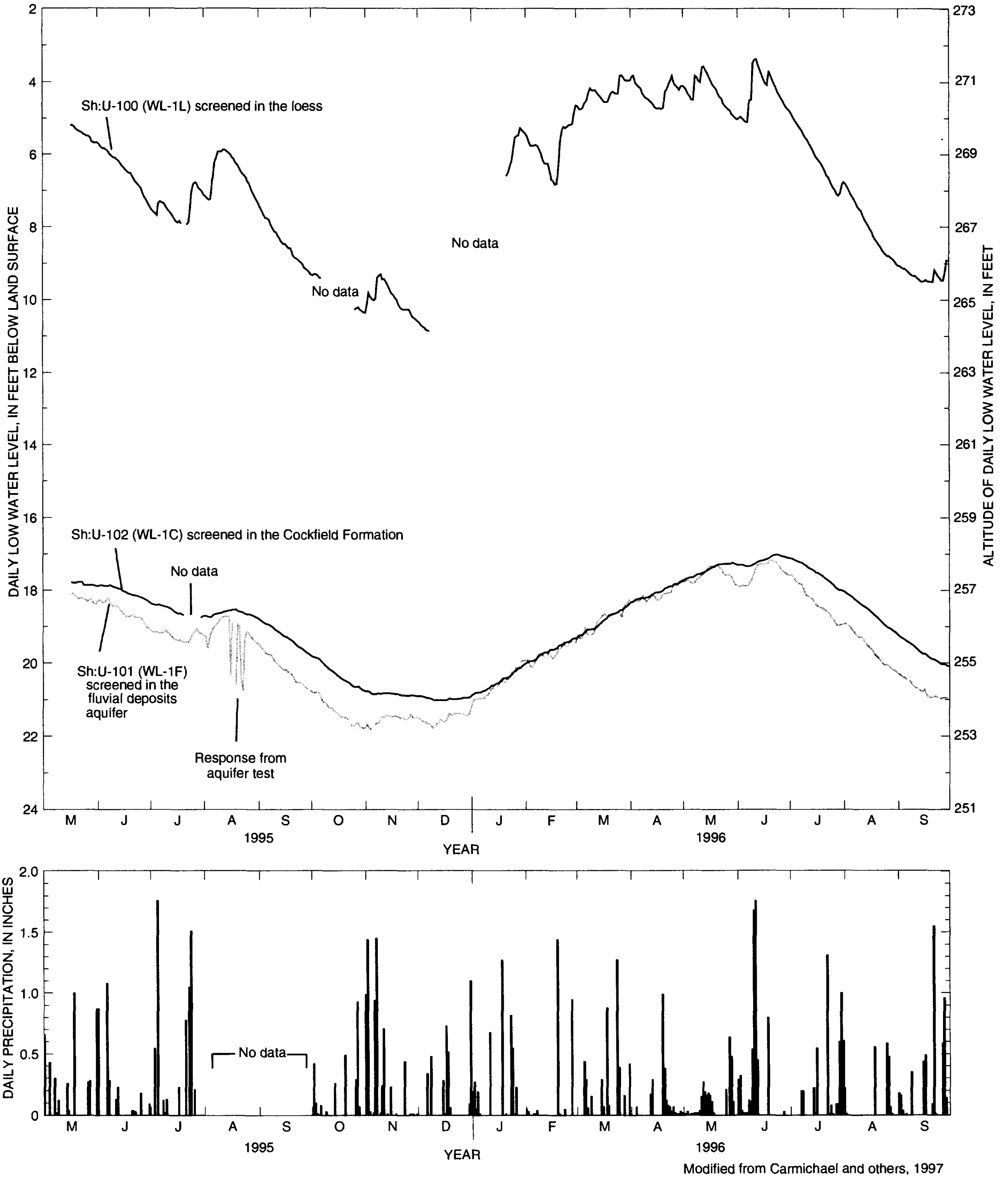
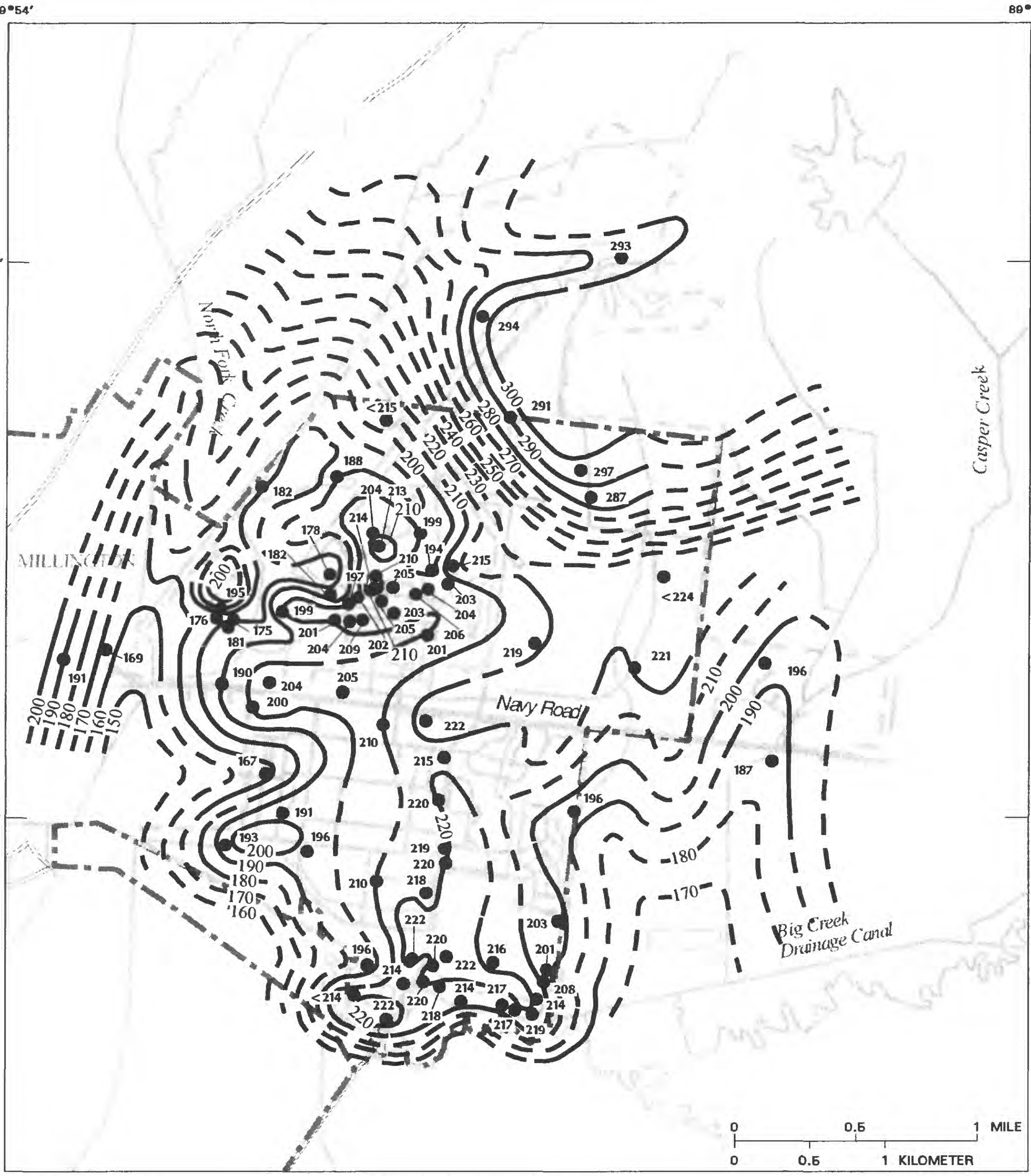


Figure 6. Hydrographs showing water levels recorded in wells Sh:U-100, Sh:U-101, and Sh:U-102, and daily precipitation at Naval Support Activity Memphis, May 1995 through September 1996 (precipitation data for May through July 1995 from Naval Support Activity Memphis; precipitation data for October 1995 through September 1996 from USGS gage near Millington, Tennessee).



Base from U.S. Geological Survey Digital Line Graphs 1:24,000 and U.S. Navy Digital Orthophotography 1:7,600

From Carmichael and others, 1997

EXPLANATION

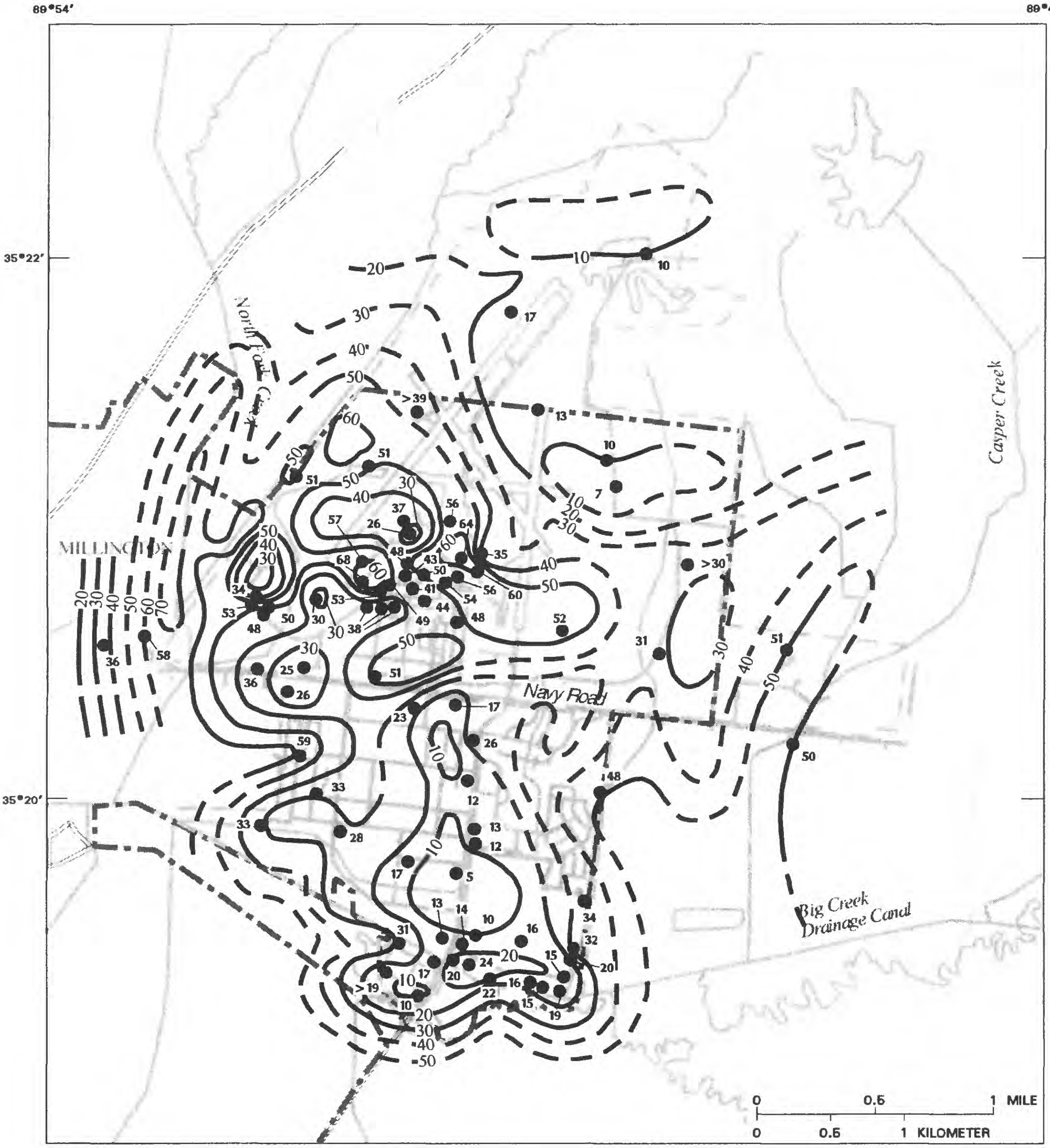
NAVAL SUPPORT ACTIVITY MEMPHIS BOUNDARY

MILLINGTON CITY BOUNDARY

210 SUBSURFACE CONTOUR - - Shows altitude of base of sand and gravel in lower part of alluvium or fluvial deposits. Dashed where approximate. Datum is sea level. Contour interval 10 feet

191 WELL - - Number is altitude, in feet, of base of sand and gravel in lower part of alluvium or fluvial deposits. Datum is sea level

Figure 7. Altitude of base of sand and gravel in lower alluvium or fluvial deposits at Naval Support Activity Memphis, Millington, Tennessee.



Base from U.S. Geological Survey Digital Line Graphs 1:24,000 and U.S. Navy Digital Orthophotography 1:7,600

From Carmichael and others, 1997

EXPLANATION

NAVAL SUPPORT ACTIVITY MEMPHIS BOUNDARY

MILLINGTON CITY BOUNDARY

—30— — LINE OF EQUAL THICKNESS OF SAND AND GRAVEL IN LOWER PART OF ALLUVIUM OR FLUVIAL DEPOSITS -- Number is thickness. Dashed where approximate. Contour interval 10 feet

● 36 WELL -- Number is thickness, in feet, of sand and gravel in lower part of alluvium or fluvial deposits

Figure 8. Thickness of sand and gravel in lower alluvium or fluvial deposits at Naval Support Activity Memphis, Millington, Tennessee.

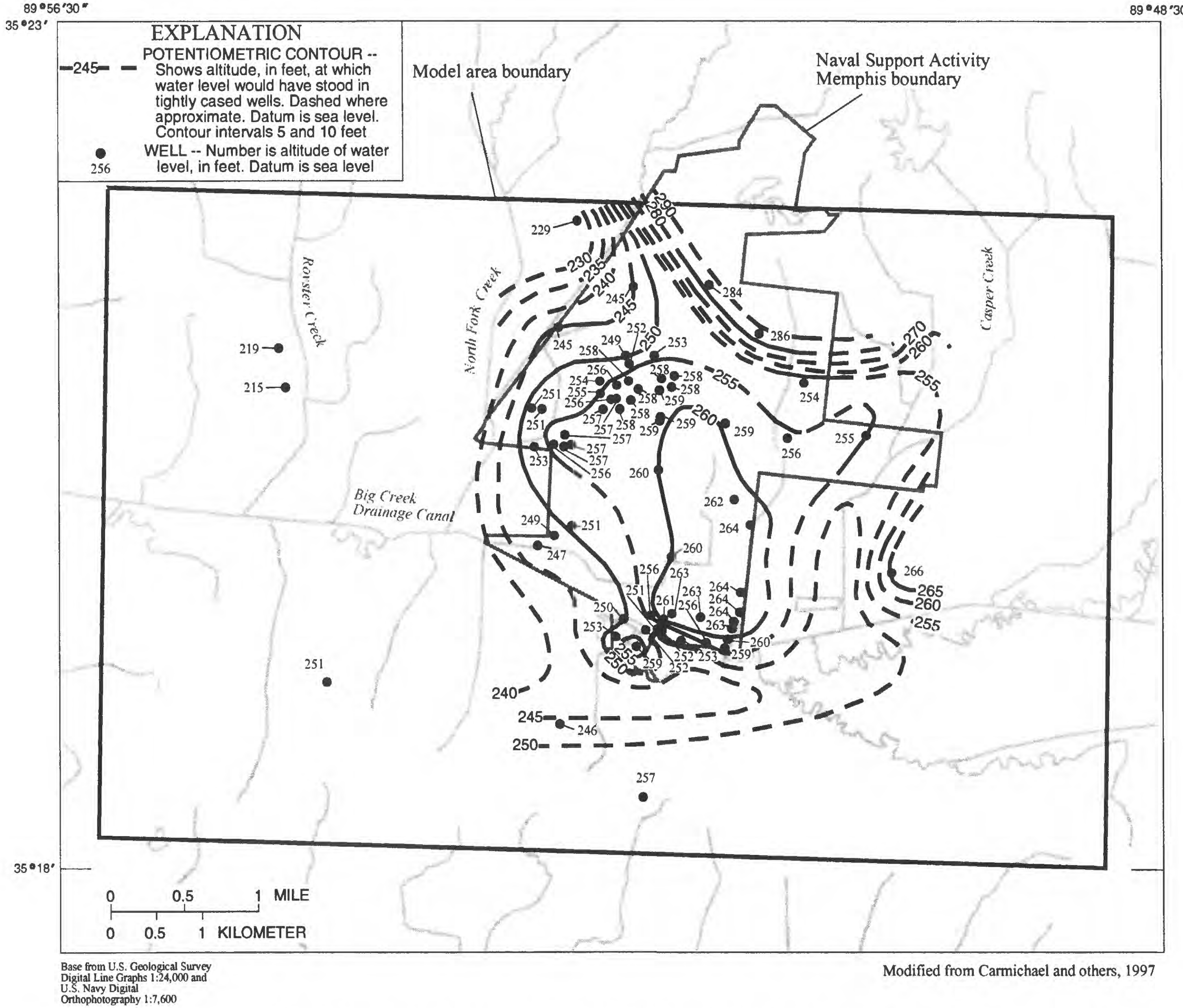


Figure 9. Altitude of the potentiometric surface of the alluvial-fluvial deposits aquifer at Naval Support Activity Memphis, Millington, Tennessee, April 1996.

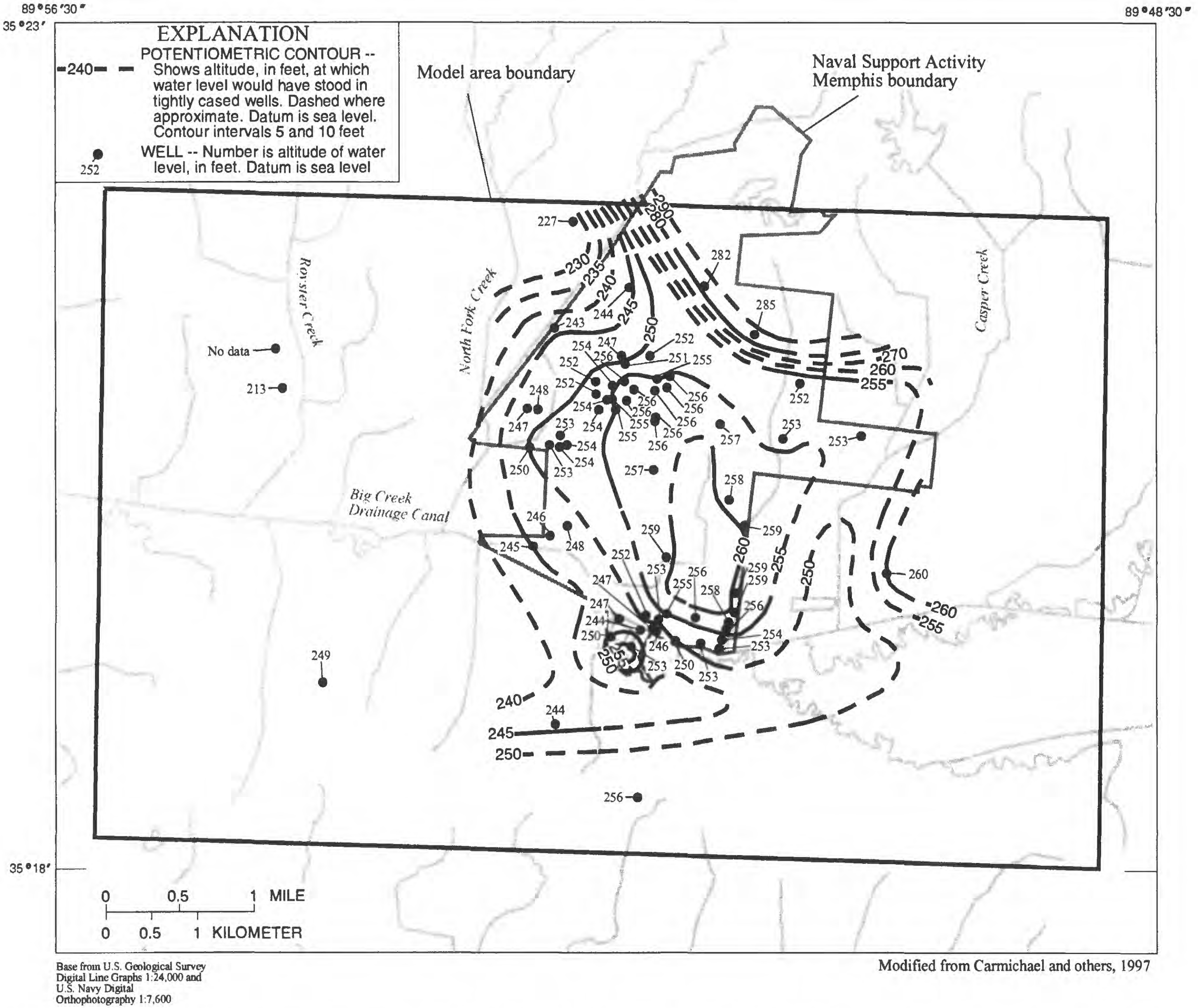


Figure 10. Altitude of the potentiometric surface of the alluvial-fluvial deposits aquifer at Naval Support Activity Memphis, Millington, Tennessee, October 1996.

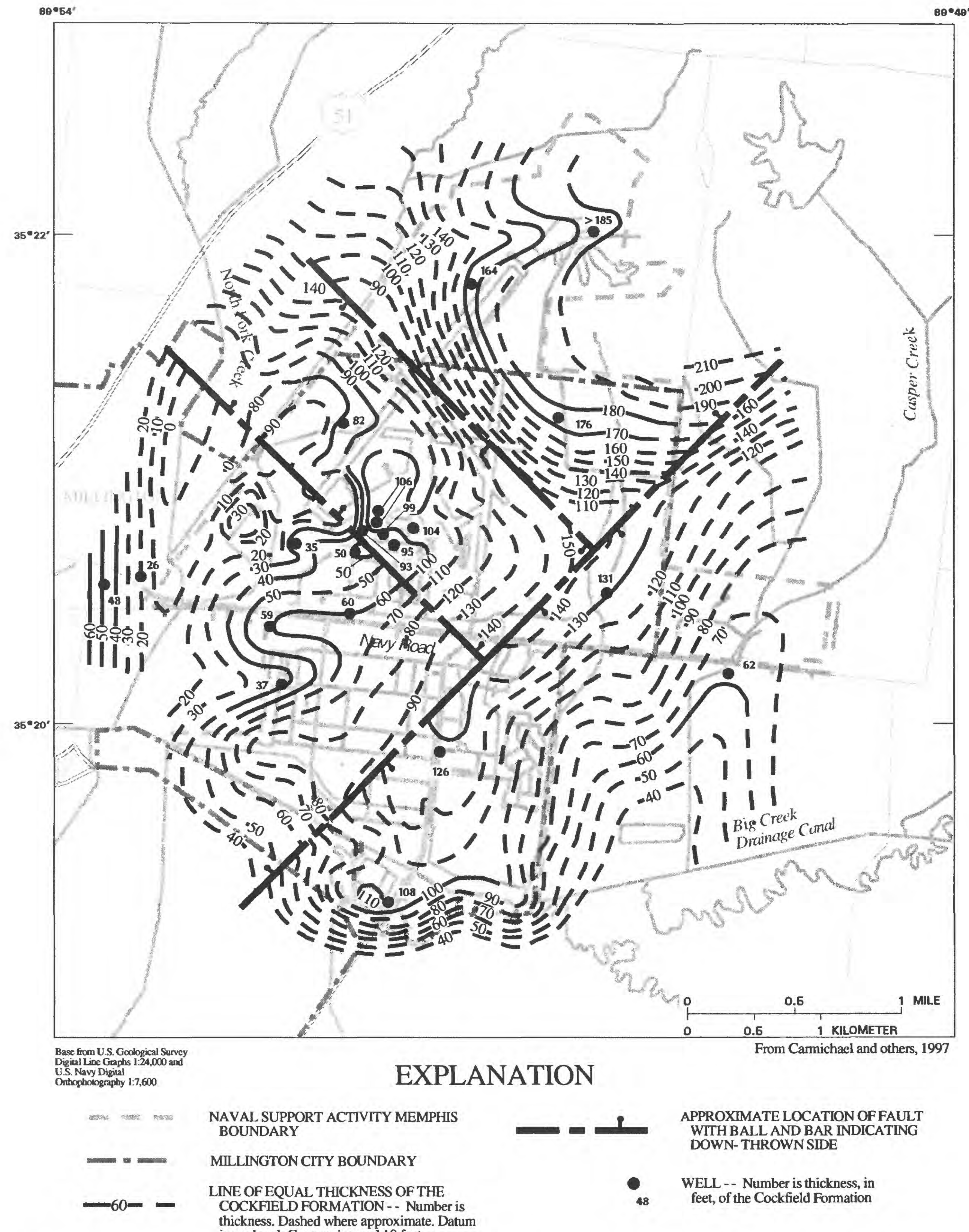
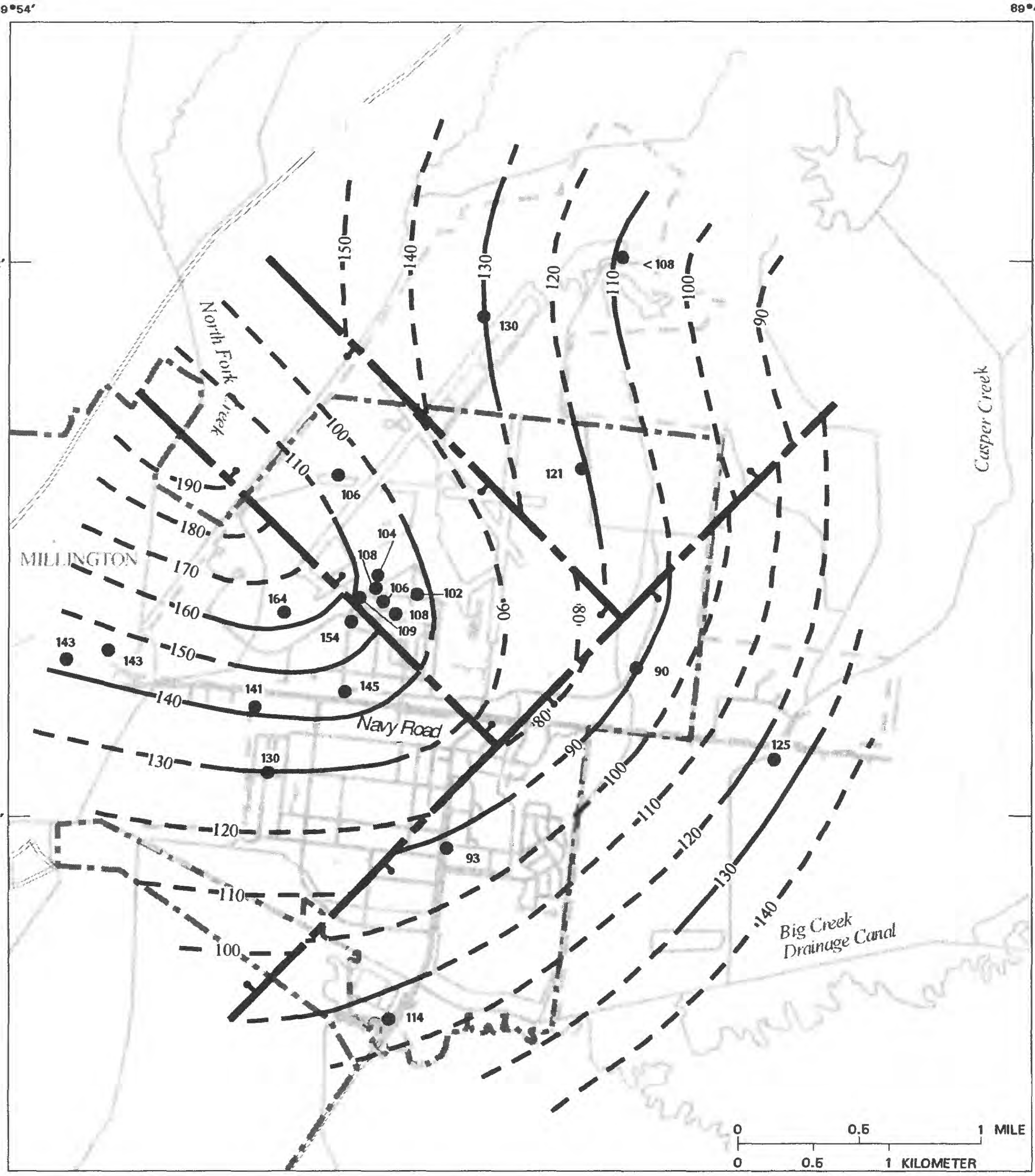


Figure 11. Thickness of the Cockfield Formation and locations of faults that displace the Cockfield and Cook Mountain Formations at Naval Support Activity Memphis, Millington, Tennessee.



Base from U.S. Geological Survey Digital Line Graphs 1:24,000 and U.S. Navy Digital Orthophotography 1:7,600

From Carmichael and others, 1997

EXPLANATION

NAVAL SUPPORT ACTIVITY MEMPHIS BOUNDARY

MILLINGTON CITY BOUNDARY

—140— SUBSURFACE CONTOUR -- Shows altitude of base of Cockfield Formation (top of Cook Mountain Formation). Dashed where approximate. Datum is sea level. Contour interval 10 feet

APPROXIMATE LOCATION OF FAULT WITH BALL AND BAR INDICATING DOWN-THROWN SIDE

130 WELL -- Number is altitude, in feet, of base of Cockfield Formation (top of Cook Mountain Formation). Datum is sea level

Figure 12. Altitude of base of Cockfield Formation (top of Cook Mountain Formation) and locations of faults that displace these formations at Naval Support Activity Memphis, Millington, Tennessee.

stratigraphic horizons (Parks, 1990). The Memphis aquifer is a regional aquifer in Tennessee, Missouri, Kentucky, and Arkansas. In the Memphis area, this aquifer is the principal source of water for municipal, industrial, and commercial supplies. Direct recharge to the Memphis aquifer occurs east of Memphis in a broad belt trending northeastward across western Tennessee where the aquifer is at or near land surface. Thickness of the Memphis aquifer in Shelby County, Tennessee, ranges from 600 to 900 feet with an average thickness of about 700 feet (Parks and Carmichael, 1990b). Parks and Carmichael (1990b) report an average transmissivity and storage coefficient (based on 52 tests) of 33,400 feet squared per day (ft^2/d) and 0.001, respectively, for the Memphis aquifer in Shelby County. The most recent potentiometric map of the Memphis aquifer in the Memphis, Tennessee, area is for September 1995 (Kingsbury, 1996). The potentiometric surface of the Memphis aquifer, taken from Kingsbury (1996) for part of the Memphis area in northern Shelby County, Tennessee, near NSA Memphis is shown in figure 13.

At NSA Memphis, the Memphis aquifer is present at depths ranging from about 150 to greater than 220 feet below land surface (Carmichael and others, 1997). Thickness ranges from about 865 to 880 feet. Wells Sh:V-4 (fig. 5) and Sh:V-20, located within the NSA Memphis Northside, are screened in the Memphis aquifer. Analyses of water samples collected from these wells showed concentrations of tritium less than detectable limits, indicating that near the wells leakage of water from the shallower aquifers was not a major source of recharge to the Memphis aquifer (Carmichael and others, 1997).

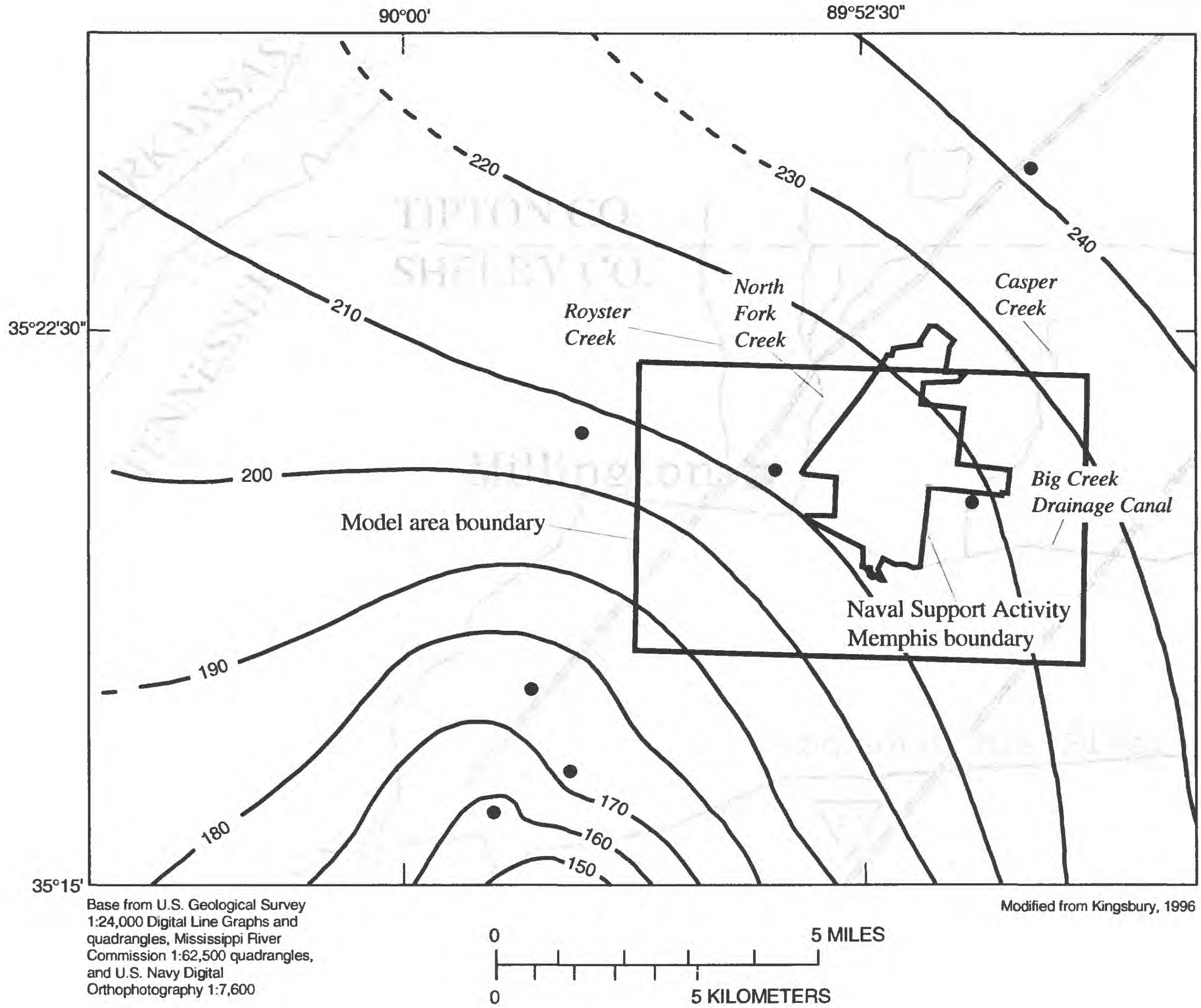
Unique Hydrogeologic Features

The occurrence and pattern of flow of ground water in the alluvial-fluvial deposits aquifer at NSA Memphis appears to be influenced by (1) faulting, (2) buried river valleys, (3) "windows" in the Cockfield and Cook Mountain confining units, and (4) an erosional scarp. The location and area of influence for each of these features was estimated from geologic and hydrogeologic data collected during drilling and water-level mapping.

Carmichael and others (1997) mapped faults in the Memphis Sand and the Cook Mountain and Cockfield Formations, but found no evidence for faulting of sediments younger than the Cockfield Formation. This finding agrees with the estimated time of last movement on faults in the Memphis area (Kingsbury and Parks, 1993). An overlay of the locations of faults mapped at NSA Memphis onto the potentiometric map of the alluvial-fluvial deposits aquifer is illustrated in figure 14. No relation is evident between the occurrence of ground water in the alluvial-fluvial deposits aquifer and two of the faults; but a potentiometric low is centered over the northeasternmost of the two northwest trending faults. One possible explanation for the potentiometric low is that the fault has created a zone of increased hydraulic connection between the alluvial-fluvial deposits aquifer and the Cockfield and Memphis aquifers, which have lower potentiometric heads. Comparison of the altitude of the potentiometric surface in the alluvial-fluvial deposits aquifer in the depression (less than 255 feet) to the altitude of the potentiometric surface in the Memphis aquifer in the NSA Memphis area (figure 13) indicates a vertical head difference of about 40 feet downward between the two units. This condition would allow water to flow vertically downgradient towards the deeper aquifer(s) creating a potentiometric low in the alluvial-fluvial aquifer.

Carmichael and others (1997) show the potentiometric maps for the alluvial-fluvial deposits aquifer for April and October of 1996 (figs. 9 and 10) with lower ground-water levels centered over the inferred valleys of Big Creek Drainage Canal and its major tributaries. Possible explanations for the shape of the potentiometric surface include preferential flow of ground water along the axis of buried river valleys through thick alluvial deposits, and increased hydraulic connection between the alluvial-fluvial deposits aquifer and the Cockfield and Memphis aquifers, with lower potentiometric heads resulting from erosional windows in the confining unit in the areas of the river valleys. Geologic section *C-C′* in the area of well Sh:V-9 (fig. 4b) may illustrate the second situation. The natural gamma-ray log of well Sh:V-9 can be interpreted to indicate no clay confining unit between the alluvial-fluvial deposits aquifer and a sand lens in the Cockfield Formation.

Low water levels in two wells completed in the alluvial-fluvial deposits aquifer, located west of NSA Memphis near Royster Creek (figs. 9 and 10), are only about 5 feet higher than the potentiometric surface of the Memphis aquifer for the same area (fig. 13). These low water levels may result from a window in the upper confining unit of the Memphis aquifer. The

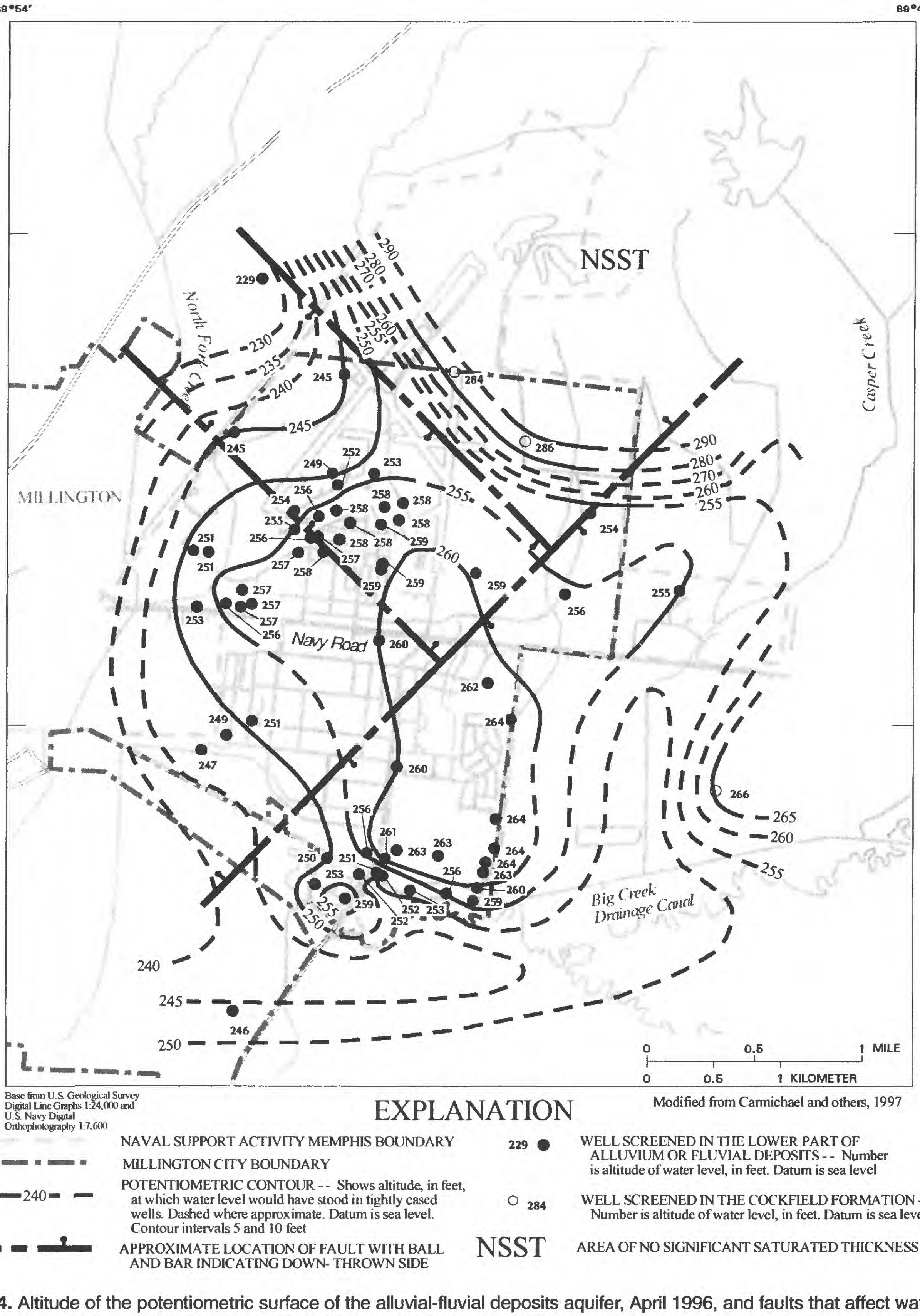


EXPLANATION

—180— — POTENTIOMETRIC CONTOUR -- Shows altitude, in feet, at which water level would have stood in tightly cased wells, September 1995. Dashed where approximate. Datum is sea level. Contour interval 10 feet

● WELL IN WHICH WATER-LEVEL MEASUREMENT WAS MADE, SEPTEMBER 1995

Figure 13. Altitude of the potentiometric surface of the Memphis aquifer in northern Shelby County near Naval Support Activity Memphis, Millington, Tennessee.



EXPLANATION

NAVAL SUPPORT ACTIVITY MEMPHIS BOUNDARY

MILLINGTON CITY BOUNDARY

240 — POTENTIOMETRIC CONTOUR -- Shows altitude, in feet, at which water level would have stood in tightly cased wells. Dashed where approximate. Datum is sea level. Contour intervals 5 and 10 feet

APPROXIMATE LOCATION OF FAULT WITH BALL AND BAR INDICATING DOWN-THROWN SIDE

229 ● WELL SCREENED IN THE LOWER PART OF ALLUVIUM OR FLUVIAL DEPOSITS -- Number is altitude of water level, in feet. Datum is sea level

○ 284 WELL SCREENED IN THE COCKFIELD FORMATION -- Number is altitude of water level, in feet. Datum is sea level

NSST AREA OF NO SIGNIFICANT SATURATED THICKNESS

Figure 14. Altitude of the potentiometric surface of the alluvial-fluvial deposits aquifer, April 1996, and faults that affect water movement at Naval Support Activity Memphis, Millington, Tennessee.

confining unit is known to be absent or thin locally in the Memphis area (Parks, 1990; Kingsbury and Parks, 1993).

CONCEPTUAL HYDROGEOLOGIC MODEL OF THE SHALLOW AQUIFER SYSTEM

The shallow aquifers described by Carmichael and others (1997) have been treated as separate units by previous investigators. For this report, however, based on the stratigraphic and structural correlations made using lithologic and geophysical logs, the aquifers were organized into a shallow aquifer system. The structure and thickness maps of the units (Carmichael and others, 1997), along with geophysical and lithologic logs, were used to determine the vertical distribution and thickness of the hydrogeologic units. The results of the aquifer test, well specific-capacity tests, and sediment-core analyses were used as estimates of the hydraulic properties of the hydrogeologic units. The potentiometric-surface maps for the alluvial-fluvial deposits aquifer were used to infer the importance of depositional, erosional, and structural features to the occurrence of ground water and the pattern of ground-water flow at NSA Memphis.

For this study, the shallow aquifer system is subdivided into five hydrogeologic units: (1) the alluvium-loess confining unit; (2) the A1 aquifer that, southwest of the erosional scarp (fig. 4b), includes the entire alluvial-fluvial deposits aquifer (fig. 15a), and northeast of the erosional scarp, also comprises sand lenses in the upper part of the Cockfield aquifer (fig. 15b); (3) the Cockfield confining unit; (4) the sand lenses within the lower part of the Cockfield aquifer; and (5) the Cook Mountain confining unit. The hydrogeologic framework of the shallow aquifer system is shown in table 5 and on section *B-B′* in figure 16. In the conceptual hydrogeologic model, the alluvial-fluvial deposits aquifer southwest of the erosional scarp is hydraulically connected with shallow sand units in the upper Cockfield Formation that are present northeast of the scarp.

Recharge to the shallow aquifer system occurs as infiltration from precipitation across the alluvium-loess confining unit. Ground-water discharge occurs primarily as leakage across the Cook Mountain confining unit to the Memphis aquifer. The pattern of ground-water flow is heavily influenced by faulting and buried river valleys. The shallow aquifer system appears to have limited interaction with the surface drainage network, except for short segments of Big Creek Drainage Canal, Casper Creek, and North Fork Creek along the southern boundary of NSA Memphis. In general, ground-water flow in the A1 aquifer is away from topographic highs, and radially away from the center of NSA Memphis.

Table 5. Stratigraphy, hydrogeologic units, and conceptual hydrogeologic model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee

Stratigraphic unit	Hydrogeologic unit	Conceptual hydrogeologic model
Upper alluvium/loess	Confining unit	Shallow aquifer system
Lower alluvium–fluvial deposits	A1 aquifer (southwest of erosional scarp)	
Cockfield Formation	A1 aquifer (northeast of erosional scarp)	
	Confining unit	
	Cockfield aquifer	
Cook Mountain Formation	Confining unit	Base of shallow aquifer system
Memphis Sand	Memphis aquifer	Deep aquifer system

SIMULATION OF GROUND-WATER FLOW IN THE SHALLOW AQUIFER SYSTEM

A finite-difference model was used to simulate ground-water flow in the shallow aquifer system at NSA Memphis. The modeling objectives were to (1) test the conceptual model of the ground-water-flow system and (2) generate the velocity-vector field required by the particle-tracking program to simulate ground-water-flow directions and travel times. The McDonald and Harbaugh (1988) modular model (MODFLOW) was used to simulate flow in the shallow aquifer system because this model can easily be used to simulate layered aquifer systems, and because the particle-tracking program MODPATH (Pollock, 1989, 1994) uses the output from the modular model. The MODFLOW model can use the quasi-three-dimensional approach to simulate flow within multi-aquifer systems [three-dimensional (x, y, z) flow in aquifers and one-dimensional vertical (z) flow through confining units using leakance terms and ignoring storage] or the three-dimensional approach by specifying a model layer for each hydrogeologic unit.

Model Assumptions

In order to simplify the modeling approach, several assumptions were made. Ground-water-flow divides were assumed to generally coincide with major surface-water divides. The shallow aquifer system was assumed to exist in steady-state condition. The clastic sediments that comprise the shallow aquifers were assumed to transmit water as uniform porous media, and the aquifers are homogeneous and isotropic within individual hydrogeologic units.

Many studies of local and regional ground-water systems (Hubbert, 1940; Toth, 1962; Faye and Mayer, 1990; and Robinson and others, 1997) have assumed that surface-water and ground-water divides coincide, especially for small drainage basins. The primary utility of this assumption for the model analysis is in the location and assignment of types of model boundaries. Specifically, surface-water and ground-water divides are simulated as no-flow boundaries.

The shallow aquifer system at NSA Memphis was assumed to be in a steady-state condition. Data that support this assumption include continuous water-level measurements in three wells completed in the loess, alluvial-fluvial deposits aquifer, and in a clayey unit of the upper Cockfield Formation (fig. 6) and two synoptic water-level measurement surveys made in April and October 1996 (table 4). Within the study area, ground-water levels in the shallow aquifers changed seasonally about 1 to 5 feet, which is small relative to the saturated thickness of the shallow aquifers (10 to 60 feet) and to the difference between the water levels of the shallow aquifer system and the Memphis aquifer (about 40 feet). Horizontal ground-water gradients across the site also were relatively constant. Therefore, a steady-state ground-water-flow model was considered adequate to address most of the questions raised by site assessments and remediation plans.

The assumption that the sediments which comprise the shallow aquifers transmit water as uniform porous media is reasonable for coarse-grained, clastic, unconsolidated sediments such as the lower part of the alluvium and the fluvial deposits. Darcy's Law can be assumed to apply to ground-water flow in these sediments, and the use of the finite-difference model MODFLOW to simulate ground-water flow in these sediments is appropriate.

The final assumption, that the aquifers at NSA Memphis are homogeneous and isotropic, may not necessarily be true, but data are insufficient to determine the variability of the hydraulic characteristics of the aquifers. However, even conduit-flow aquifers can be modeled as homogeneous as long as the scale of investigation is large enough (Glenn and others, 1989; Nelson, 1989). For the model of the shallow aquifer system at NSA Memphis, the relatively coarse grid size used should compensate for small-scale heterogeneities in the aquifers. The assumption of homogeneity of the aquifers on a gross scale can be partially tested by inspection of the aquifer-test data from the site.

The best estimate of the representative horizontal hydraulic conductivity of the alluvial-fluvial deposits aquifer (about 5 ft/d) was assumed to have been determined by the constant-withdrawal aquifer test performed by the USGS at the location of the continuous water-level observation wells (fig. 2). This test utilized observation wells to measure a response in the aquifer at 76 and 555 feet away from the pumped well (Sh:U-103) and to monitor water levels in an area as far as 6,600 feet away from the pumped well. A ground-water-flow model, VS2DT (Lappala and others, 1987; Healy, 1990), was used to simulate the response of the shallow aquifer system to pumping a well completed in the alluvial-fluvial deposits aquifer. A significant finding from this analysis was that the VS2DT model adequately simulated the response of the shallow aquifer system to pumping using a single

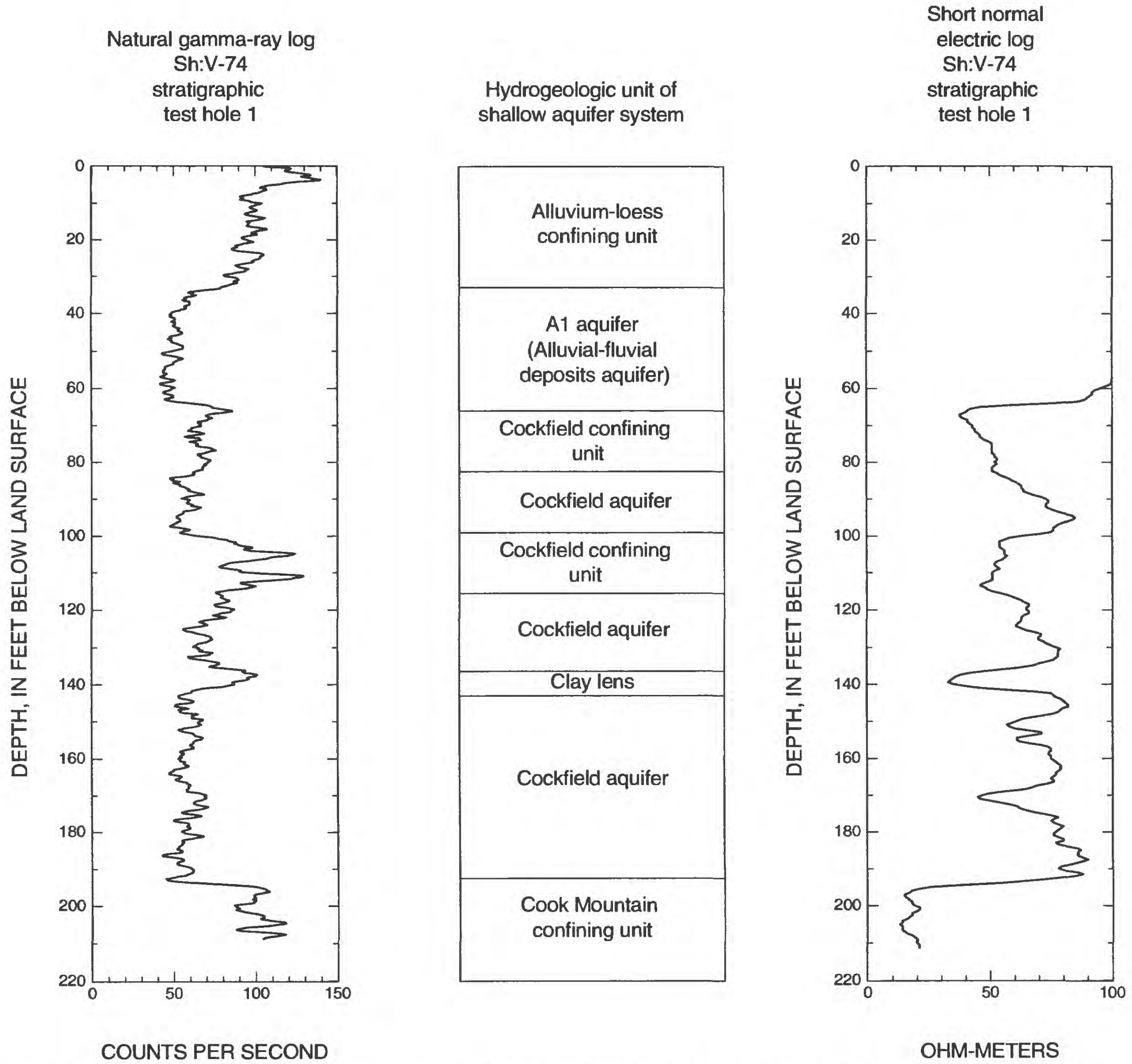


Figure 15a. Borehole geophysical logs of test hole 1 (Sh:V-74) and hydrogeologic units of the shallow aquifer system southwest of the erosional scarp at Naval Support Activity Memphis, Millington, Tennessee.

representative value of hydraulic conductivity for each of the aquifers included in the model. The shallow aquifers at NSA Memphis were further assumed to be isotropic with respect to horizontal hydraulic conductivity. This assumption is not unreasonable for coarse-grained unconsolidated sediments such as those in the lower part of the alluvium and the fluvial deposits.

Model Grid and Boundary Conditions

The conceptual model of the ground-water-flow system was represented with a 33-row by 43-column model grid simulating an area of 23,500 feet by 36,000 feet, respectively, or about 30 mi^2 (fig. 17). The active cells ranged in size from 1,000 x 1,000 to 600 x 600 feet. The smaller cells were used in areas within the NSA Memphis perimeter, and the largest cells were near model boundaries. The grid was generally oriented parallel to the primary surface-water drainages: Big Creek Drainage Canal, and Casper, North Fork, and Royster Creeks (fig. 17). The model was discritized vertically into three layers (fig. 18). Model layer 1 represents the A1 aquifer: the alluvial-fluvial deposits aquifer southwest of the erosional

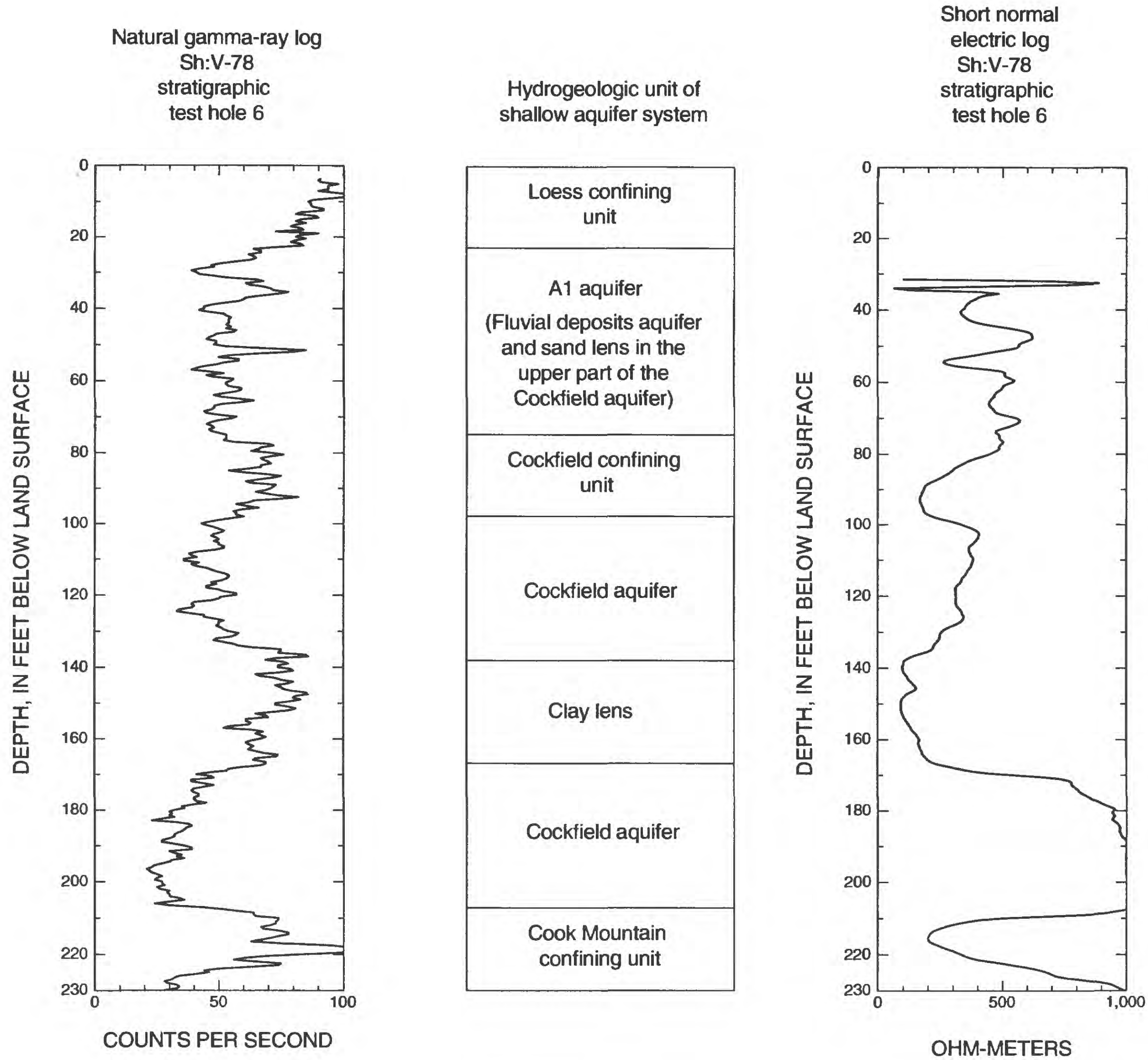


Figure 15b. Borehole geophysical logs of test hole 6 (Sh:V-78) and hydrogeologic units of the shallow aquifer system northeast of the erosional scarp at Naval Support Activity Memphis, Millington, Tennessee.

scarp and sand layers of the upper part of the Cockfield aquifer northeast of the scarp. Model layer 2 represents the sand layers of the lower part of the Cockfield aquifer. Layer 3 represents the Memphis aquifer. Vertical movement of water across confining units was simulated using the quasi-three-dimensional approach.

Proper representation of model boundary conditions is one of the most important aspects in the simulation of ground-water flow. Model boundaries are assigned to correspond to actual hydrologic boundaries as accurately as possible. If model boundaries necessarily are highly generalized, they are placed far enough away from the influence of hydrologic stresses in the model area to minimize their effects on simulation results. The upper boundary of this model is a specified-flux boundary formed by using the recharge package of MODFLOW to simulate the infiltration of water from the alluvium-loess confining unit to the A1 aquifer. The lower boundary of the model is formed by the specified heads of model layer 3 based on the potentiometric surface of the Memphis aquifer (Kingsbury, 1996). Seasonal changes in water levels in the shallow aquifer system (1 to 5 feet) were not considered

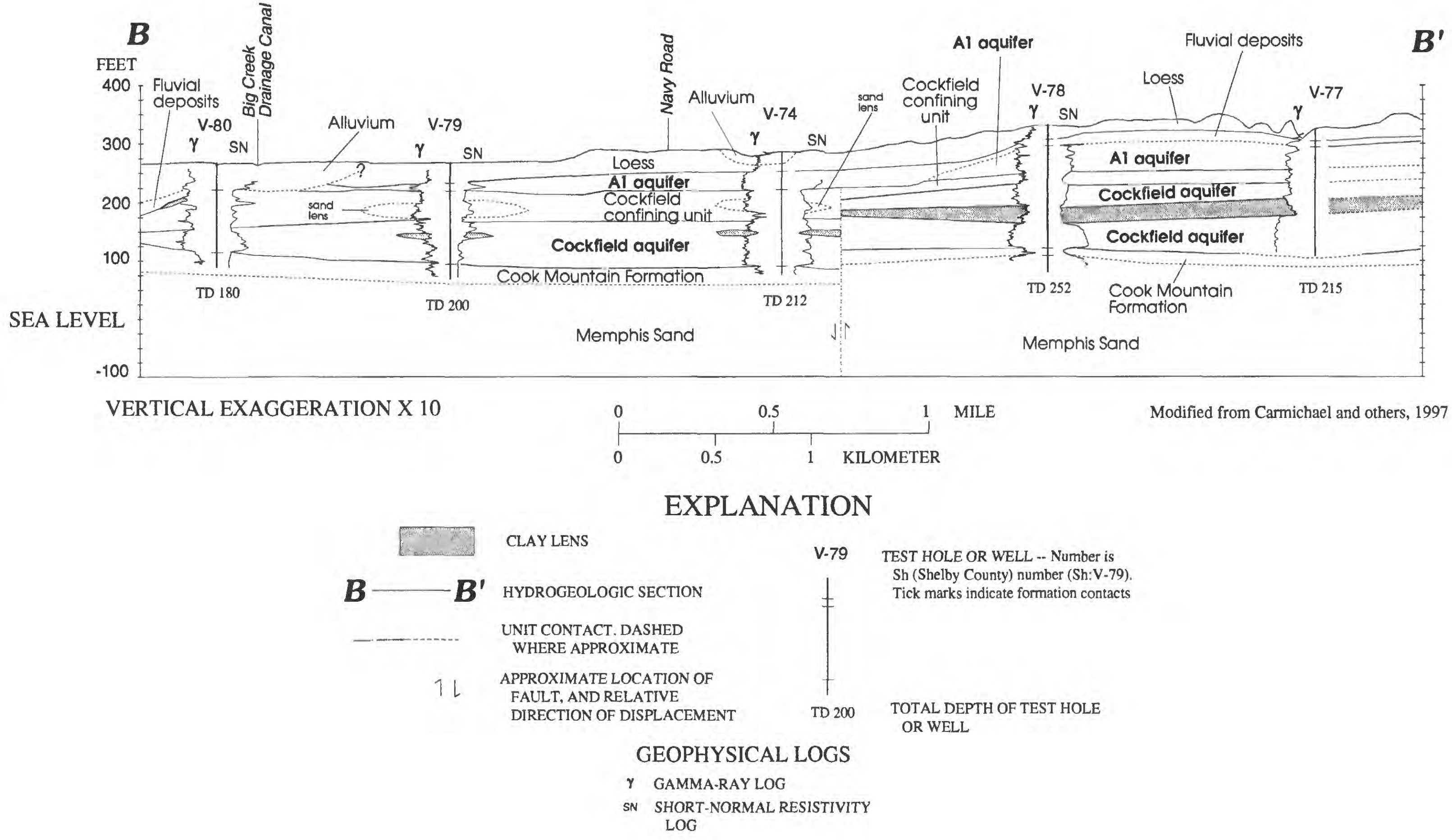


Figure 16. Hydrogeologic section *B-B′* showing the aquifers and confining units in the shallow aquifer system at Naval Support Activity Memphis, Millington, Tennessee.

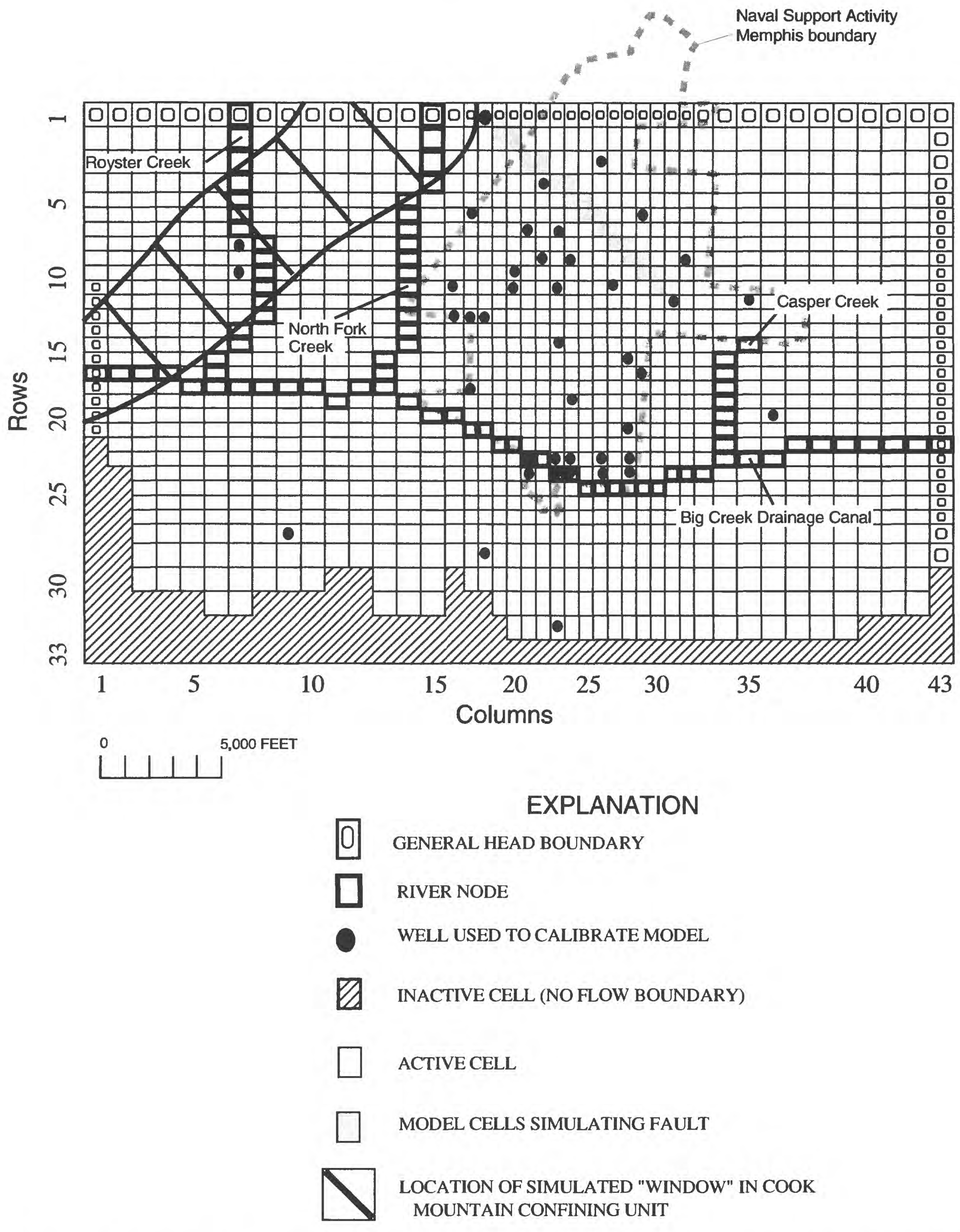


Figure 17. Model grid, wells used to calibrate model, cells simulating fault, location of simulated window in Cook Mountain confining unit, and boundary conditions for the flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee.

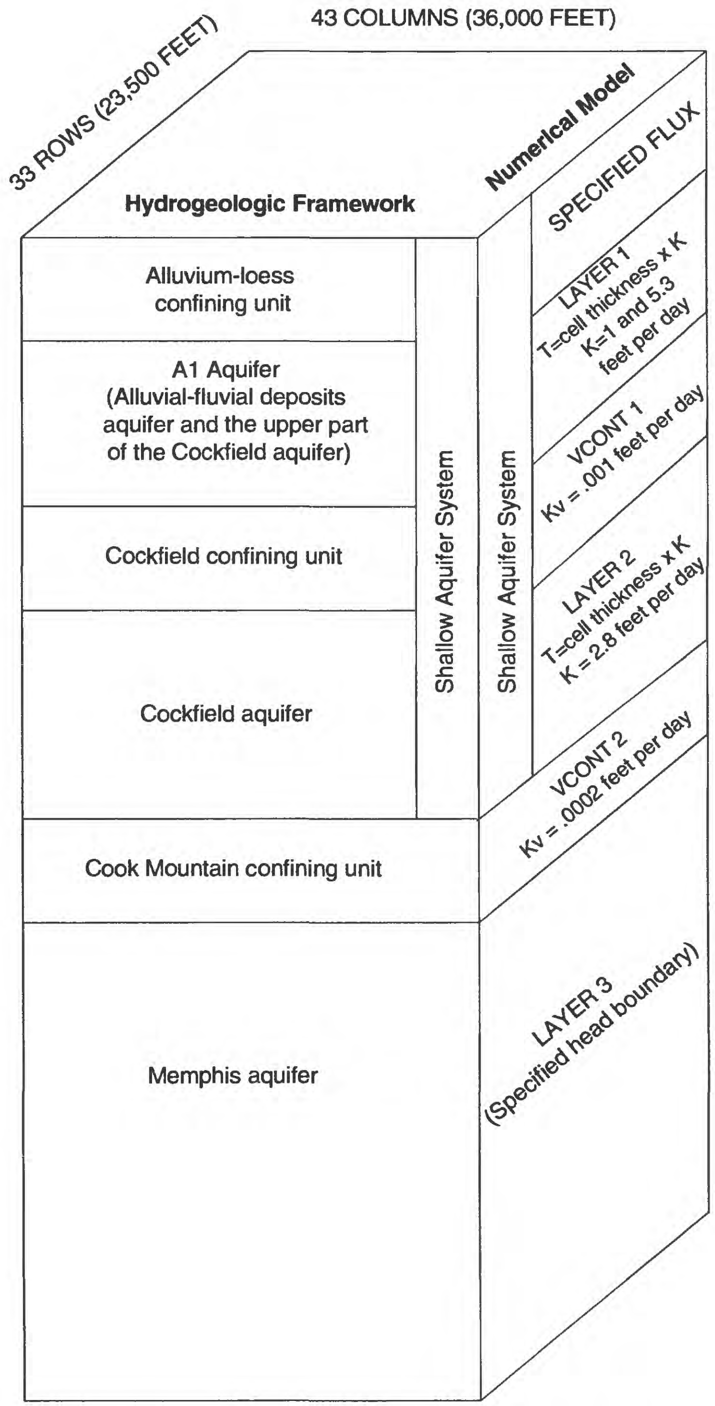


Figure 18. Hydrogeologic framework of the flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee.

because they were small relative to the saturated thickness of the shallow aquifers (10 to 60 feet) and to the difference between the water levels of the shallow aquifer system and the Memphis aquifer (about 40 feet). Because ground-water levels in the Memphis aquifer are lower than in the shallow aquifer system, layer 3 functions as a sink and removes water from the model. The lateral model boundaries in each layer are simulated either as no-flow boundaries assumed to be ground-water divides that coincide with surface-water divides, or general head boundaries where flow into and out of the model varies depending upon the head difference between the model cell and some external source (fig. 17).

Input Parameters

Initial input parameters for the flow model were estimated from the aquifer and specific-capacity tests, and sediment-core analyses. Model calibration was facilitated by a parameter-estimation program (Halford, 1992). No measurements of anisotropy were available and a lateral isotropy ratio of 1 to 1 was used for simulation. Input parameters were systematically varied until the simulated water levels for the A1 aquifer approximated the mean water levels estimated from the data collected during the two synoptic water-level measurement surveys (tables 4 and 6).

Recharge to the A1 aquifer occurs as leakage across the loess and alluvium. Initial estimates of 1 inch per year (in/yr) proved too large. A tentative estimate of about 0.3 in/yr produced better results, and final estimates provided by the parameter-estimation program (table 7) were similar to the tentative estimate. During calibration, about 0.67 to 1.8 in/yr of additional recharge to the A1 aquifer were determined necessary to generate the high potentiometric levels centered on the NSA Memphis facility. Inspection of the April 1996 potentiometric map of the alluvial-fluvial deposits aquifer (fig. 10) and cultural features at NSA Memphis shows that the ground-water mound is located beneath base housing developments, parks, and areas where the alluvium-loess confining unit has been disturbed (SWMU 2, Southside Landfill, fig. 2). Water leaks from the base water distribution and sewerage systems, watering of lawns and green areas at parks, and reduced confinement in the SWMU 2 area where the alluvium-loess confining unit was excavated during solid-waste disposal operations possibly result in recharge rates greater than the "background" rates (Carmichael and others, 1997). For simplicity and to separate the anthropogenic or "human induced" recharge rates from the background or natural recharge rate, the MODFLOW well package was used to allocate the additional anthropogenic recharge to the model.

The initial vertical conductance arrays used to represent confining units in the model were calculated based on the vertical hydraulic conductivities determined for samples of the confining units (table 2), confining unit thickness, and equation 53 of McDonald and Harbaugh (1988). Increased vertical conductance values used to simulate features such as faults and windows in the confining units were determined during calibration using the parameter-estimation program.

The transmissivity array for model layer 1 (fig. 19) was calculated by multiplying the horizontal hydraulic conductivity determined for either the alluvial-fluvial deposits aquifer (about 5 ft/d) or the sand unit representing the upper part of the Cockfield aquifer (about 1 ft/d) by the estimated thickness of the appropriate unit for each model cell of layer 1. The locations of suspected buried river valleys (fig. 19) are indicated by areas of increased transmissivity simulating thicker sand and gravel sequences. The thickness values available for the sand and gravel of the lower part of the alluvium or fluvial deposits from Carmichael and others (1997) were accepted as a known value and held constant during the calibration process. However, substantial parts of the modeled area were not within the study area of Carmichael and others (1997), and the values representing the thickness of the alluvial-fluvial deposits aquifer or the sand unit of the Cockfield aquifer in those model cells were adjusted as necessary to match observed ground-water levels. Thicknesses of the units were not adjusted beyond the upper or lower limits reported by Carmichael and others (1997).

During the calibration process, ground-water levels generated by the model were determined to be too low for the section of layer 1 representing the A1 aquifer northeast of the erosional scarp. Possible causes for this result include higher actual recharge rates or a lower hydraulic conductivity for the A1 aquifer than was input to the model. Additional recharge in that part of the model was not justified, and no data existed that would suggest that the hydraulic conductivity of the A1 aquifer was significantly less than elsewhere. Ground-water levels northeast of the erosional scarp were eventually simulated by reducing

Table 6. Measured water levels in the A1 aquifer, April 8-26 and October 23-25, 1996, mean water levels in the A1 aquifer, and water levels simulated for layer 1 of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee
[Modified from Carmichael and others, 1997]

USGS local well number	Altitude of land surface, in feet above sea level	Depth to water, in feet, on April 8-26, 1996	Depth to water, in feet, on October 22-24, 1996	Mean depth to water	Mean water level used for model calibration, in feet above sea level	Simulated water level, in feet above sea level
			Alluvium			
Sh:V-117	267	7.27	13.51	10.39	257	256
Sh:V-121	267	10.82	14.48	12.65	254	255
Sh:V-124	267	15.31	20.62	17.96	249	251
Sh:V-127	270	9.55	17.12	13.34	257	255
Sh:V-130	267	3.95	10.96	7.46	260	259
Sh:V-133	267	3.29	9.51	6.40	261	258
Sh:V-134	269	4.90	10.28	7.59	261	260
Sh:V-173	270	17.94	21.26	19.60	250	250
Sh:V-175	267	13.92	17.50	15.71	251	249
Sh:V-176	268	17.95	20.84	19.40	249	248
Sh:V-187	264	7.68	12.50	10.09	254	252
			Fluvial deposits			
Sh:U-33	263	47.98	49.55	48.76	214	216
Sh:U-101	275	17.64	21.20	19.42	256	256
Sh:U-107	266	12.90	16.18	14.54	251	249
Sh:U-110	268	11.55	14.96	13.26	255	252
Sh:U-112	267	9.73	12.95	11.34	256	254
Sh:U-115	269	17.96	21.43	19.70	249	247
Sh:U-119	282	53.08	54.35	53.72	228	230
Sh:U-121	274	28.66	30.46	29.56	244	243
Sh:U-133	278	23.17	25.64	24.40	254	254
Sh:U-135	264	14.82	17.69	16.26	248	248
Sh:U-138	291	46.18	46.73	46.46	245	248
Sh:U-152	265	46.42	Not measured	Not measured	218	217
Sh:U-153	292	41.88	43.84	42.86	249	250
Sh:V-81	294	48.20	49.43	48.82	245	244
Sh:V-83	284	28.31	31.20	29.76	254	254
Sh:V-85	272	9.06	13.18	11.12	261	258

Table 6. Measured water levels in the A1 aquifer, April 8-26 and October 23-25, 1996, mean water levels in the A1 aquifer, and water levels simulated for layer 1 of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee—Continued

USGS local well number	Altitude of land surface, in feet above sea level	Depth to water, in feet, on April 8-26, 1996	Depth to water, in feet, on October 22-24, 1996	Mean depth to water	Mean water level used for model calibration, in feet above sea level	Simulated water level, in feet above sea level
			Fluvial deposits—Continued			
Sh:V-89	284	24.90	27.81	26.36	258	258
Sh:V-107	296	34.34	38.36	36.35	260	259
Sh:V-112	300	46.02	48.24	47.13	253	252
Sh:V-113	313	53.48	56.08	54.78	258	257
Sh:V-114	269	9.28	12.03	10.66	258	260
Sh:V-115	290	34.33	36.48	35.40	255	253
Sh:V-164	282	33.68	35.07	34.38	248	249
Sh:V-166	289	36.00	37.23	36.62	252	251
Sh:V-168	297	38.21	40.81	39.51	257	255
Sh:V-171	285	26.94	29.45	28.20	257	255
Sh:V-180	269	8.37	9.87	9.12	260	260
Sh:V-189	320	63.47	63.92	63.70	256	256
			Cockfield Formation			
Sh:V-108	289	23.46	28.68	26.07	263	258
Sh:V-110	320	36.69	38.63	37.66	282	283
Sh:V-111	321	34.90	35.80	35.35	286	284

the hydraulic conductivity of the model cells in layer 1 at and proximate to the erosional scarp at NSA Memphis. The relatively low hydraulic conductivity at the scarp produces a "hydraulic dam" causing higher ground-water levels in the upgradient area. A relatively low hydraulic conductivity for the alluvial-fluvial deposits in the area of the erosional scarp could be the result of a large fraction of fine sediments eroded off the tread and deposited in the scarp.

The transmissivity array for model layer 2 (fig. 20) was calculated by multiplying an assumed horizontal hydraulic conductivity of 2.8 ft/d for the Cockfield aquifer by the corresponding thickness for that unit in each model cell of layer 2. The values representing the thickness of the Cockfield aquifer were adjusted during calibration because both the horizontal hydraulic conductivity and the thickness of the sand units were estimated from comparatively few data. Within the NSA Memphis boundary, final values for the transmissivity array of layer 2 were determined with the parameter-estimation program. Some additional modifications to the values generated by the parameter-estimation program were made to more closely match observed ground-water levels in areas not within the NSA Memphis boundary.

The major surface-water drains within the modeled area (fig. 3) were simulated with the MODFLOW river package (fig. 17). Surface-water stage was fixed at 1 foot above the elevation of the creek bottoms. Elevations of creek bottoms were taken from survey data presented in an urban flood-control study performed by the U.S. Army Corps of Engineers (1989a, b). Riverbed hydraulic conductance was estimated using the vertical hydraulic conductivity of the upper part of the alluvium (table 2) and the dimensions of the model cell for the river node (fig. 34, McDonald and Harbaugh, 1988).

Calibration Approach

Calibration is the attempt to reduce the difference between model results and measured data by

Table 7. Input parameters for the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee

Parameter	Model Layer	Adjusted Value	Source
Natural recharge, in inches per year.		0.32	Estimated during model calibration with parameter-estimation program.
Anthropogenic recharge, in inches per year.		0.67 - 1.8	Estimated during model calibration with parameter-estimation program.
Altitude of starting heads, in feet.	Layer 3	184 - 229	Estimated using September 1995 potentiometric map of Memphis aquifer (Kingsbury, 1996).
Transmissivity, in feet squared per day.	Layer 1: Southwest of erosional scarp.	53 - 371	Estimated using horizontal hydraulic conductivity of alluvial-fluvial deposits aquifer determined by August 1995 aquifer test and thickness of alluvial-fluvial deposits.
	Northeast of erosional scarp.	53 - 265	Estimated using horizontal hydraulic conductivity of upper sand units of Cockfield Formation determined by specific-capacity tests and thickness of those units in stratigraphic test holes.
	Area of erosional scarp.	2	Estimated during model calibration.
	Layer 2	28 - 300	Estimated during model calibration with parameter-estimation program.
	Layer 3	Not applicable	The transmissivity is irrelevant because layer 3 is a specified head boundary.
Vertical conductance between layers, in feet per day per foot.	Layer 1: Buried river valleys.	4×10^{-4}	Estimated during model calibration.
	Fault	4.9×10^{-5}	Estimated during model calibration with parameter-estimation program.
	Elsewhere	1×10^{-7}	Calculated using vertical hydraulic conductivity of sediment cores and unit thickness with equation 53 (McDonald and Harbaugh, 1988).
	Layer 2: Fault	4.9×10^{-4} to 4.9×10^{-3}	Estimated during model calibration with parameter-estimation program.
	Window in confining unit	8.8×10^{-5}	Estimated during model calibration with parameter-estimation program.
	Elsewhere	1×10^{-6}	Calculated using vertical hydraulic conductivity of sediment cores and unit thickness with equation 53 (McDonald and Harbaugh, 1988).

adjusting model input. Calibration is accomplished by adjusting input values until an acceptable calibration criterion is achieved. Improvement in the calibration of a model is based on the differences between simulated and measured ground-water levels and flow rates. Simulated water levels from a calibrated, deterministic ground-water model usually depart from measured water levels, even after substantial calibration has been accomplished. The discrepancy between model results and measurements (model error) usually is caused by the heterogeneity of aquifers and confining units, and the difficulty in obtaining sufficient measurements to account for the corresponding spatial variation in hydraulic characteristics within the model area.

Some stresses must be known to calibrate a model if both recharge rates and hydraulic conductivity are being adjusted. The shallow ground-water system at NSA Memphis is believed to have only limited connection to the surface-water system; therefore, discharge measurements of streams could not be used to estimate ground-water discharge to the surface-water system. Such data would have provided an independent estimate of recharge rates. To constrain the

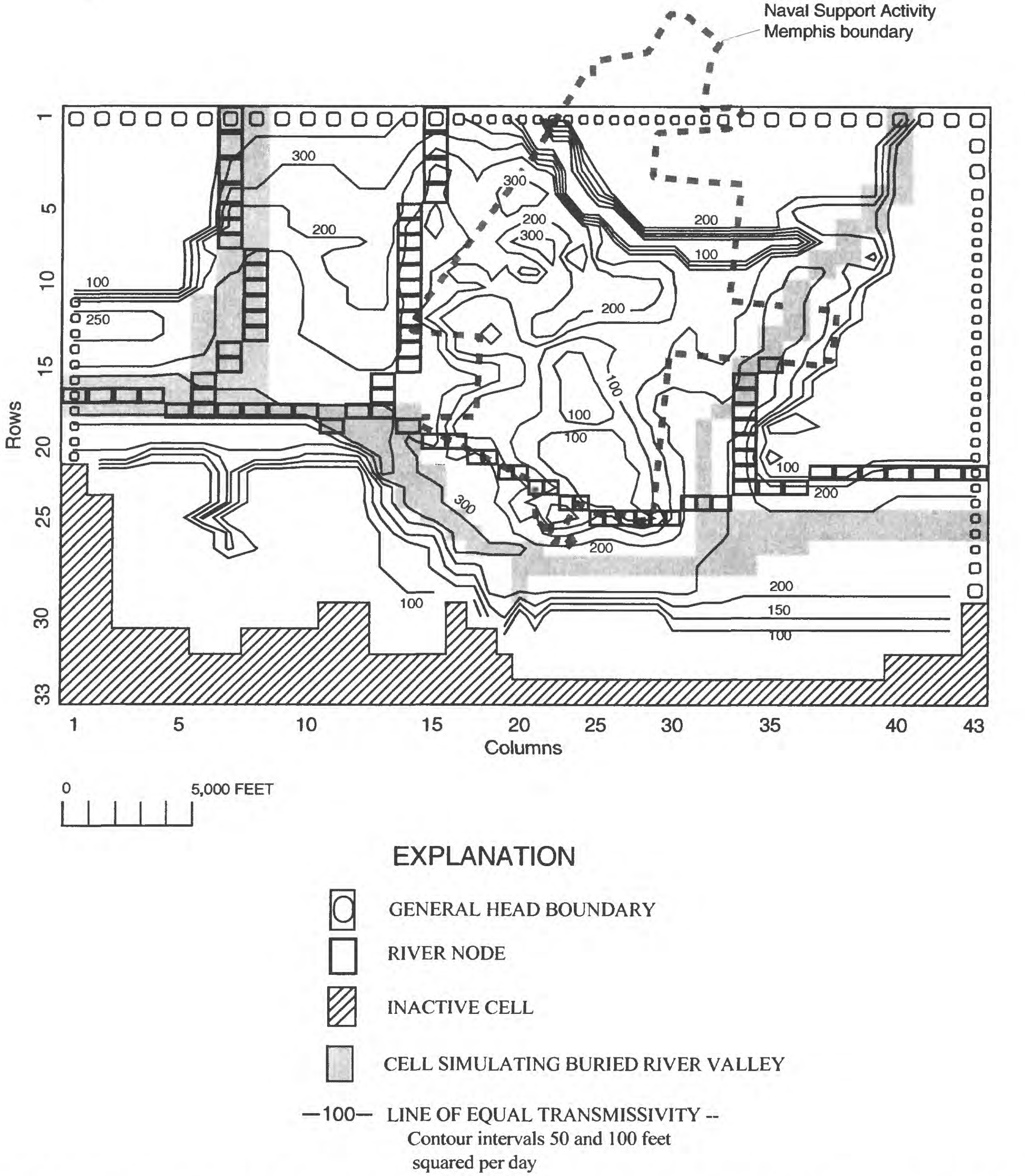


Figure 19. Transmissivity array for layer 1 of the calibrated flow model and locations of cells simulating buried river valleys in the area of Naval Support Activity Memphis, Millington, Tennessee.

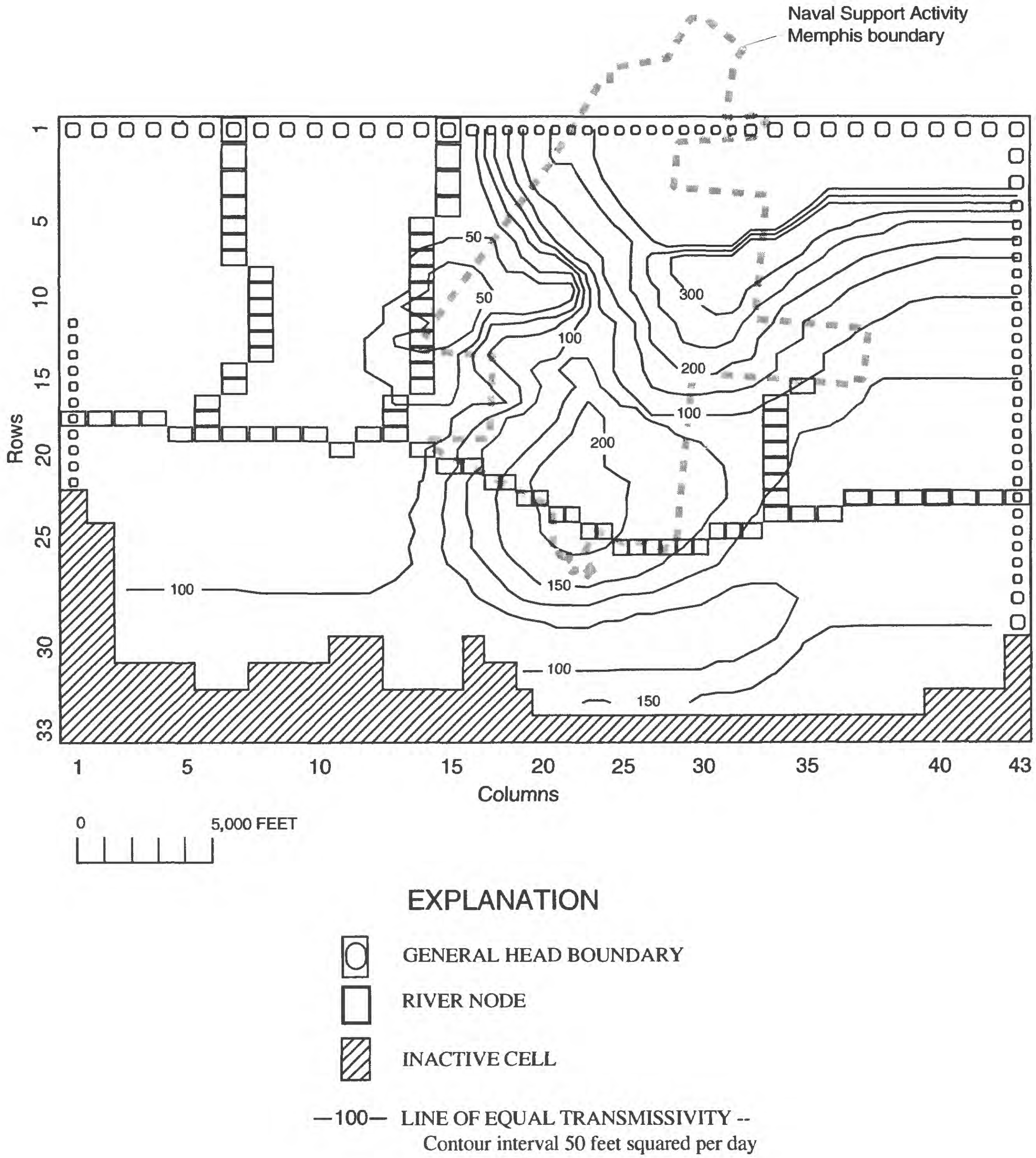


Figure 20. Transmissivity array for layer 2 of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee.

simulation, the USGS aquifer test was assumed to provide a representative hydraulic conductivity for the A1 aquifer and this value was held constant during calibration. The model was calibrated by adjusting recharge rates to layer 1 and the vertical conductance arrays used to control vertical flow between model layers. Calibration improvement was determined by decreases in sum-of-squares error (SSE) that is defined by:

$$SSE = \sum_{k=1}^{nwl} \left(\hat{h}_k - h_k \right)^2 , \quad (1)$$

where

$\hat{h}_k$ is the k[th] simulated water level, in feet;

h_k is the k[th] measured water level, in feet; and

nwl is the number of water-level comparisons.

The root mean square error (RMSE) is reported instead because the RMSE is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set. RMSE is related to the SSE by:

$$RMSE = \sqrt{\frac{SSE}{nwl}} . \quad (2)$$

The ground-water-flow model for this study was calibrated to ground-water levels determined during two synoptic surveys.The calibration criteria selected for the numerical model of the shallow aquifer system at NSA Memphis was a maximum difference of 3 feet between simulated and mean water levels calculated for the A1 aquifer. This criteria was selected because the water levels generated by the calibrated model would then fall within the measured seasonal variation of the shallow aquifer system.

Parameter Estimation

Model calibration was facilitated using parameter estimation (Halford, 1992). The parameter-estimation process begins by using the model to establish the initial differences between simulated and mean groundwater levels. These differences, or residuals, are minimized by the parameter-estimation program. The sensitivity coefficients, the derivatives of simulated water-level change with respect to parameter change, were calculated by the influence coefficient method (Yeh, 1986) using the initial model results. This method required changing each parameter a small amount and using MODFLOW to compute new water levels. A quasi-Newton procedure (Gill and others, 1981) was used to compute new values of the parameters that should improve the model. The model was updated to reflect the latest parameter estimates, and a new set of residuals was calculated. The entire process of changing a parameter in the model, calculating new residuals, and computing a new value for the parameter was continued iteratively until model error or model-error change was reduced to a specified level or until a specified number of iterations were made.

Logs of the parameters, *log*(x), were estimated because the hydraulic conductivities are usually log-normally distributed (Domenico and Schwartz, 1990). Log parameters are better behaved from a numerical perspective because estimates are restricted to positive values and are scaled to some degree. Consequently, all sensitivities, covariances, and correlation coefficients are based on

$$\frac{\partial}{\partial \log x} \hat{h} .$$

The computation of a covariance matrix is another benefit from this type of analysis. This matrix is ranked by the magnitude of the main diagonal because it is a rough indicator of the relative sensitivity of the model to a parameter. Specifically, the main diagonal is

$$C_{i,i} = \sum_{k=1}^{nwl} \frac{\partial \hat{h}_k}{\partial \log x_i}^2 .$$

The off-diagonal components, $C_{i,j}$, describe the degree of interdependence between parameters, but evaluation is difficult without some sort of normalization (Gill and others, 1981).

Normalization is achieved by computing correlation coefficients (Hill, 1992),

$$\rho_{i,j} = \frac{C_{i,j}}{\sqrt{C_{i,i} C_{j,j}}} ,$$

similar to the coefficient computed for a linear regression. If $\rho_{i,j}$ is ± 1, then x_i is a dependent variable of x_j. Alternatively, if $\rho_{i,j}$ is 0, then x_i is an independent variable of x_j. Correlation coefficients greater than 0.95 usually indicate that a pair of parameters are highly correlated and cannot be estimated independently (Hill, 1992).

Seven parameters (table 8) were used as multipliers that changed the value of either hydraulic conductivity, vertical conductance, or recharge by a fixed amount for specified zones within the model grid. The initial values of horizontal hydraulic conductivity came from the results of the aquifer and specific-capacity tests (table 3), and initial values for the vertical hydraulic conductivity of confining units were estimated from analyses of sediment-core samples (table 2). Water levels at 38 wells within the NSA Memphis boundary were selected as control points for the parameter-estimation program. The RMSE of the model after the parameter-estimation program had run was 2.25 feet. Many of the parameters were highly correlated, but not to a degree that prevented independent estimation (table 8).

Steady-State Calibration

The calibrated steady-state model minimized residuals between simulated water levels and mean ground-water levels calculated from measurements made during the two synoptic water-level measurement surveys of April and October 1996 (table 4). Water levels at 42 wells were selected as calibration control points (table 6). RMSE of the final calibrated model was 1.82 feet. A comparison of simulated to mean water levels was made (fig. 21). Simulated water levels at two wells exceeded the calibration criteria of a residual equal to 3 feet or less; however, these locations were not within the perimeter of NSA Memphis. The model error could be reduced by using a variable background recharge rate, but the application of variable rates could not be supported by data or reasonable inference based on data. The simulated potentiometric surface for layer 1 of the calibrated flow model is shown in figure 22.

Analysis of Model Water Budget

The simulated water budget of the shallow aquifer system was analyzed to determine if the indicated sources and sinks of water (table 9) were consistent with the conceptual hydrogeologic model. The model water budget describes a ground-water-flow system with a pronounced downward component of flow. Seventy-five percent of the water entering the model is derived from recharge to model cells. Horizontal flow boundaries supply only about 23 percent of the water, and leakage from surface-water drainages supplies only about 2 percent. Specified head cells simulating the Memphis aquifer are points of discharge for 79 percent of the water from the simulated shallow aquifer system. Simulated discharge to general head boundaries accounts for only 14 percent of the water, and simulated discharge to surface-water drainages accounts for 7 percent.

The distribution of water simulated by the flow model is consistent with the proposed concept of flow in the shallow aquifer system at NSA Memphis. The

Table 8. Jacobian correlation coefficients between model parameters for the flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee

Estimated parameter	Correlation coefficients						
	Well	Rech	Vflt	K2	Vwin	Kero	Vriv
Induced recharge (Well)	1.00						
Recharge (Rech)	0.84	1.00					
Vertical conductance of fault (Vflt)	-0.90	-0.076	1.00				
Hydraulic conductivity of layer 2 (K2)	-0.80	-0.90	0.70	1.00			
Vertical conductance of window in Cook Mountain confining unit (Vwin).	-0.54	-0.56	0.46	0.45	1.00		
Hydraulic conductivity of layer 1 in area of erosional scarp (Kero).	0.01	-0.26	0.06	0.16	-0.01	1.00	
Vertical conductance beneath buried river valleys (Vriv).	-0.78	-0.84	0.76	0.90	0.69	0.20	1.00
Normalized main diagonal $\sqrt{\frac{C_{i,i}}{C_{1,1}}}$	1.00	0.34	0.12	0.05	0.01	0.006	0.0003

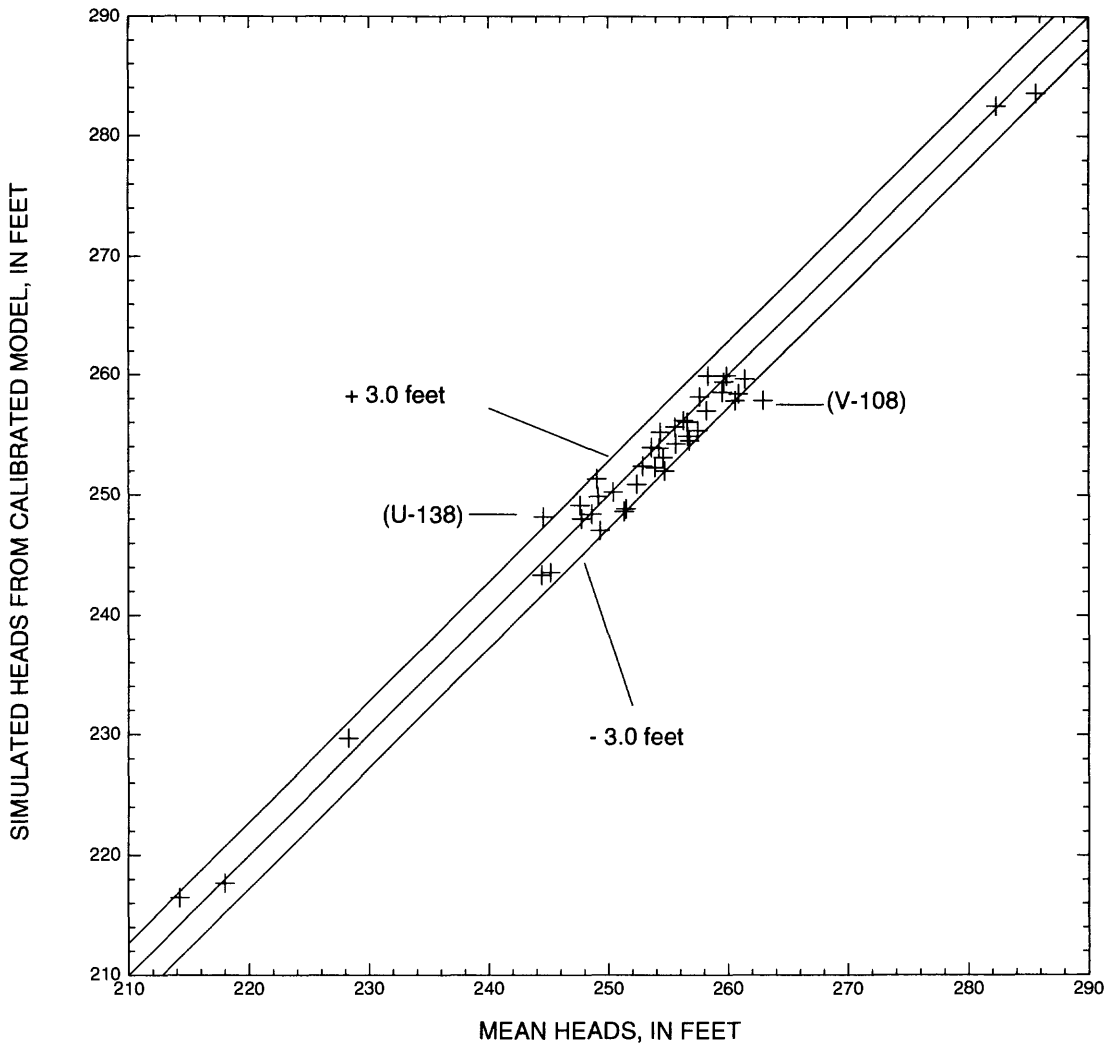


Figure 21. Simulated water levels generated by the calibrated flow model and mean water levels in the alluvial-fluvial deposits aquifer in the area of Naval Support Activity Memphis, Millington, Tennessee.

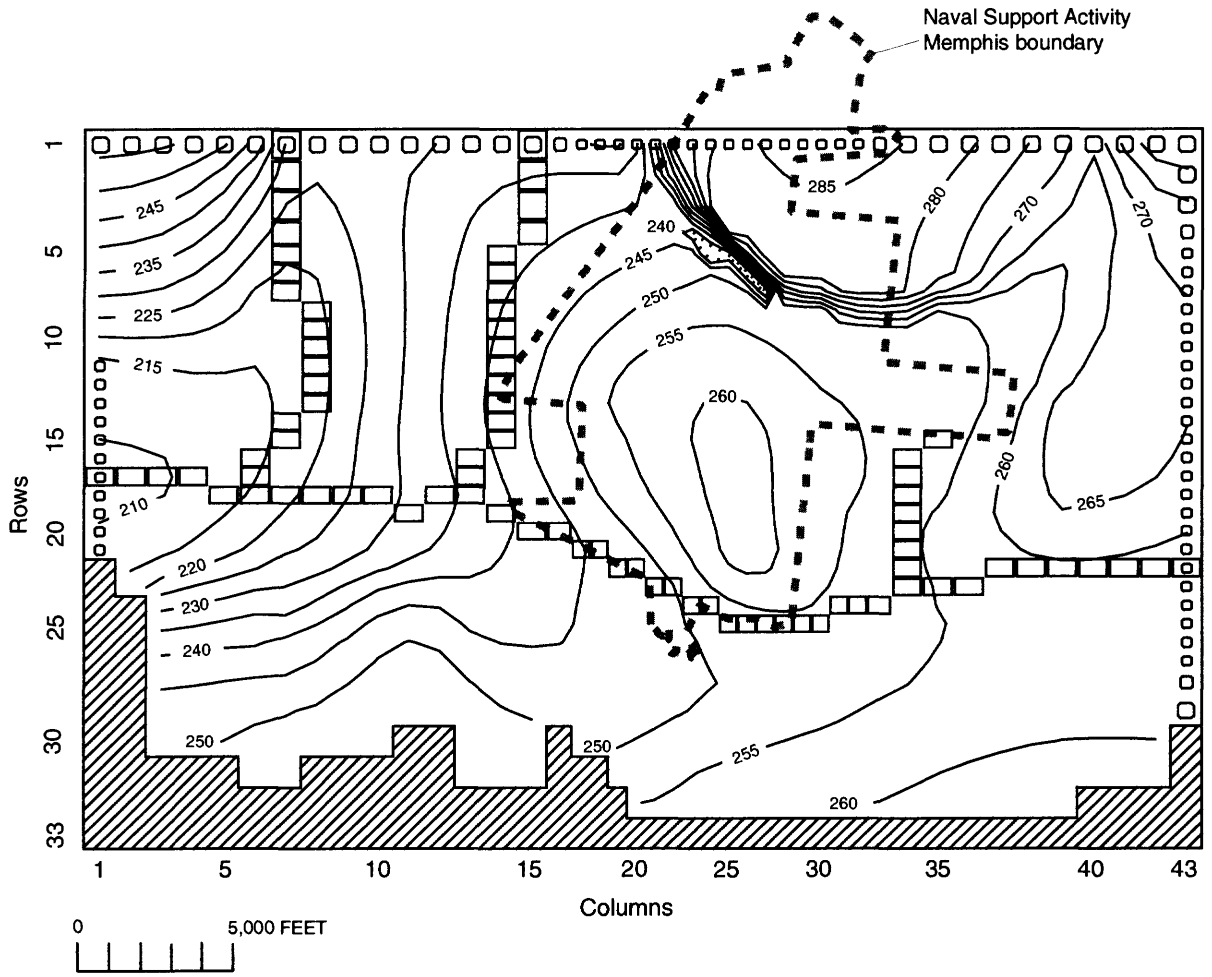
hydraulic connection between the ground-water and surface-water systems probably is limited; therefore, the volume of water passing between the two systems should be relatively small. The hydraulic conductivities of the A1 and Cockfield aquifers are relatively low, and a downward hydraulic gradient exists between the shallow aquifer system and the Memphis aquifer. Under such conditions, ground-water-flow directions should be predominantly downward, and the flow path of water moving laterally through the shallow aquifer system would be relatively short prior to drainage to the Memphis aquifer.

Sensitivity Analysis

The sensitivity of the model to nine input parameters or boundary conditions was evaluated. Each parameter was varied independently by a factor of either one-half or two to determine the sensitivity of the model to individual parameters. Model sensitivity was described in terms of RMSE using the difference between the simulated and calculated mean ground-water levels for layer 1 (table 10). The model was determined to be most sensitive to changes in the anthropogenic recharge, the transmissivity of layer 1, and the natural recharge rate. The model displays an intermediate degree of sensitivity to changes in the vertical conductance rates between layers, the transmissivity of layer 2, and riverbed conductance; and is relatively insensitive to changes in the boundary conditions.

Limitations of Model Analysis

The numerical model constructed for this study is a simplified mathematical approximation of the



EXPLANATION

GENERAL HEAD BOUNDARY

RIVER NODE

INACTIVE CELL

—260— POTENTIOMETRIC CONTOUR -- Shows altitude of water level in layer 1 generated by model. Hachures indicate depression. Datum is sea level. Contour interval 5 feet

Figure 22. Altitude of the simulated potentiometric surface of layer 1 of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee.

Table 9. Water budget simulated by the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee

[Ft^3/d, cubic feet per day]

	Ft^3/d (x1,000)	Percent
INFLOW		
Specified head (Memphis aquifer)	0	0
Recharge	78	75
River leakage	2	2
Head dependent boundaries	24	23
Total	104	100
OUTFLOW		
Specified head (Memphis aquifer)	82	79
River leakage	7	7
Head dependent boundaries	15	14
Total	104	100

conceptual model of the ground-water-flow system at and near NSA Memphis. The conceptual model is, in turn, a simplified approximation of the ground-water-flow system. A numerical model will not provide accurate predictions on a scale finer than the grid resolution used to build the model. The model is valid only for the finite area where the hydrogeology has been defined. The model may not provide accurate simulation results if natural conditions in the ground-water system change from those to which the model was calibrated, or if assumptions upon which the model was based prove false. The spatial variation of aquifer characteristics is usually unknown or poorly defined, and uniform properties are commonly assumed by default. The aquifers simulated in this study were assumed to be isotropic and, within identified hydrogeologic units, homogeneous at the simulation scale.

The horizontal ground-water gradient in a confined porous media is depicted graphically in two dimensions by potentiometric maps (figs. 9 and 10 for the A1 aquifer). Comparison of figures 9 and 10 to figure 22 and inspection of figure 21 and table 6 show that the model adequately simulates the ground-water gradient in the A1 aquifer at NSA Memphis. However, no water-level measurements were available for the Cockfield aquifer within the modeled area at NSA Memphis because no wells exist in this zone; therefore, determination of whether or not the model accurately simulates the potentiometric surface of the Cockfield aquifer is not possible.

The results of model sensitivity analyses indicate that the model is relatively insensitive to the lateral boundary conditions (table 10). Most of the water moving through the model enters and exits a vertical boundary (table 9). For this reason only moderate confidence can be placed in the accuracy of the lateral boundaries. The model also is insensitive to changes in the conductance values of the river nodes. The volume of water moving between the surface-water and ground-water systems at NSA Memphis is probably relatively small because the two systems are generally not in direct hydraulic connection. Under these conditions, the model may not accurately quantify the volume of water exchanged between the surface-water and ground-water systems.

The most serious limitation of the model analysis is the lack of an independent check of the simulated water budget. A brief discussion of Darcy's Law can be used to illustrate the problems that result from this situation. Darcy's Law (3) is expressed here as:

$$Q = -KA\, dh/ds, \qquad (3)$$

where

Q is the volumetric flow, in cubic feet per day;

K is the hydraulic conductivity of the porous flow medium, in feet per day;

A is the cross-sectional area of flow, in square feet;

ds is the horizontal distance of flow, in feet; and

dh is the difference in fluid potential, in feet over ds.

Table 10. Results of sensitivity analyses of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee

Parameter tested	Change in parameter	Number of wells with residual error greater than 3 feet	Root mean square error
Calibrated model		2	1.82
Induced recharge rate	x 0.5	37	10.46
	x 2.0	38	14.87
Transmissivity of layer 1.	x 0.5	30	8.99
	x 2.0	33	6.78
Natural recharge rate	x 0.5	36	5.50
	x 2.0	40	8.19
Vertical conductance of layer 1.	x 0.5	19	3.29
	x 2.0	24	4.34
Vertical conductance of layer 2.	x 0.5	17	3.23
	x 2.0	31	4.51
Transmissivity of layer 2.	x 0.5	5	2.13
	x 2.0	20	3.64
Riverbed conductance	x 0.5	5	2.12
	x 2.0	12	2.72
General head boundary conductance terms.	x 0.5	5	2.37
	x 2.0	5	2.15
Specified head boundaries instead of general head boundaries.		5	2.32

A rearrangement of Darcy's Law shows that the ground-water gradient (dh/ds) for any defined flow section is proportional to the ratio of Q/-KA:

$$Q/\text{-}KA = dh/ds. \quad (4)$$

The model closely simulates the ground-water gradient in the A1 aquifer at NSA Memphis. However, because no measurement of Q is available as an independent check, Q or K cannot be independently quantified. Thus, the model could generate the same potentiometric surface for layer 1, simulating the potentiometric surface of the A1 aquifer using a variety of flow rates (Q) and lateral hydraulic conductivities (K), as long as the ratio of Q/K in the model remained the same. The model solution is not unique because many combinations of parameters exist that will result in the same solution.

The significance of the above limitation is illustrated when the equation for the average linear velocity of ground-water flow in a porous flow medium is examined (modified from eq. 2.82, p. 71, Freeze and Cherry, 1979):

$$v = Q/nA = K/n\ (dh/ds), \quad (5)$$

where
v is the average linear velocity, in feet per day;
Q is the volumetric flow, in cubic feet per day;
n is the effective porosity of the flow media, in percent;
A is the cross-sectional area of flow, in square feet;
K is the hydraulic conductivity of the porous flow medium, in feet per day;
ds is the horizontal distance of flow, in feet; and
dh is the difference in fluid potential, in feet.

Inspection of equation 5 shows that the average linear velocity is directly proportional to Q and K, and inversely proportional to n and A. Doubling or halving Q and K would double or halve the average linear velocity. This relation between ground-water-flow velocity, Q, and K reduces the confidence that can be placed in the estimated time-of-travel for ground water simulated by the particle-tracking analyses; however, the simulated direction of ground-water flow is not affected.

SIMULATION OF GROUND-WATER FLOW AND TRAVEL TIME WITH ADVECTIVE FLOW PARTICLE-TRACKING PROGRAM

The particle-tracking program MODPATH (Pollock, 1989, 1994) was used to simulate ground-water-flow directions and times-of-travel at NSA Memphis. The objective of the particle-tracking analysis was to characterize and illustrate ground-water flow in the shallow aquifer system at NSA Memphis and to simulate the advective transport of contaminants in the ground-water system. The analysis of ground-water flow and potential movement of contaminants within the shallow aquifer system was addressed using the calibrated model driven by the long-term average (calibrated) recharge rate. Ground-water-flow paths and time-of-travel within the A1 aquifer were simulated at two sites within the Northside area and at SWMU 2 in the Southside area.

The MODPATH program computes particle locations and travel times in three dimensions based on advective flow in a uniformly porous medium. MODPATH can track particles forward in time and space in the direction of ground-water flow, or backward toward recharge areas. Physical, chemical, and biological processes that attenuate chemical constituents in ground water are not considered, and the dissolved contaminant is assumed to not appreciably alter the density of the ground water. MODPATH cannot be used to predict solute concentrations.

The cell-by-cell flow terms from the calibrated steady-state MODFLOW model were used as input to MODPATH. Ground-water travel time in the shallow aquifer system was simulated using a uniform value of effective porosity for each hydrogeologic unit represented in the model. Equation 5 introduced in the preceding discussion quantifies the relation between ground-water-flow velocity, the volume of water moving through the model, and effective porosity of the porous media. The porosity values reported for core samples of the hydrogeologic units at NSA Memphis are total porosity. For coarse-grained, unconsolidated sediments, such as those forming the A1 aquifer, effective porosity will approach the total porosity, but the effective porosity will be somewhat less.

A particle-tracking analysis of ground-water flow in the shallow aquifer system at NSA Memphis was performed for each of three scenarios: (1) effective porosity was assumed to approximate the total porosity values reported for core samples of the hydrogeologic units, (2) minimum effective porosity was used based on reported values in the literature for the type of sediments present at NSA Memphis (Freeze and Cherry, 1979), and (3) intermediate porosity values were used between these endpoints. The residence time of water within the A1 aquifer was simulated by seeding one particle on the lower faces of each active cell of layer 1 and performing a backward-tracking analysis. For effective porosity values ranging from 20 to 33 percent, typical ground-water-flow velocities ranged from about 15 to 25 ft/yr, and average residence times ranged from about 645 to 1,000 years. The variability in the results of particle-tracking analyses (table 11), theoretically, should encompass the range of potential ground-water travel times at NSA Memphis.

Ground-water-flow directions in the A1 aquifer were simulated by seeding the upper faces of layer 1 cells and performing a forward-tracking analysis. Most of the particles traveled for relatively short distances in layer 1 before they were either "captured" by a river node, entered a deeper layer, or exited the model through one of the boundary cells (fig. 23). Most of the ground water (79 percent) moves vertically through the model. The highest rates of vertical movement are within the western half of the study area where a window in the Cook Mountain confining unit was simulated, and under the hypothesized buried river valleys where a window in the Cockfield confining unit was simulated. Vertical flow is also accelerated in the area of the simulated fault, but because the fault is a long narrow feature, a smaller area is affected compared to the windows in the confining units and less water is transmitted than through the windows.

Intermediate porosity values (table 11) were used for particle-tracking analyses of contaminant migration at NSA Memphis. Ground-water-flow paths and times-of-travel within the A1 aquifer were simulated at three sites: (1) the former N-6 hangar area and (2) the grassy area near SWMU 7, both within the Northside AOC; and (3) at SWMU 2 (fig. 24). The

Table 11. Results of particle-tracking simulation of ground-water travel time at Naval Support Activity Memphis, Millington, Tennessee
[~, approximately]

Parameter	Porosity value, in percent Time-of-travel, in years		
	Total	**Intermediate**	**Minimum**
Porosity:			
Layer 1 porosity	33	25	20
Confining unit 1	48	40	30
Layer 2 porosity	30	25	20
Confining unit 2	36	33	30
Average residence time in layer 1	~1,000 yrs	~800 yrs	~645 yrs
Average time-of-travel to:			
Layer 3 from the former N-6 hangar area	~350 yrs	~280 yrs	~225 yrs
Layer 3 from grassy area near SWMU 7	~490 yrs	~380 yrs	~300 yrs
Discharge to river node from SWMU 2	~30 yrs	~26 yrs	~20 yrs

contaminants detected within the A1 aquifer are estimated to first have been used about 40 years ago in the mid- to late 1950's. The advective transport of contaminants in the A1 aquifer was simulated by seeding the upper face of the appropriate cell(s) in layer 1 and using forward-tracking analyses. This approach simulates the introduction of contaminants into the A1 aquifer through leakage from the overlying loess or alluvium and subsequent advective transport within the aquifer. Particle locations were plotted after 40 years of travel, simulating a worst case scenario in which the contaminant entered the aquifer as soon as the contaminant began to be used. For simplicity, the assumption was also made that a single release of contaminants occurred.

The location of suspected plumes of contaminants were noted within the Northside AOC (fig. 25). Particle-tracking analyses of the former N-6 hangar area (fig. 26) indicate that ground water moves north-northwest from the suspected source area for about 4,000 feet, and then flows vertically downward along the simulated fault towards layer 3. The average time-of-travel to layer 3, the simulated Memphis aquifer, was about 280 years (table 11). The simulated flow path and travel distance after 40 years compares favorably with the identified extent of migration of the hypothesized plumes (fig. 26).

Particle-tracking analyses of the grassy area near SWMU 7 (fig. 26) indicate that ground water moves north-northwest from the suspected source area until it enters the area-of-influence of the simulated fault and moves downward towards layer 3. The average time-of-travel to layer 3 was about 380 years (table 11). The simulated flow path and travel distance after 40 years also compares favorably with the identified extent of migration of the hypothesized plumes (fig. 26).

The close agreement between the estimated locations of the hypothesized contaminant plumes and the distance traveled in 40 years predicted by the particle-tracking analyses for the two sites within the Northside AOC indicates that the estimates of hydraulic conductivity and effective porosity of the A1 aquifer are reasonably accurate for these areas. Based on the results of particle-tracking analyses, the potential for contaminants to reach the Memphis aquifer in the next 100 years is negligible.

Particle-tracking analyses of the SWMU 2 area (fig. 27) indicate that ground water moves rapidly towards Big Creek Drainage Canal. Out of 40 particles tracked, 39 were removed from the model by river nodes, which simulates ground-water discharge from the A1 aquifer to Big Creek Drainage Canal. The average time-of-travel was about 26 years; however, at present, there is no map of the extent of contaminant migration at SWMU 2 to compare to particle-tracking simulations.

The calibrated flow model and the MODPATH program were not used to evaluate remedial designs at NSA Memphis. The results of the calibrated flow model and MODPATH analyses may simulate the

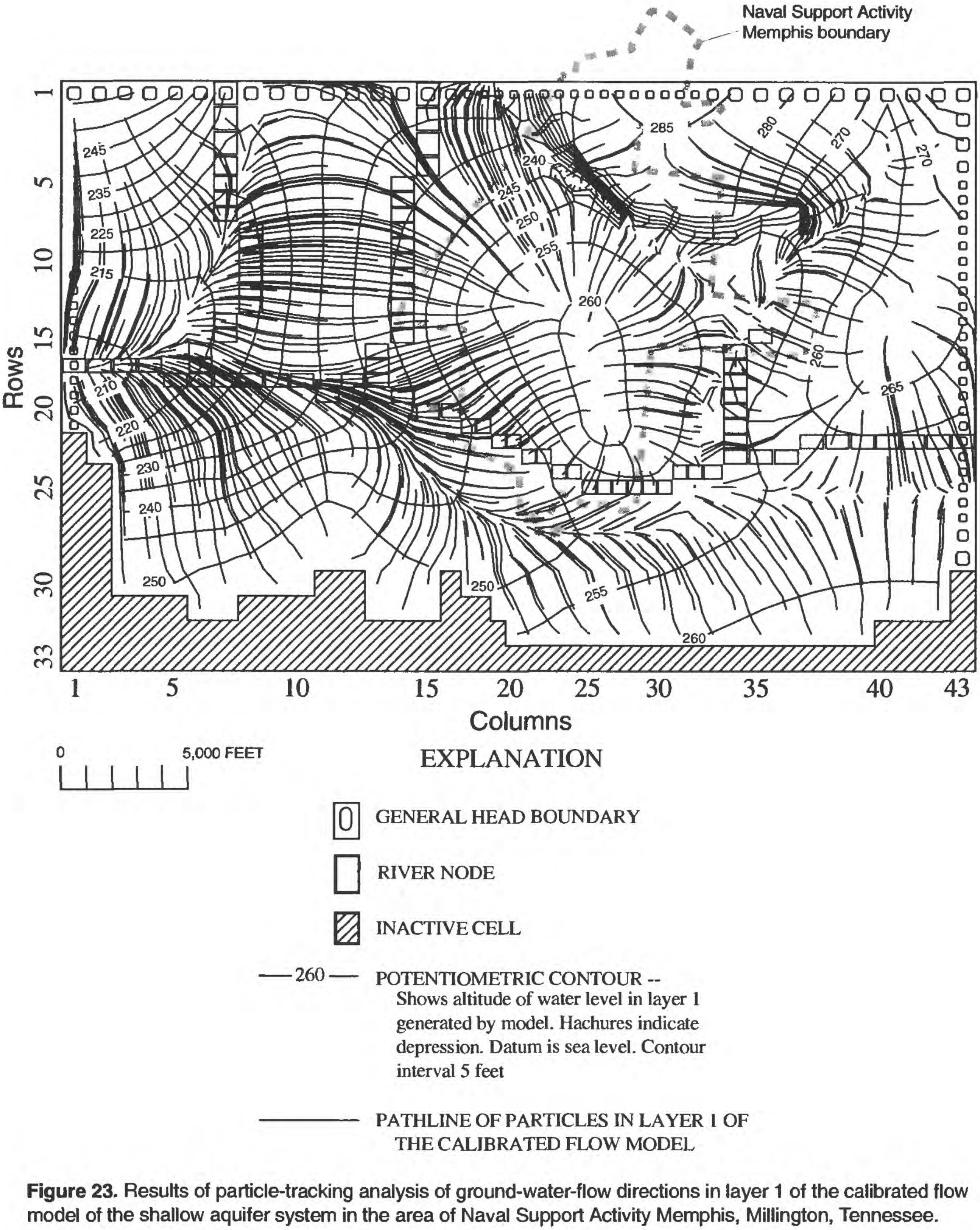
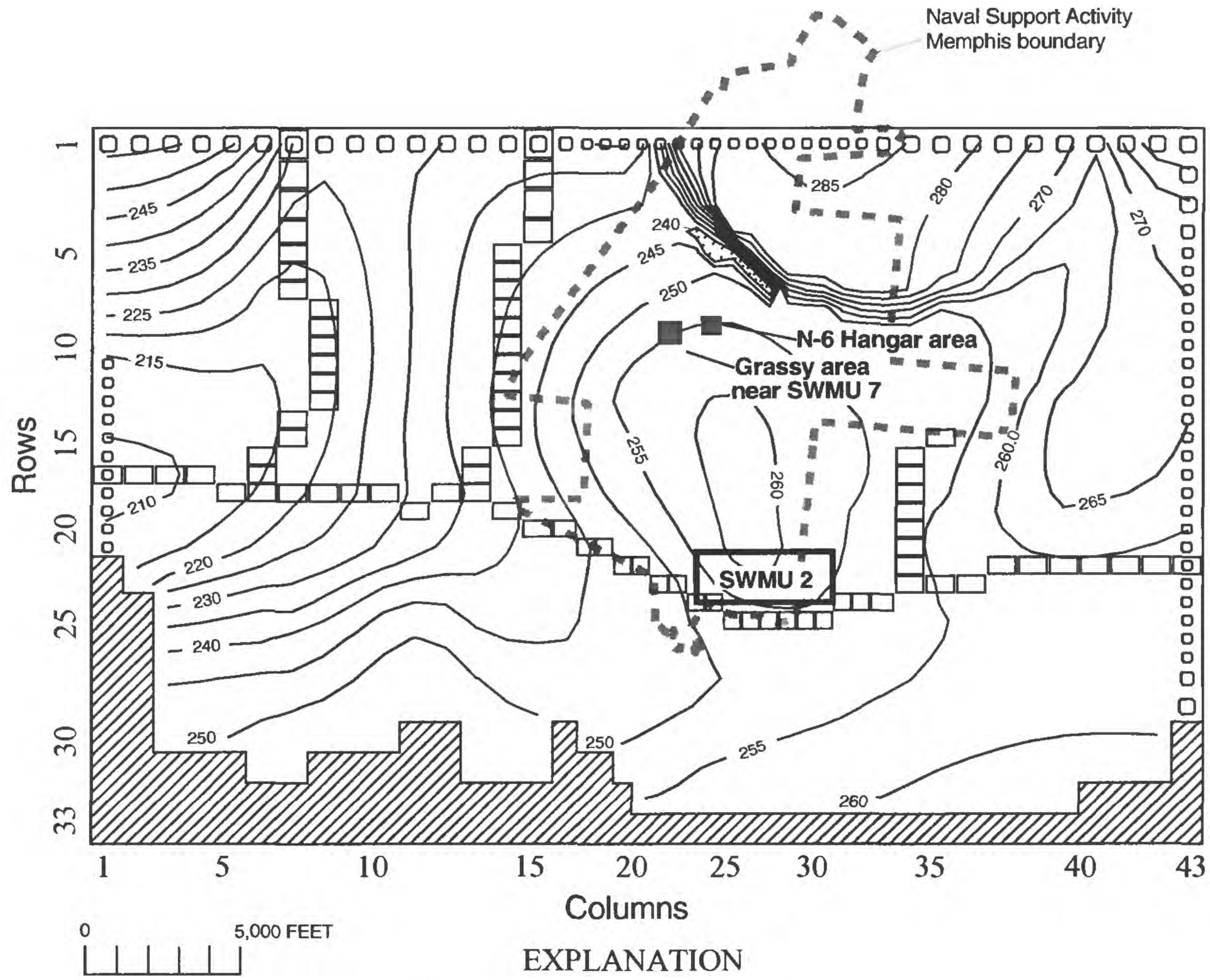


Figure 23. Results of particle-tracking analysis of ground-water-flow directions in layer 1 of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee.



EXPLANATION

GENERAL HEAD BOUNDARY

RIVER NODE

INACTIVE CELL

SOURCE AREA FOR HYPOTHESIZED PLUME OF CONTAMINATION

— 260 — POTENTIOMETRIC CONTOUR -- Shows altitude of water level in layer 1 generated by model. Hachures indicate depression. Datum is sea level. Contour interval 5 feet

Figure 24. Locations where particle-tracking analyses were performed for layer 1 of the calibrated flow model of the shallow aquifer system in the area of Naval Support Activity Memphis, Millington, Tennessee.

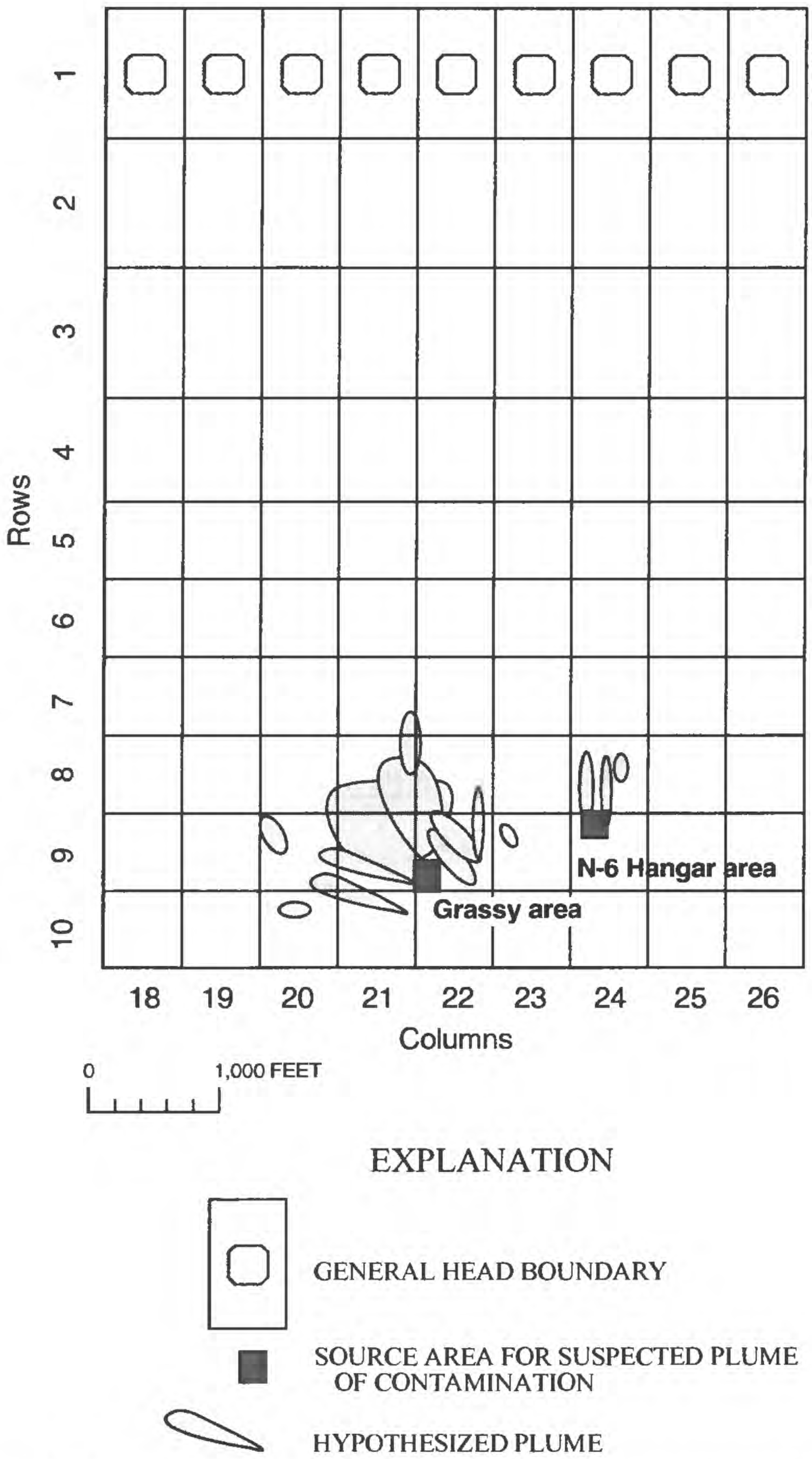
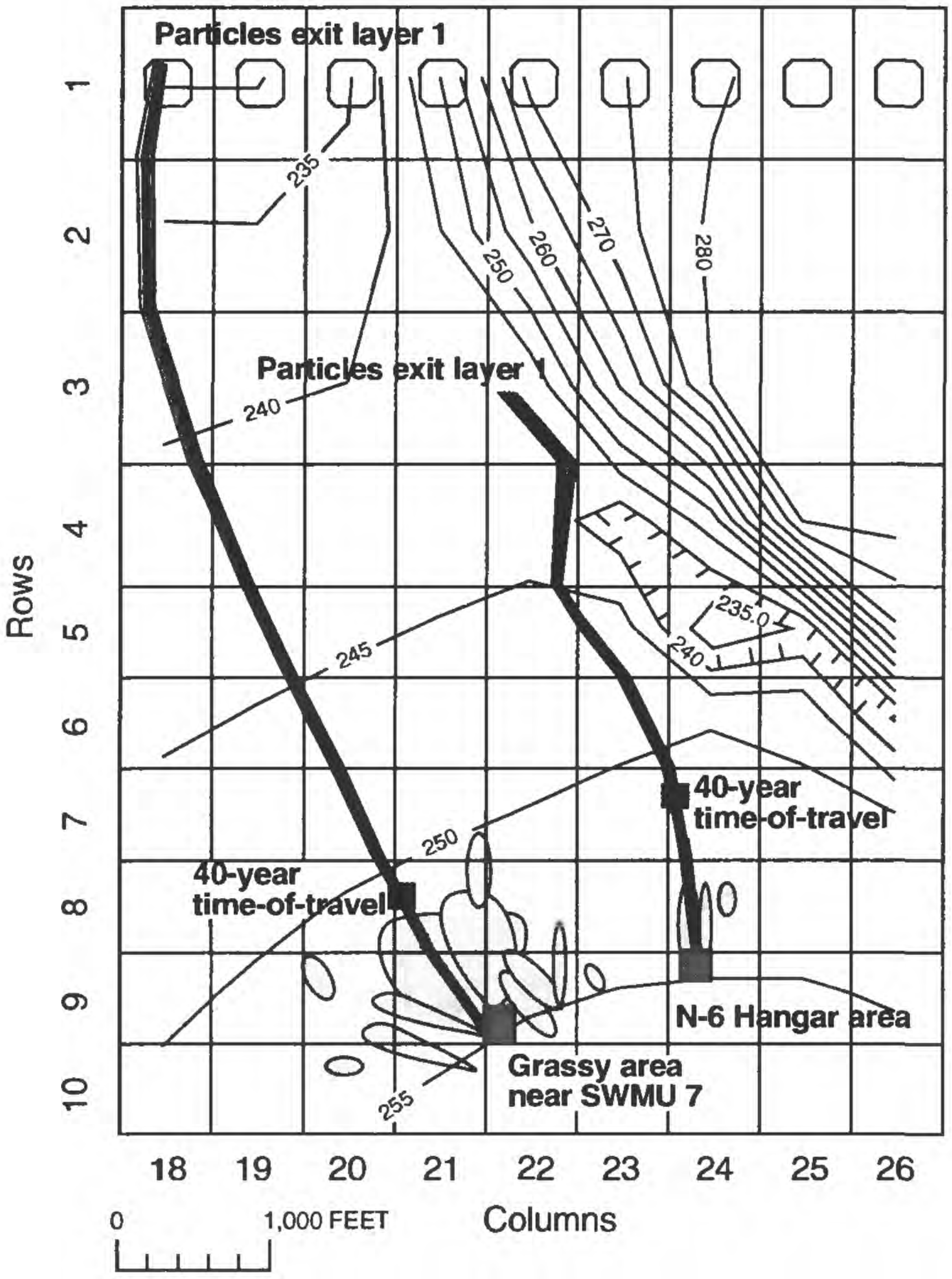


Figure 25. Locations of selected hypothesized plumes of contamination in the alluvial-fluvial deposits aquifer at two sites within the Northside Area of Concern at Naval Support Activity Memphis, Millington, Tennessee (Source: EnSafe, written commun., 1997).



EXPLANATION

GENERAL HEAD BOUNDARY

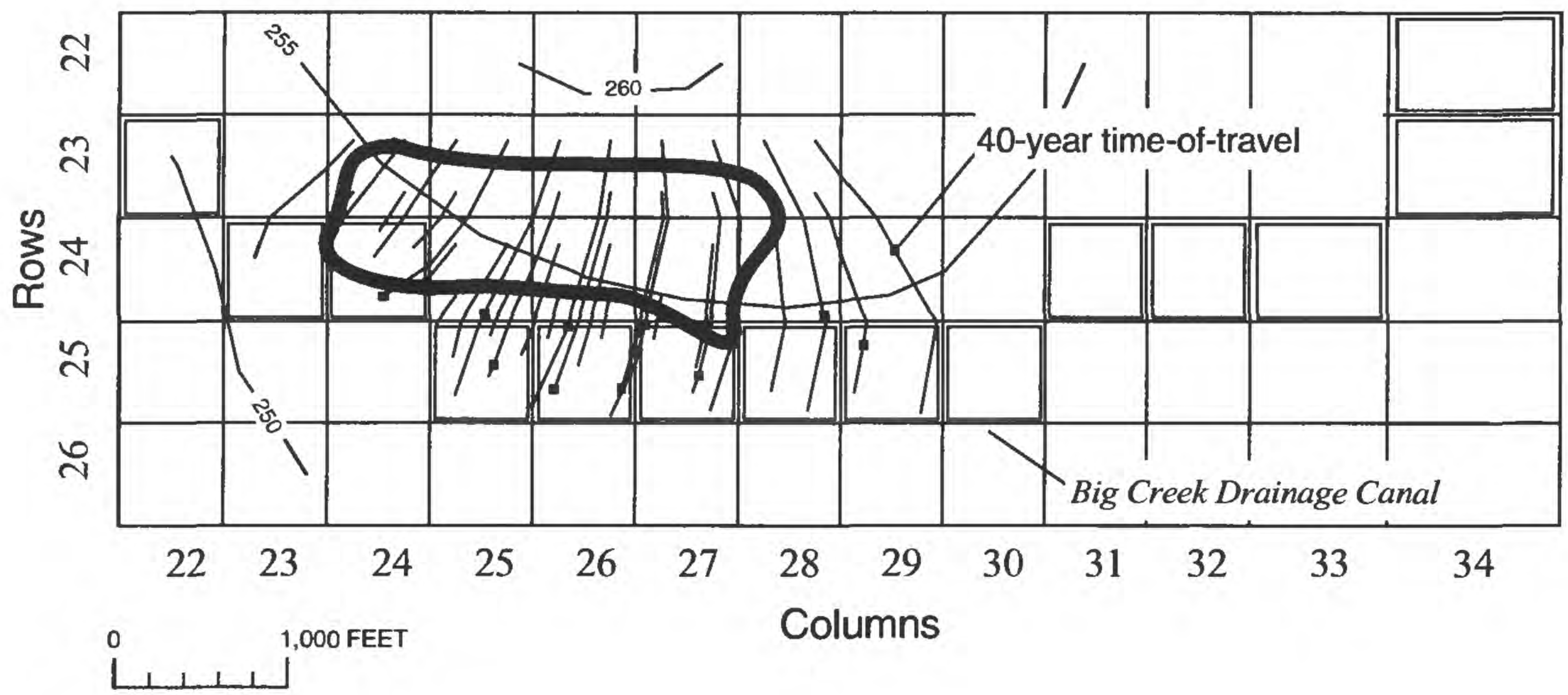
SOURCE AREA FOR SUSPECTED PLUME OF CONTAMINATION

HYPOTHESIZED PLUME

— 260 — POTENTIOMETRIC CONTOUR -- Shows altitude of water level in layer 1 generated by model. Hachures indicate depression. Datum is sea level. Contour interval 5 feet

PATHLINE OF PARTICLES IN LAYER 1 OF THE CALIBRATED FLOW MODEL

Figure 26. Results of particle-tracking analysis at the former N-6 hangar area and the grassy area near Solid Waste Management Unit (SWMU) 7, showing location of 40-year time-of-travel and pathlines of particles in layer 1 of the calibrated flow model of the shallow aquifer system at Naval Support Activity Memphis, Millington, Tennessee (Plumes from EnSafe, written commun., 1997).



EXPLANATION

APPROXIMATE LOCATION OF SWMU 2

— 260 — POTENTIOMETRIC CONTOUR -- Shows altitude of water level in layer 1 generated by model. Datum is sea level. Contour interval 5 feet

———— PATHLINE OF PARTICLES IN LAYER 1 OF THE CALIBRATED FLOW MODEL

RIVER CELL

Figure 27. Results of particle-tracking analysis at Solid Waste Management Unit (SWMU) 2, showing 40-year time-of-travel and pathlines of particles in layer 1 of the calibrated flow model of the shallow aquifer system at Naval Support Activity Memphis, Millington, Tennessee.

expected direction and extent of contaminant migration if no remedial actions are undertaken.

SUMMARY AND CONCLUSIONS

Naval Support Activity Memphis is a Department of the Navy facility located at Millington, Tennessee, in northern Shelby County. Past operations at NSA Memphis locally have contaminated the soil, ground water, and surface water. Sixty-seven Solid Waste Management Units (SWMU's) and one Area of Concern (AOC) have been identified at the facility. The SWMU's and AOC are under investigation as part of the Resource Conservation and Recovery Act (RCRA) Corrective Action Program. The Navy seeks to determine if contaminants in the shallow ground-water system may move in the subsurface or along nearby creeks to other parts of the facility or to off-base property. As part of the U.S. Department of Defense Installation Restoration Program, the Navy is considering remedial-action options to control the movement of contaminants at NSA Memphis. A numerical model of the ground-water-flow system at the site was constructed and calibrated so that quantifiable estimates of ground-water-flow rates, direction, and time-of-travel could be made.

The shallow aquifers in the NSA Memphis area are, in descending order, the alluvial-fluvial deposits aquifer and the Cockfield aquifer. Silt and clay in the upper alluvium and the loess overlie and confine the alluvial-fluvial deposits aquifer which is separated from the Cockfield aquifer by strata of low permeability in the upper part of the preserved section of the Cockfield Formation. Silt and clay of the Cook Mountain Formation comprise a confining unit and separate the Cockfield aquifer from the underlying Memphis aquifer. The Memphis aquifer is the principal aquifer used for water supply by NSA Memphis and the city of Memphis.

The vertical hydraulic conductivity of core samples of the alluvium-loess confining unit ranged from 8.5×10^{-5} to 1.6×10^{-2} ft/d. Total porosity of the samples ranged from 35 to 48 percent. The results of an aquifer test were used to estimate a horizontal hydraulic conductivity of about 5 ft/d for the alluvial-fluvial deposits aquifer. The total porosity of core samples of the alluvial-fluvial deposits aquifer ranged from about 22 to 39 percent. The vertical hydraulic conductivity of core samples of the Cockfield confining unit ranged from about 4.5×10^{-5} to 2.5×10^{-3} ft/d, and the total porosity ranged from about 41 to 55 percent. Well specific-capacity tests indicate that the horizontal hydraulic conductivity of sand units that comprise the Cockfield aquifer range from about 0.5 to 3 ft/d. The vertical hydraulic conductivity of core samples of the Cook Mountain confining unit ranged from about 5.0×10^{-6} to 9.9×10^{-4} ft/d, and the total porosity ranged from about 30 to 42 percent.

A conceptual hydrogeologic model of the ground-water-flow system was formulated based on the results of stratigraphic and structural correlations. In the conceptual hydrogeologic model, the shallow aquifer system is composed of five hydrogeologic units: (1) the alluvium-loess confining unit; (2) the A1 aquifer including the entire alluvial and fluvial deposits aquifer and sand lenses in the upper part of the Cockfield aquifer; (3) the Cockfield confining unit; (4) the Cockfield aquifer comprising sand lenses within the lower part of the Cockfield aquifer; and (5) a confining unit formed by sediments of low permeability within the Cook Mountain confining unit. Surface-water drainages at NSA Memphis may not be major discharge areas for the ground-water system. A comparison of streambed elevations of the major drainages in the NSA Memphis area to the potentiometric surface of the A1 aquifer indicates that the potentiometric surface of the aquifer is lower than streambed elevations, except for limited reaches of Big Creek Drainage Canal, Casper Creek, and North Fork Creek along the southern boundary of NSA Memphis and near SWMU 2. Structural and depositional features that affect the occurrence of ground water in the shallow aquifer system include faulting, an erosional scarp, and windows in the confining units. The Memphis aquifer underlies the shallow aquifer system.

A three-layer, quasi-three-dimensional, steady-state numerical model of the shallow aquifer system was constructed and calibrated to the potentiometric surface of the A1 aquifer using MODFLOW. Model calibration was facilitated using a parameter-estimation program. Values for model input parameters were based on the results of sediment core analyses, an aquifer test, well specific-capacity tests, and a parameter-estimation program. Results of numerical modeling support the proposed conceptual hydrogeologic model of the shallow aquifer system. The particle-tracking program MODPATH was used to simulate ground-water-flow direction and time-of-travel in the shallow aquifer system. An effective porosity of 25 percent produced typical ground-water-flow velocities on the order of 15 to 25 ft/yr in layer 1, which represented the A1 aquifer in the model. The average residence time of particles seeded in layer 1 was about 800 years.

Ground-water-flow paths and time-of-travel within the A1 aquifer was simulated at three sites: (1) the former N-6 hangar area; (2) the grassy area near SWMU 7; and (3) at SWMU 2. The close agreement between the estimated extent of migration of the contaminant plumes at the former N-6 hangar area and the grassy area near SWMU 7 and the 40-year travel distance predicted by the particle-tracking analyses suggests that the estimates of effective porosity and hydraulic conductivity for the A1 aquifer in these areas are reasonably accurate. Based on the results of particle-tracking analyses, the potential for contaminants to reach the Memphis aquifer in the next 100 years is negligible. Particle-tracking analysis of the SWMU 2 area indicates that ground-water time-of-travel to Big Creek Drainage Canal from SWMU 2 is generally less than 30 years; however, at present, there is no map of the extent of contaminant migration at SWMU 2 to compare to particle-tracking simulations. The calibrated flow model and the MODPATH program were not used to evaluate remedial designs at NSA Memphis. The results of the calibrated model and MODPATH analyses may simulate the expected contaminant migration if no remedial actions are undertaken.

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