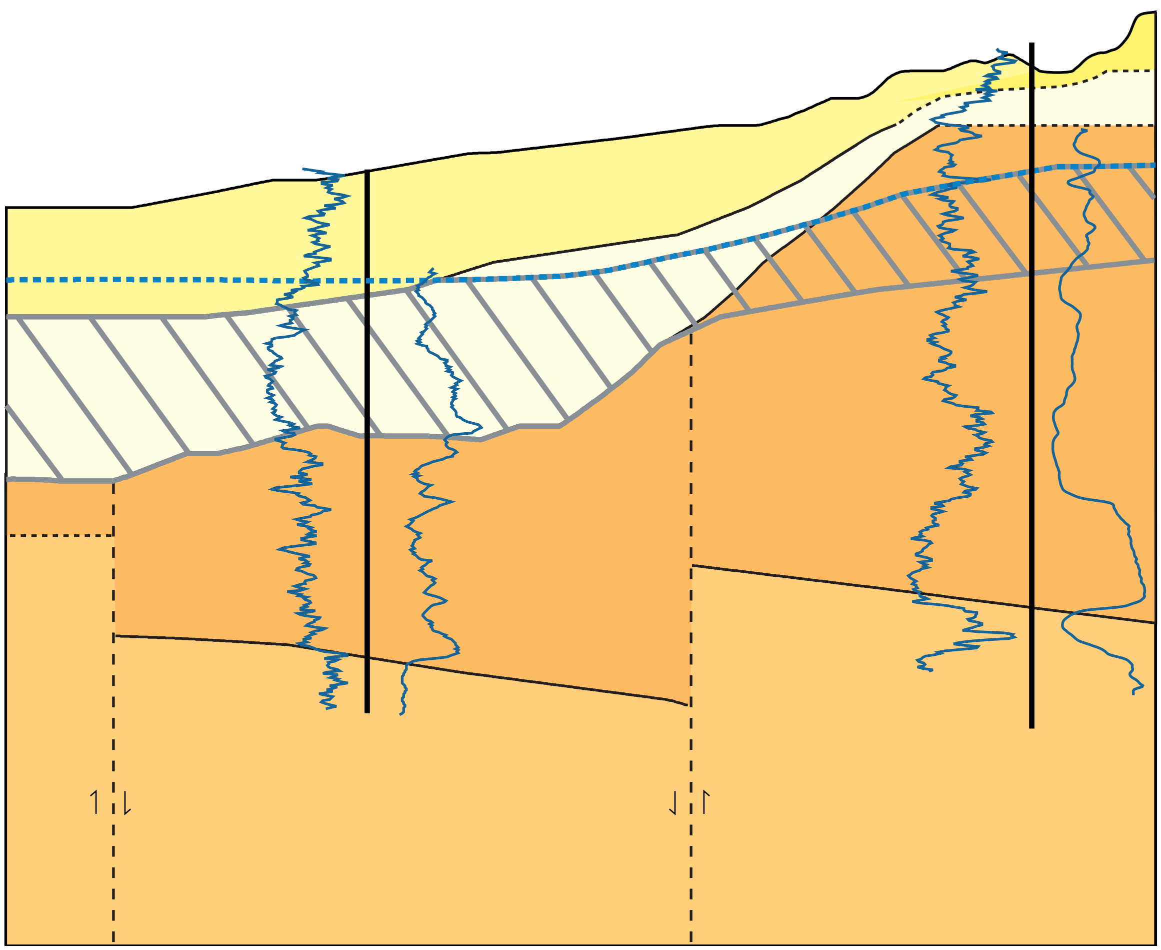
Prepared in cooperation with the
Department of the Navy, Southern Division,
Naval Facilities Engineering Command

Hydrogeology and Ground-Water-Flow Simulation in the Former Airfield Area of Naval Support Activity Mid-South, Millington, Tennessee



Scientific Investigations Report 2004-5040

U.S. Department of the Interior
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Cover. See figure 6b, page 13.

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By Connor J. Haugh, John K. Carmichael, and David E. Ladd

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Conversion Factors, Datums, Well-Numbering Information, and Acronyms

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (^oF) can be converted to degrees Celsius (^oC) as follows:

$^oC = 5/9 \times (^oF-32)$

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 meter 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)."

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Well-numbering system: The U.S. Geological Survey assigns each well in this report a local Tennessee well number. The local well number in Tennessee 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; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Sh:U-98, for example, indicates that the well is located in Shelby County on the "U" quadrangle and is identified as well 98 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

Acronyms

AOC	Area of Concern
BRAC	Base Closure and Realignment
DCE	Dichloroethene
IRP	Installation Restoration Program
NAS	Naval Air Station
NATTC	Naval Aviation Technical Training Center
NSA	Naval Support Activity
PCE	Tetrachloroethene
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RMSE	Root mean square error
TCE	Trichloroethene
USGS	U.S. Geological Survey

Hydrogeology and Ground-Water-Flow Simulation in the Former Airfield Area of Naval Support Activity Mid-South, Millington, Tennessee

By Connor J. Haugh, John K. Carmichael, and David E. Ladd

Abstract

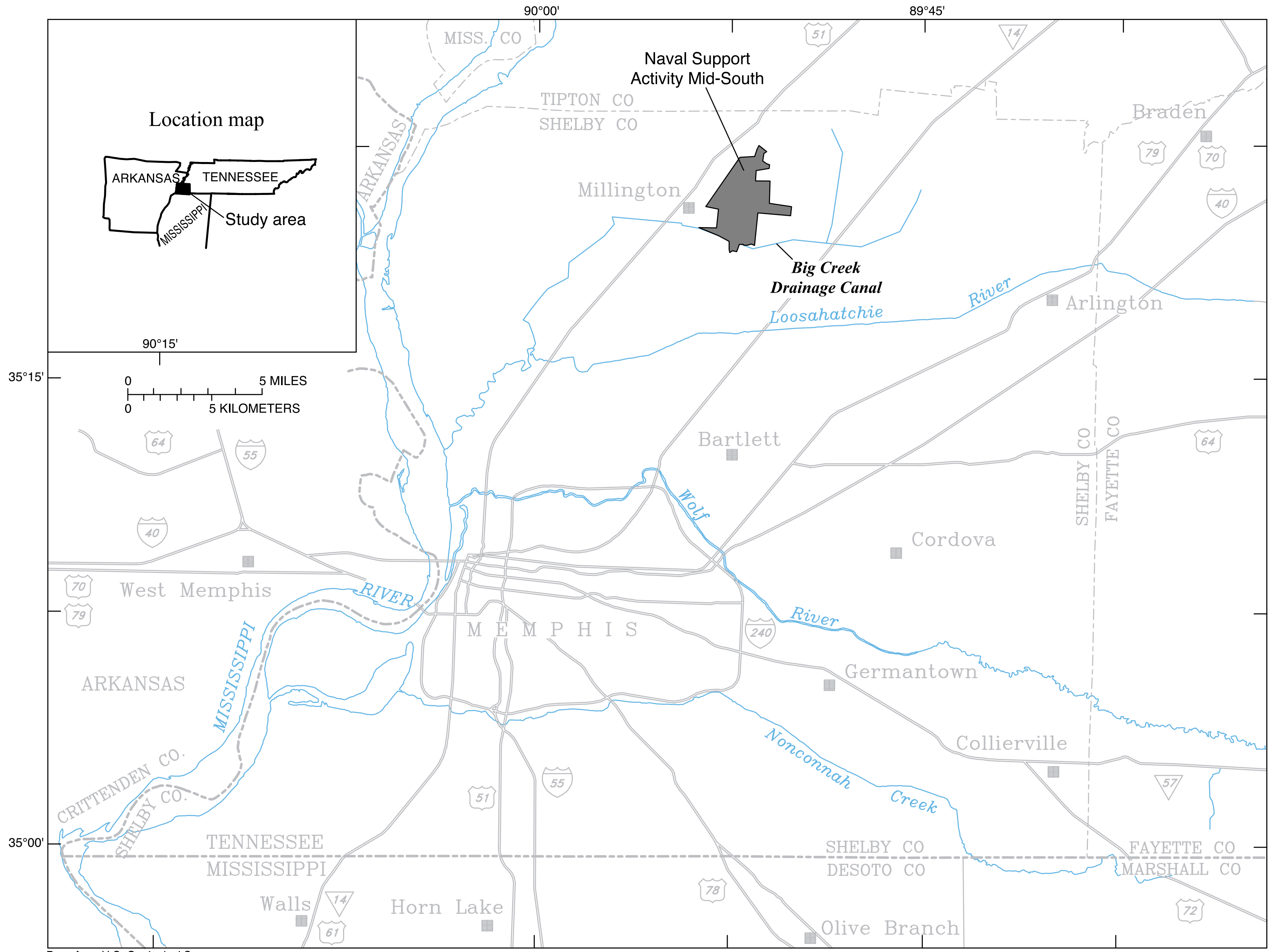
Naval Support Activity Mid-South is a Department of the Navy base located in Millington, Tennessee. The facility was home to the Naval Aviation Technical Training Center from 1943 until 1996. As part of the Base Closure and Realignment Act of 1990, the primary training mission of the facility was realigned and most of the northern part of the base, referred to as the Northside and consisting primarily of an airfield, was transferred to the city of Millington in January 2000. During environmental investigations at the base, plumes of dissolved chlorinated solvents resulting from past aircraft maintenance and training operations were identified in shallow ground water beneath the airfield area. The airfield area containing the plumes has been designated as Area of Concern (AOC) A. Chlorinated solvents, primarily trichloroethene (TCE), are the principal contaminants in ground water at AOC A, with TCE identified in concentrations as high as 4,400 micrograms per liter. The nature and extent of these plumes at AOC A were addressed during a Resource Conservation and Recovery Act Facility Investigation, and selected options for remediation currently are being implemented under a corrective action program. As part of these efforts, the U.S. Geological Survey (USGS) is working with the Navy and its consultants to study the hydrogeologic framework of the base and surrounding area, with a focus on AOC A.

Since 1997, investigations at and near the facility have produced data prompting revisions and additions to information published that year in two USGS reports. The updates are presented in this report and consist primarily of (1) refinements to selected hydrogeologic maps presented in the 1997 reports, on the basis of data collected from new wells at on- and off-base locations, (2) additional hydraulic-conductivity data collected for the alluvial-fluvial deposits aquifer at AOC A, and (3) construction of a potentiometric-surface map of the shallow aquifer for the former part of the Naval Support Activity Mid-South Northside and adjacent off-base locations for February and March 2000 water-level conditions. Additionally, a numerical ground-water-flow model of AOC A was developed and calibrated to the February and March 2000 potentiometric-surface data, the results of which also are presented in this report. Particle-tracking simulations were used with the model to simulate ground-water-flow paths from two sites suspected of being contaminant source areas at AOC A. The flow paths indicated by the particle tracking simulations agree reasonably well with maps of the interpreted extents of TCE plumes. The time-of-travel plots show that advective travel times from the two suspected source areas to the model boundary are controlled by relative proximities of the source areas to a part of AOC A identified from investigations and simulated with the model as having the highest horizontal hydraulic conductivity.

Introduction

Naval Support Activity (NSA) Mid-South is a Department of the Navy (Navy) base located in Millington, Tennessee (fig. 1). The facility was commissioned in 1942 as the Naval Reserve Aviation Base. From 1943 until 1995, the base was known as the Naval Air Station (NAS) Memphis. During this period, NAS Memphis was the home of the Naval Aviation Technical Training Center (NATTC) and consisted of two parts informally referred to as the Northside, which included an airfield and supporting structures, and the Southside, which included housing and training facilities (fig. 2). In 1993, as part of the Base Closure and Realignment (BRAC) Act of 1990, NAS Memphis was designated for realignment of its primary training mission and partial closure. In 1995, NAS Memphis became NSA Memphis as part of the BRAC process. In 1996, the Navy relocated its NATTC operations from NSA Memphis to NAS Pensacola. In 1998, NSA Memphis became NSA Mid-South, and the Navy's Bureau of Personnel was relocated to the facility. In January 2000, a large part of the Northside, including the airfield, was transferred to the city of Millington. Currently (2004), the base includes all of the Southside and the southernmost part of the Northside (fig. 2).

Plumes of dissolved chlorinated solvents have been identified in ground water in the alluvial-fluvial deposits aquifer, part of the shallow aquifer that is present from about 40 to 100 ft below land surface, beneath the airfield area of the former northern part of the NSA Mid-South Northside. The plumes, identified during environmental investigations conducted under



Base from U.S. Geological Survey 1:24,000, Mississippi River Commission 1:62,000, and Navy Digital Orthophotography 1:7,600

Figure 1. Location of Naval Support Activity Mid-South, Millington, Tennessee.

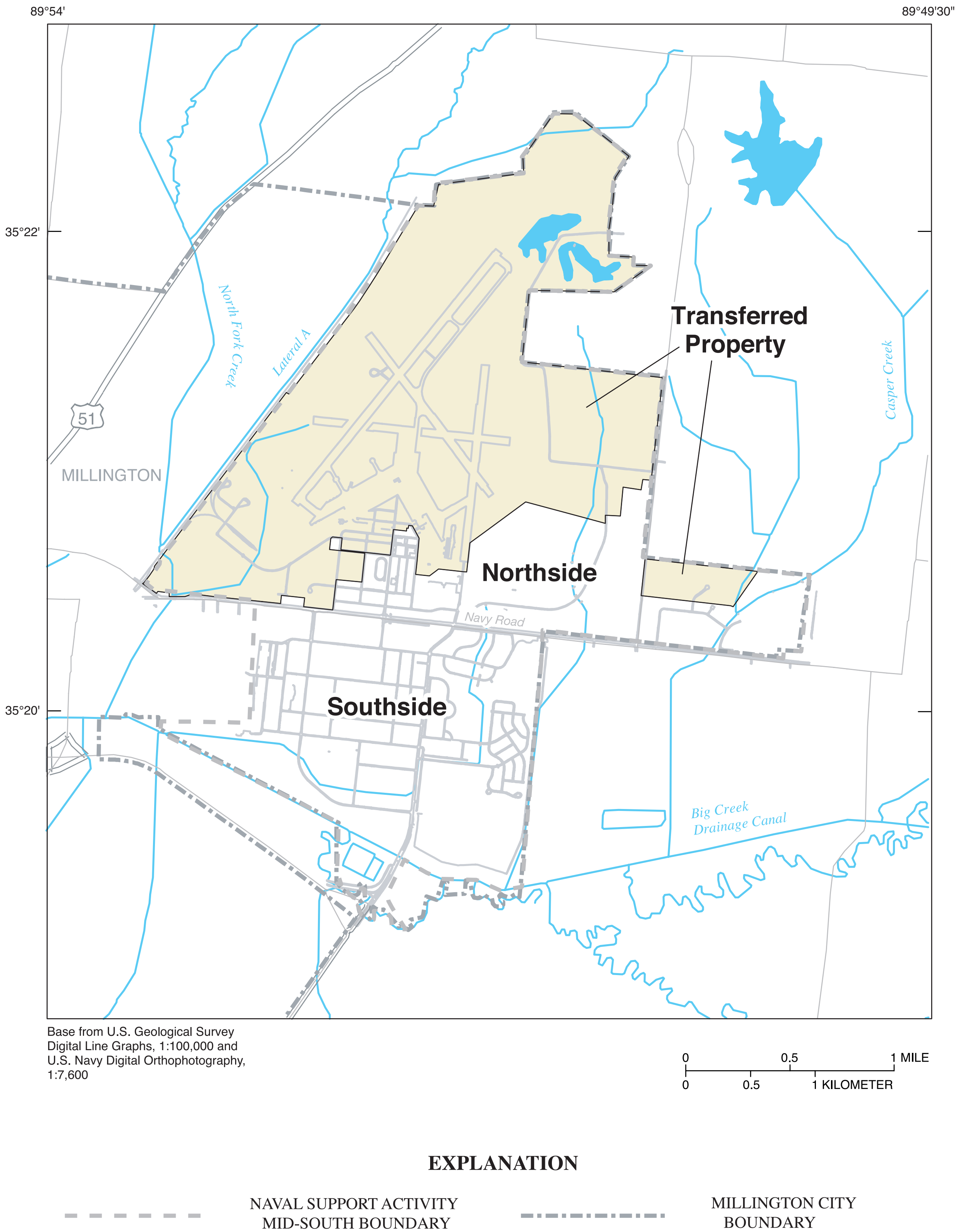


Figure 2. Naval Support Activity Mid-South, the Northside and Southside, and property transferred to the city of Millington.

the Navy's Installation Restoration Program (IRP) at the base, are the result of past aircraft maintenance and training operations conducted in the airfield apron area when the base was NAS Memphis. Chlorinated solvents, primarily trichloroethene (TCE), are the principal contaminants in ground water beneath the airfield. TCE has been identified in ground-water samples near one of the suspected primary source areas in concentrations as high as 4,400 micrograms per liter (µg/L). Tetrachloroethene (PCE), dichloroethene (DCE), and carbon tetrachloride also have been detected in lower concentrations. The presence of low concentrations of the cis- isomer of DCE and weakly reducing geochemical conditions identified in ground water at some locations indicates that natural attenuation of PCE and TCE by reductive dechlorination and possibly other processes may be occurring within the plumes.

The identification of multiple chlorinated-solvent plumes in the airfield area has led to interpretations of multiple source areas, most of which are thought to have resulted from relatively small-volume releases of the contaminants. The two largest plumes, however, appear to be the result of significantly larger releases; the plume containing the highest solvent concentrations extends about 1 mi downgradient of the suspected source areas. Defining the nature and extent of individual source areas and resulting plumes has been complicated by the apparent coalescing of some of the plumes as they migrate northwestward with ground-water flow in the alluvial-fluvial deposits aquifer. Rather than attempt to investigate all possible sources and plumes within the airfield, an area has been delineated that contains all confirmed and probable locations of solvent contamination in the alluvial-fluvial deposits aquifer that are suspected of originating from releases in and near the airfield. This area is designated as Area of Concern (AOC) A. Work conducted under the IRP in compliance with the Resource Conservation and Recovery Act (RCRA) Correction Action Program at AOC A has focused primarily on the two largest plumes containing the highest concentrations of chlorinated solvents present at NSA Mid-South (fig. 3). The nature and extent of these plumes were addressed during a RCRA Facility Investigation (RFI), and selected options for remediation, including monitored natural attenuation and enhanced biodegradation, currently are being implemented under a corrective action program. As part of the RFI process, the U.S. Geological Survey (USGS) has been assisting the Navy, Southern Division, Naval Facilities Engineering Command, and its contractors in hydrogeologic investigations, including development and calibration of a numerical ground-water-flow model of AOC A.

Purpose and Scope

This report provides revisions to maps and interpretations of the hydrogeology of NSA Mid-South, including AOC A, that appear in previously published reports prepared by the USGS. Information from the previous reports is updated for use in the design and construction of a ground-water-flow model of AOC A and nearby areas. This report documents the AOC A model, including data and parameters used in model development and calibration, and presents a description and the results of advective-flow particle-tracking simulations that were used to estimate ground-water-flow direction and time-of-travel from selected locations suspected as being contaminant-plume source areas within AOC A.

Previous Investigations

Several reports describe studies of the hydrogeology of NSA Mid-South and the surrounding area. Kingsbury and Carmichael (1995) present the hydrogeology of the post-Wilcox Group stratigraphic units in the area of NSA Mid-South as interpreted from available geologic data for the area, including the results of a test-drilling program conducted on the NSA Mid-South Northside by the USGS in 1994 prior to the onset of site-specific subsurface investigations on this part of the base. Carmichael and others (1997) update information on the hydrogeology at NSA Mid-South following a second series of test holes drilled by the USGS on the NSA Mid-South Southside in 1995 prior to the onset of site-specific subsurface investigations on this part of the base, and include a description of water quality in the principal water-bearing units beneath the facility. Robinson and others (1997) present the results of a study conducted by the USGS from 1995 through 1997 to simulate ground-water flow in the shallow aquifer system using a numerical model calibrated for an approximately 30 square-mile (mi^2) area that included all of the NSA Mid-South Southside and most of the Northside. A series of reports prepared by EnSafe, Inc., Memphis, Tenn., and other consultants to the Navy also describe the results of site-specific environmental investigations conducted under the IRP at NSA Mid-South.

Hydrogeology

Descriptions of the physical setting of NSA Mid-South and the hydrogeologic framework of the base and surrounding area are presented in previous reports by Kingsbury and Carmichael (1995), Carmichael and others (1997), and Robinson and others (1997). Carmichael and others (1997) describe the post-Wilcox Group geologic units underlying the NSA Mid-South area (table 1). Primary geologic units studied under the RFI at AOC A include the alluvium, loess, fluvial deposits, and Cockfield Formation. Brief descriptions of these units and their hydrogeologic significance provide a framework for the ground-water-flow model of AOC A.

Alluvium of Pleistocene through Holocene age is present in the valleys of streams in the Memphis area, including Big Creek Drainage Canal and its tributaries that drain NSA Mid-South (fig. 2). In the valley of Big Creek Drainage Canal and along the lower reaches of its larger tributaries such as North Fork Creek, the alluvium consists of silt and clay with minor amounts of sand in the upper part, and sand and gravel in the

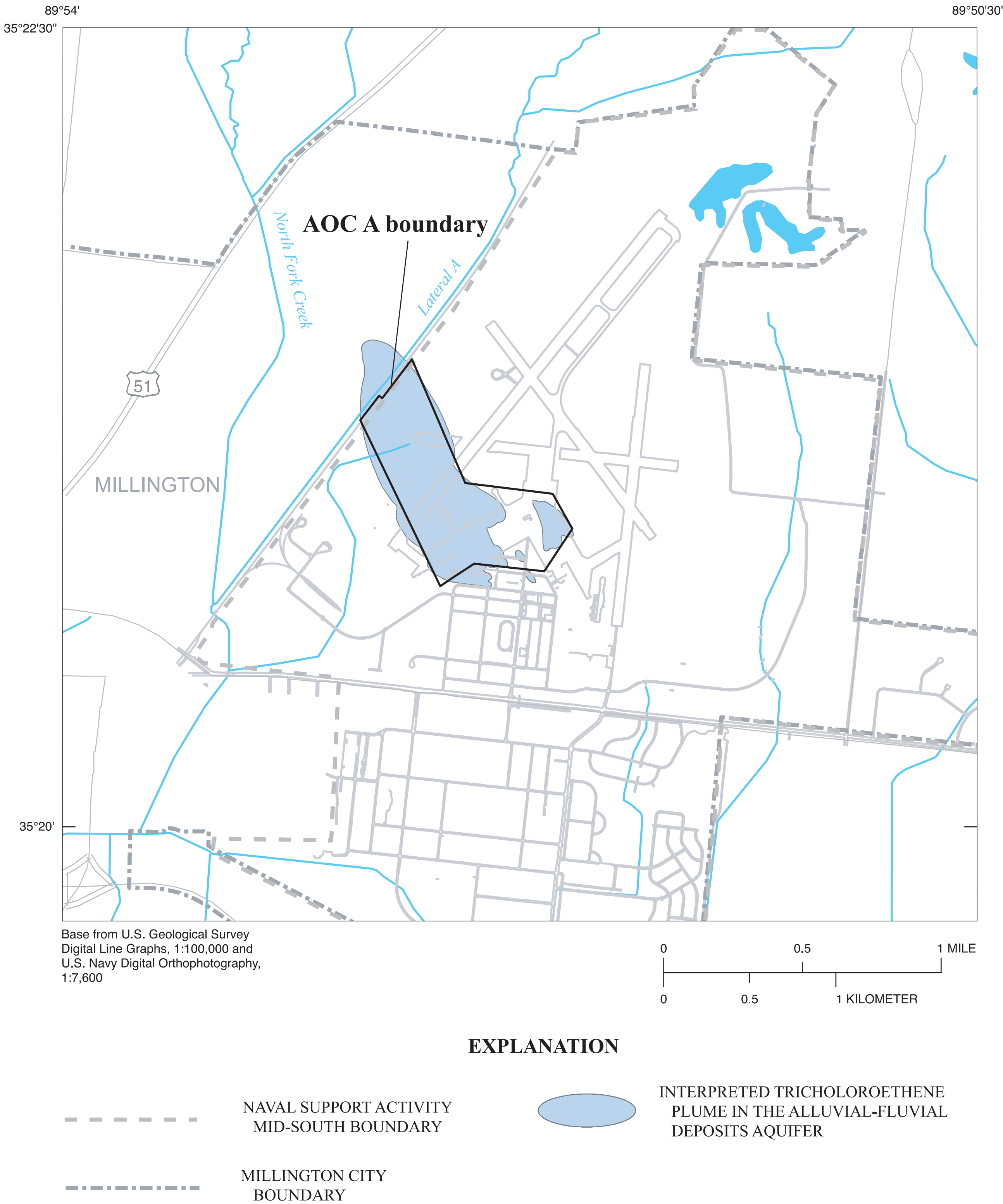


Figure 3. Locations of study area, Area of Concern (AOC) A, and interpreted plumes of trichloroethene in the alluvial-fluvial deposits aquifer beneath the former airfield area part of the Naval Support Activity Mid-South Northside, Millington, Tennessee.

Table 1. Post-Wilcox Group geologic units underlying Naval Support Activity Mid-South, Millington, Tennessee, and their hydrologic significance

[Modified from Parks and Carmichael, 1989, 1990; Kingsbury and Parks, 1993; Kingsbury and Carmichael, 1995; 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 and tributary streams. A sand and gravel horizon in the lower part of the unit is connected to the fluvial deposits and constitutes part of the alluvial-fluvial deposits aquifer.
	Pleistocene		Loess	15-45	Silt, clay, and sand. Predominantly silt with silty clay and silty, fine sand at various horizons. Principal unit at the surface in upland areas. Thinnest on the tops of hills and ridges; thickest on the valley slopes. Generally serves as the upper confining unit for the alluvial-fluvial deposits aquifer. Locally contains perched water tables in the upper part.
Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)		Fluvial deposits (terrace deposits)	5-80	Sand and gravel; minor clay and ferruginous sandstone. Underlies the loess in upland areas. Thickness varies greatly because of erosional surfaces at top and base. Constitutes part of the alluvial-fluvial deposits aquifer. Provides water to some domestic and farm wells in the NSA Mid-South area.
Tertiary	Eocene	Claiborne	Cockfield Formation	0-185	Sand, silt, clay, and lignite. Interbedded and interlensed. Thickness of formation is variable because of erosional surfaces at top and base. Locally contains sand lenses (which compose the Cockfield aquifer) in which domestic and farm wells are screened. Sand lenses are more prevalent in northern and eastern NSA Mid-South. Commonly consists predominantly of fine sediments and serves as part of the upper confining unit for the Memphis aquifer.
			Cook Mountain Formation	10-60	Clay, silt, and sand. Generally consists of clay and silt, but locally contains some very fine sand. Locally serves as part of the lower confining unit for the Cockfield aquifer and is the principal part of the upper confining unit for the Memphis aquifer.
			Memphis Sand	865-880	Sand, silt, clay, and minor lignite. Consists of a thick body of sand with clay lenses at various horizons. Sand is fine to medium or medium to coarse. Upper part contains lenses of fine sand and clay. Constitutes the Memphis aquifer—the principal aquifer providing water for most domestic, commercial, industrial, and municipal supplies in the Memphis area. Provides water to three wells at NSA Mid-South and four wells at Millington.

lower part (Carmichael and others, 1997). Thickness of the alluvium ranges from 0 to 70 ft at NSA Mid-South (table 1). The alluvium thins as the altitude of its base rises and the coarse-grained lower part becomes absent in the middle and upper reaches of the valleys of the main tributaries to Big Creek Drainage Canal. The upper part of the alluvium is interpreted to grade laterally and to be hydraulically similar to the loess, and the lower part of the alluvium is interpreted to grade laterally and to be hydraulically similar to the fluvial deposits. Saturated sand and gravel in the lower part of the alluvium constitute the alluvial aquifer in the Memphis area. At NSA Mid-South, ground water in the alluvial aquifer is confined locally by the overlying finer-grained upper alluvium.

Loess of Pleistocene age, which overlies the fluvial deposits in upland parts of the Memphis area outside the alluvial plains of streams, consists of silt with silty clay and silty, fine sand. Thickness of the loess ranges from less than 15 to 45 ft at NSA Mid-South (table 1). In general, the loess is thinnest on the hilltops and thickest on the valley slopes. Locally, silt and clay on the valley slopes may include loess reworked or redeposited as colluvial or alluvial deposits. At NSA Mid-South, the lithologic similarity and subtle transition laterally from undisturbed loess to reworked loess or alluvium makes differentiation between these deposits difficult based solely on general lithologic descriptions (Carmichael and others, 1997). A transitional zone ranging from about 3 to 7 ft thick and grading from sandy silt at the top to silty sand at the base is present between silt in the loess and sand and gravel in the fluvial deposits at NSA Mid-South. Because of the low permeability of the silt, the loess generally serves both to retard downward movement of recharge to and as the upper semi-confining to confining unit for the fluvial deposits. Locally, however, the base of the loess lies above the potentiometric surface of the fluvial deposits beneath the higher land-surface altitude parts of the NSA Mid-South area. The loess commonly contains a perched saturated zone with water levels that fluctuate seasonally from about 1 to 15 ft below land surface.

The fluvial (terrace) deposits of Pliocene(?) and Pleistocene age underlie the loess in upland parts of the Memphis area and consist of sand and gravel with minor amounts of clay. Thickness of the fluvial deposits ranges from 5 to 80 feet at NSA Mid-South (table 1). Locally, the sand in the upper part of the formation is very fine to fine and silty or clayey, and is similar in character to the transitional zone between the loess and fluvial deposits described by Carmichael and others (1997). Gravel is present in the fluvial deposits as lenses at various horizons but is more common in the lower part. Therefore, the fluvial deposits may be described as a coarsening downward sequence that generally is composed of silty sand or sandy silt in the upper part, and sand or sand and gravel through the remaining part, but with gravel more common in the lower part.

Two levels of fluvial deposits are present at NSA Mid-South, a lower level having a basal altitude of about 220 feet above NGVD 29 and ranging from about 5 to 80 feet in thickness, and an upper level having a basal altitude of about 300 feet above NGVD 29 and ranging from about 10 to 20 feet in thickness. At NSA Mid-South, the lower-level fluvial deposits are located beneath most of the facility outside the stream valleys where land-surface altitudes generally range from about 265 to 300 feet above NGVD 29, and the upper-level fluvial deposits are located beneath the northernmost former part of the Northside where land-surface altitudes generally range from about 320 to 350 feet above NGVD 29. The transition between the two levels of fluvial deposits is thought to be present in the north-central part of the airfield area, northeast of the northwest-southeast trending runway (fig. 2), and where land-surface altitudes range between about 300 and 320 feet above NGVD 29. An erosional scarp in the underlying Cockfield Formation also is thought to be present in the transition area across which the two levels of fluvial deposits may be hydraulically connected. The lower-level fluvial deposits generally are saturated and ground water locally is under artesian pressure. The upper-level fluvial deposits commonly are dry or contain only a thin perched-water zone at their base.

Saturated sand and gravel in the fluvial deposits constitute the fluvial deposits aquifer in the Memphis area. Where hydraulically connected, saturated sand and gravel in the lower alluvium and the fluvial deposits constitute the alluvial-fluvial deposits aquifer, the primary part of the “shallow” aquifer at NSA Mid-South (Carmichael and others, 1997). Within the AOC A study area, however, the alluvial-fluvial deposits aquifer is composed of only the fluvial deposits because the coarse-grained lower part of the alluvium is not known to be present beneath the middle to upper reaches of the alluvial valleys of North Fork Creek and its tributary Lateral A located in the western part of the area (fig. 2).

The Cockfield Formation of Eocene age is the uppermost unit in the Claiborne Group in the Memphis and NSA Mid-South area (table 1). The Cockfield Formation consists of interbedded clay, silt, and sand. Thickness of the Cockfield Formation generally ranges from about 25 to 185 feet in the NSA Mid-South area, but locally the Cockfield Formation may be absent as a result of structural relief from faulting and subsequent erosion (Carmichael and others, 1997). The thickest preserved section of the Cockfield Formation is located in the northernmost part of the NSA Mid-South area beneath the upper-level fluvial deposits. Because of its primarily fine-grained texture, the Cockfield Formation and the underlying predominantly clay-rich Cook Mountain Formation together serve as the lower confining unit for the alluvial-fluvial deposits aquifer and the upper confining unit for the Memphis aquifer throughout most of the Memphis area. In western Tennessee, including the Memphis area, the Cockfield Formation locally contains discontinuous sand lenses that supply water to wells and compose the Cockfield aquifer (Parks and Carmichael, 1990). At NSA Mid-South, sand lenses in the upper part of the Cockfield aquifer that lie beneath the upper-level fluvial deposits are thought to grade laterally into and thus be hydraulically connected to the alluvial-fluvial deposits aquifer across and southwest of the erosional scarp area. Together, the alluvial-fluvial deposits aquifer and the upper part of the Cockfield aquifer lying northeast of the erosional scarp comprise the shallow aquifer at NSA Mid-South and are referred to as the A1 aquifer (Robinson and others, 1997). The A1 aquifer is confined from below by clay and silt lenses of the Cockfield Formation that form the Cockfield confining unit.

Since the publication of Carmichael and others (1997) and Robinson and others (1997), additional hydrogeologic data have been collected at and near NSA Mid-South as a result of the installation of new monitoring and production wells and the identification of existing domestic wells at both on- and off-base locations. On the basis of these additional data, geologic structure maps presented in those reports have been revised, and a potentiometric-surface map of the A1 aquifer has been constructed for the northern part of the NSA Mid-South area for February and March 2000 water-level conditions. Additional hydraulic-conductivity data also have been collected for the alluvial-fluvial deposits aquifer beneath the airfield area from a multiple-well, 24-hour, constant-rate-withdrawal aquifer test conducted by EnSafe, Inc., in 1999 as part of the RFI at AOC A (EnSafe, Inc., written commun., 2000). The implications of these new data to this study are discussed later in this report.

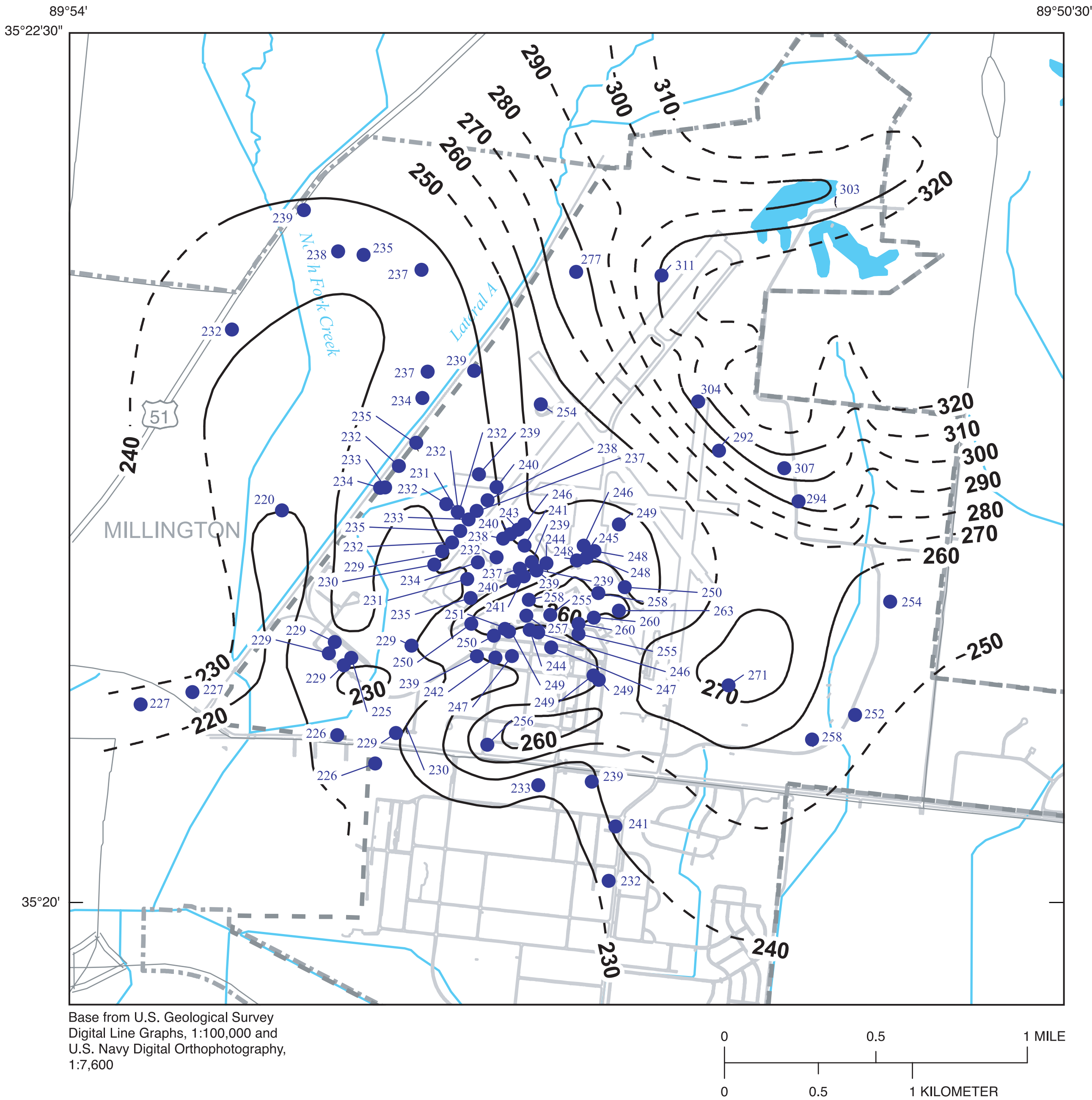
Structure

Since publication of Carmichael and others (1997) and Robinson and others (1997), hydrogeologic data collected from several new monitoring and existing domestic wells screened in the alluvial-fluvial deposits aquifer or the underlying Cockfield Formation in the NSA Mid-South area, along with data from a new production well screened in the Memphis aquifer in the southeastern part of the NSA Mid-South Northside, were used to revise two of the geologic structure maps presented in those reports. Revisions were made to the map that shows the altitude of the base of the loess or silt and clay in the upper alluvium and the map that shows the altitude of the base of sand and gravel in the lower alluvium or fluvial deposits. The revised maps were prepared at the same scale as those shown in the 1997 reports, including all of NSA Mid-South and the surrounding area. For this report, maps are presented that show revisions made within the smaller AOC A study area only (figs. 4 and 5). The revised map of the altitude of the base of the loess or silt and clay in the upper alluvium for the AOC A study area shows minor adjustments for this area, mostly as a result of additional geologic control points (fig. 4). The most significant change in the map of the altitude of the base of sand and gravel in the lower alluvium or fluvial deposits for the AOC A study area is a linear depression in this surface located in the northwestern part of the study area between Lateral A and North Fork Creek (figs. 5 and 6a). This depression defines an area where the alluvial-fluvial deposits aquifer thickens and the Cockfield confining unit appears to thin. These revised maps were used to define the top and bottom altitudes and thickness of the alluvial-fluvial deposits aquifer for that part of the area covered by the AOC A ground-water-flow model.

Shallow Aquifer

The shallow or A1 aquifer, as defined by Robinson and others (1997) for their “basewide” ground-water-flow model, is the primary hydrogeologic unit of interest for this study. Southwest of the erosional scarp in the Cockfield Formation located beneath the north-central part of the former NSA Mid-South Northside (fig. 5) , the A1 aquifer consists of the alluvial-fluvial deposits aquifer; northeast of the erosional scarp, the A1 aquifer consists of the upper part of the Cockfield aquifer (fig. 6). As described previously, the alluvial-fluvial deposits and upper part of the Cockfield aquifers are interpreted to be hydraulically connected across the scarp because the fluvial deposits thin and the basal altitude of this unit rises from about 220 feet above NGVD 29 to about 300 feet above NGVD 29 from southwest to northeast across this feature. Because of the rise in basal altitude across the scarp, the upper-level fluvial deposits commonly are dry or contain only a thin perched water zone in the area northeast of the scarp; thus, the water table in this area is in the upper part of the Cockfield aquifer. For this study, the top of that part of the A1 aquifer that consists of the alluvial-fluvial deposits aquifer was defined by the revised structure map of the base of the loess or silt and clay in the upper alluvium (fig. 4). The bottom of that part of the A1 aquifer that consists of the alluvial-fluvial deposits aquifer was defined by the revised structure map of the base of sand and gravel in the lower alluvium or fluvial deposits (fig. 5). The bottom of that part of the A1 aquifer that consists of the upper part of the Cockfield aquifer has been defined by the altitude of the top of a clay unit in the Cockfield Formation, designated the Cockfield confining unit by Robinson and others (1997). The top of the A1 aquifer in this area is the water table as defined by water levels measured in a couple of wells screened in the upper part of the Cockfield Formation in February and March 2000. Ground water in the A1 aquifer in the study area exists under artesian conditions in most of the part consisting of the alluvial-fluvial deposits aquifer, and under water-table conditions in the section consisting of the upper part of the Cockfield aquifer where water levels are below the base of the loess, with the transition in conditions occurring near the erosional scarp.

The basewide flow model presented in Robinson and others (1997) was constructed using data from the investigation described by Carmichael and others (1997). A horizontal hydraulic-conductivity value of 5.3 feet per day (ft/d) was used as input to the basewide model for that part of the A1 aquifer that consists of the alluvial-fluvial deposits aquifer, and a value of 1 ft/d was used as input for that section of the A1 aquifer that consists of the upper part of the Cockfield aquifer. The value of hydraulic conductivity used for the alluvial-fluvial deposits aquifer was obtained from a multiple-well, 24-hour constant-rate-withdrawal aquifer test conducted by the USGS in 1995 at a location south of the western end of the airfield apron and was thought at the time to be the most reliable value available for calibrating the model. The value of hydraulic conductivity used for the upper part of the Cockfield aquifer was estimated from the results of specific-capacity tests conducted by EnSafe, Inc., in wells screened in this unit (Robinson and others, 1997). In 1999, as part of the AOC A RFI, EnSafe, Inc., conducted a multiple-well, 24-hour constant-rate-withdrawal aquifer test in the alluvial-fluvial deposits aquifer within AOC A, at a location about 2,500 feet north of the USGS aquifer-test site. This test resulted in horizontal hydraulic conductivities for the pumping and for selected observation wells that range from 44.6 to 68.4 ft/d, with a geometric mean of 59.1 ft/d (EnSafe, Inc., written commun., 2000). These horizontal hydraulic conductivity values are about an order of magnitude greater than the value from the USGS test and show that the hydraulic conductivity of the alluvial-fluvial deposits aquifer in the airfield area is variable and higher in some areas than the value of 5.3 ft/d used uniformly for this aquifer in the basewide flow model. In addition to spatial variations in horizontal hydraulic conductivity, quantitative hydraulic data from slug tests and borehole-flowmeter measurements made in selected wells, as well as qualitative data from pumping rates, drawdown, and water-level recovery during well sampling, also indicate that horizontal hydraulic conductivities generally are lowest in the upper part of the fluvial deposits and increase with depth.



EXPLANATION

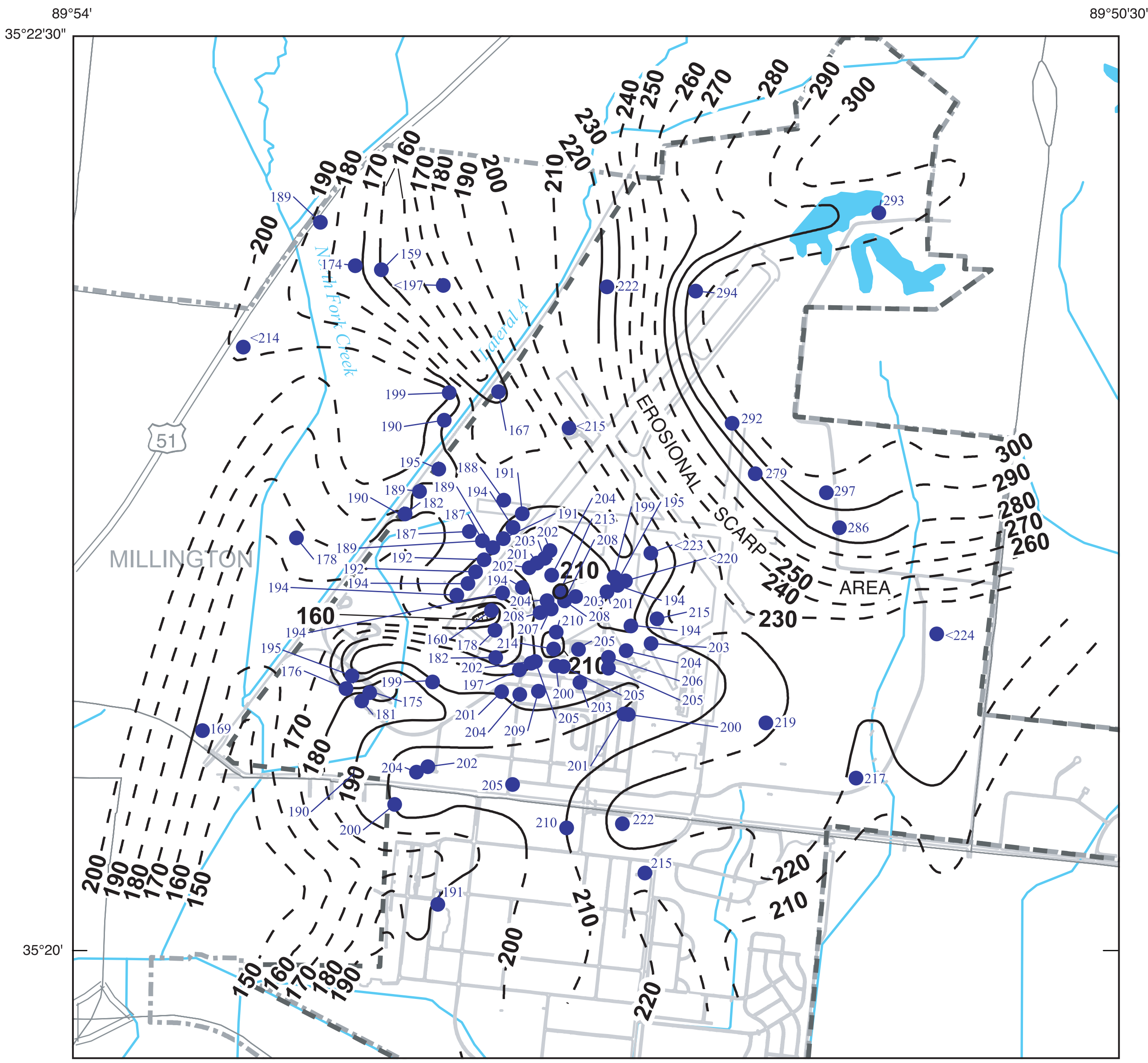
NAVAL SUPPORT ACTIVITY MID-SOUTH BOUNDARY

MILLINGTON CITY BOUNDARY

230 — SUBSURFACE CONTOUR—Shows altitude of base of loess or silt and clay in the upper alluvium. Dashed where approximate. Contour interval 10 feet. Datum is NGVD 29

232 WELL—Number is altitude of base of loess or silt and clay in the upper alluvium, in feet. Datum is NGVD 29

Figure 4. Altitude of the base of the loess or silt and clay in the upper alluvium at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.



Base from U.S. Geological Survey Digital Line Graphs 1:100,000 and U.S. Navy Digital Orthophotography 1:7,600

0 0.5 1 MILE

0 0.5 1 KILOMETER

EXPLANATION

NAVAL SUPPORT ACTIVITY MID-SOUTH BOUNDARY

MILLINGTON CITY BOUNDARY

190 SUBSURFACE CONTOUR -- Shows altitude of base of sand and gravel in the alluvial-fluvial deposits aquifer. Dashed where approximate. Hachures indicate closed depression. Contour interval 10 feet. Datum is NGVD 29

215 WELL -- Number is altitude of base of sand and gravel in the alluvial-fluvial deposits aquifer, in feet. Datum is NGVD 29

Figure 5. Altitude of the base of sand and gravel in the lower alluvium or fluvial deposits at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.

Water-level data were collected from wells in the AOC A study area in February and March 2000 and a potentiometric-surface map of the A1 aquifer was constructed (fig. 7). The potentiometric-surface map of the A1 aquifer for February and March 2000 is similar to the previous potentiometric-surface maps of the alluvial-fluvial deposits aquifer for April and October 1996 (Carmichael and others, 1997). Overall, water-levels for the February and March 2000 map are about 3 feet lower than the average water levels for April and October 1996. The February and March 2000 map also shows steep gradients and highest water-levels in the scarp area located in the northeastern part of the study area where the A1 aquifer transitions from the alluvial-fluvial deposits aquifer to the upper part of the Cockfield aquifer. This transition occurs near the 260-foot potentiometric contour (fig. 7). A ground-water divide occurs southeast of the airfield area. Ground-water flow directions generally are to the northwest in most of the model area. A depression in the potentiometric surface occurs in an off-base location in the northwestern part of the area where water levels in the A1 aquifer are at an altitude of less than 225 feet. This depression coincides with an area where data collected during monitoring-well installations show that the alluvial-fluvial deposits aquifer thickens and, on the basis of relatively flat topography in the area, the Cockfield Formation consequently thins. Downward leakage of water locally through the Cockfield and Cook Mountain confining units is indicated by observed water levels in the A1 aquifer in this depression that are approximately equal in altitude to water levels in the Memphis aquifer in the area (Robinson and others, 1997, fig. 13). Downward leakage of water from the alluvial-fluvial deposits aquifer to the Memphis aquifer has been identified on the basis of depressed water levels in the alluvial-fluvial deposits aquifer at various locations in the Memphis area (Parks, 1990).

Continuous water-level data are available for about 9 years (1995 to 2004) at well Sh:U-101 screened in the fluvial deposits located south of the western end of the airfield apron (fig. 7) at the site of the aquifer test conducted by the USGS in 1995 (Carmichael and others, 1997). These data are indicative of the timing and magnitude of water-level fluctuations in the alluvial-fluvial deposits aquifer, the primary part of the A1 aquifer in the AOC A study area. The hydrograph for well Sh:U-101 (fig. 8) shows short- and long-term water-level fluctuations in response to seasonal and annual changes in recharge. Water levels have fluctuated between 3 and 8 feet annually in this well during the period of record (1995-2004). On the basis of periodic measurements, water levels throughout the A1 aquifer in the study area generally fluctuate by about 1 to 5 feet annually (Robinson and others, 1997). The hydrograph for well Sh:U-101 shows no obvious trends, increasing or decreasing, in water levels, and no significant effects from pumping on the A1 aquifer within the study area are indicated.

Simulation of Ground-Water Flow

The physical system, described in the hydrogeology section of this report, provides the framework for design and calibration of a numerical ground-water-flow model of AOC A. Models that simulate the flow of water through aquifers are useful tools to test the understanding and conceptualization of a flow system. Although a model is necessarily a simplification of the physical system, the model should be consistent with all known hydrogeologic observations. The ground-water-flow model code used in this study, MODFLOW-2000, was developed by McDonald and Harbaugh (1988) and was recently updated (Harbaugh and others, 2000). MODFLOW uses the finite-difference technique to solve the ground-water-flow equation for three-dimensional, steady or non-steady flow in a heterogeneous and anisotropic medium.

A steady-state model of the A1 aquifer in the AOC A study area was constructed and calibrated to conditions of February and March 2000. Following model calibration, a particle-tracking simulation was used to analyze ground-water-flow paths from selected locations within AOC A.

Conceptual Model

The modeled A1 aquifer consists of the alluvial-fluvial deposits aquifer within most of the modeled area and the upper part of the Cockfield aquifer in the scarp area and to the northeast. As described in the hydrogeology section of this report, the alluvial-fluvial deposits are a coarsening downward sequence that generally is composed of silty sand or sandy silt in the upper part, and sand or sand and gravel through the remaining part, but with gravel more common in the lower part. Additionally, hydraulic conductivity generally is lowest in the upper part of the formation and increases with depth. Recharge to the modeled aquifer occurs as leakage from the overlying loess. Ground water does not discharge to streams or springs anywhere within the model area. Ground water leaves the modeled area through a constant-head boundary at the 225-foot potentiometric contour that defines a depression in the potentiometric surface in the alluvial-fluvial deposits aquifer (fig. 7). This constant-head boundary is near an area where the Cockfield confining unit is thought to thin and where water moves downward and out of the A1 aquifer.

Model Assumptions

The following assumptions were made in the development of the flow model of the hydrologic system in the AOC A study area:

1. The A1 aquifer is assumed to be in steady-state conditions because water levels in February-March 2000 were relatively stable (fig. 8).

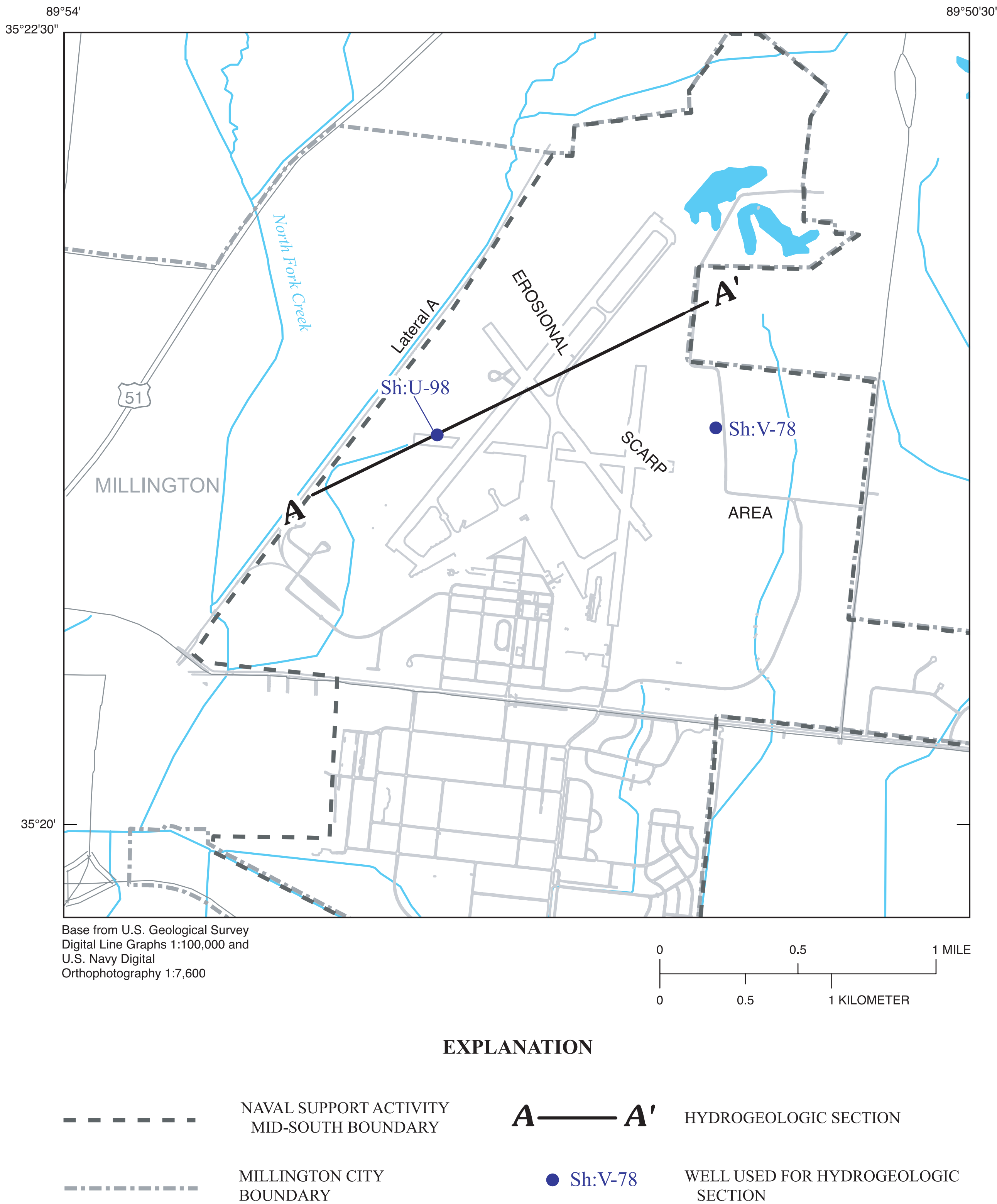


Figure 6a. Location of hydrogeologic section A-A' at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.

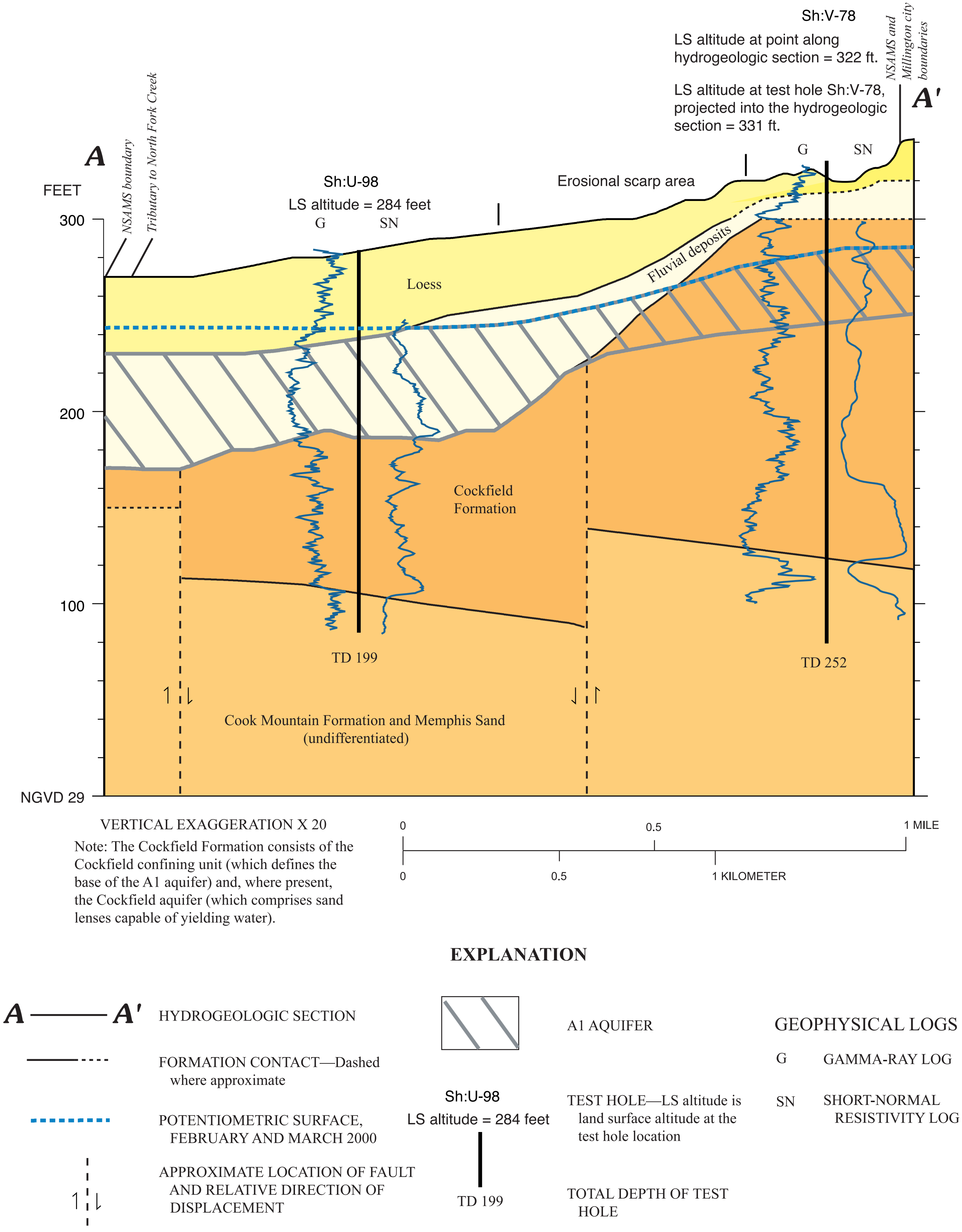
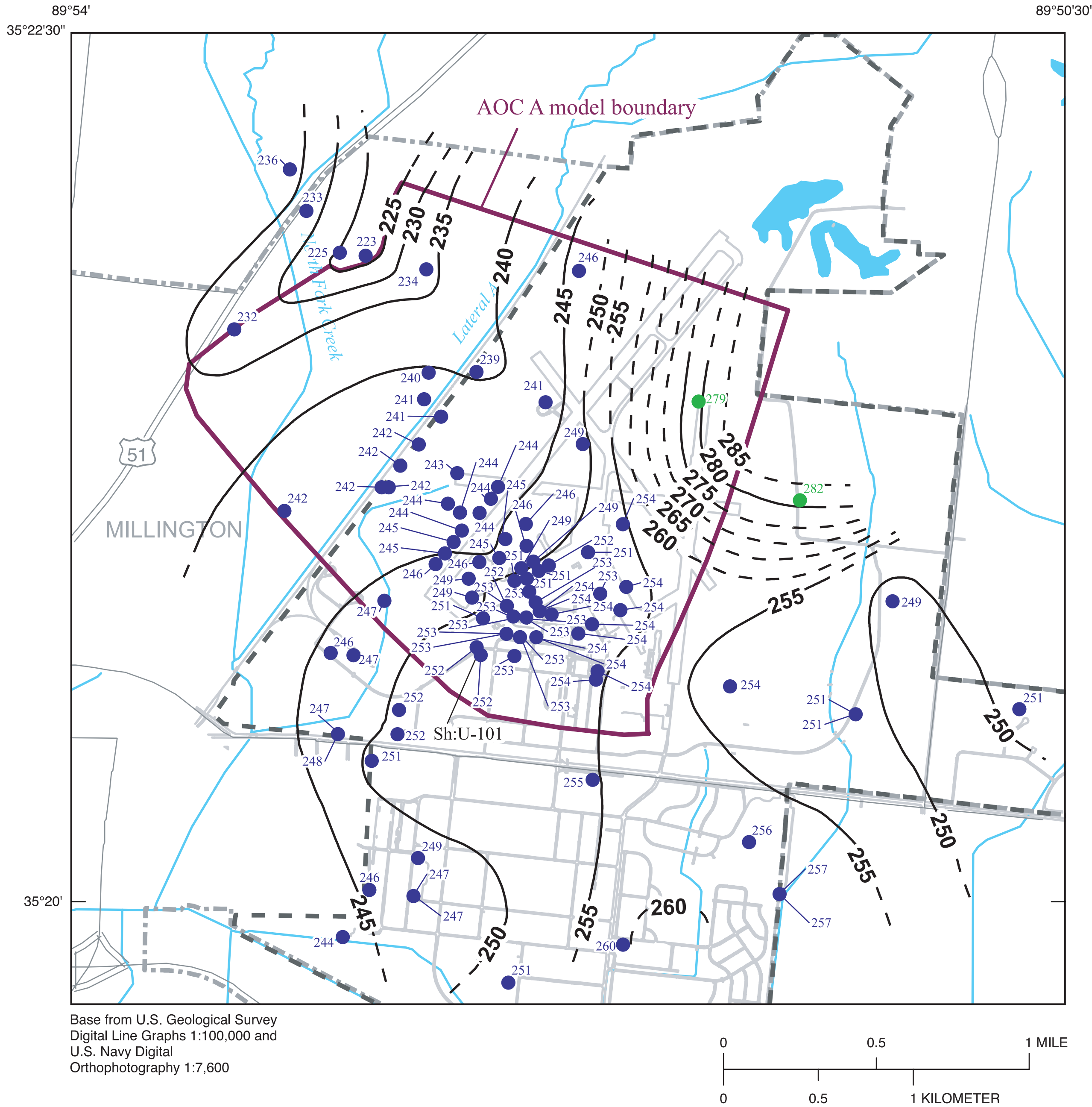


Figure 6b. Hydrogeologic section A-A' showing the A1 aquifer and related features at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.



EXPLANATION

NAVAL SUPPORT ACTIVITY MID-SOUTH BOUNDARY

MILLINGTON CITY BOUNDARY

245 POTENTIOMETRIC CONTOUR—Shows altitude, in feet, at which water level would have stood in tightly cased wells. Dashed where approximate. Contour interval 5 feet. Datum is NGVD 29

260 WELL SCREENED IN THE ALLUVIUM OR FLUVIAL DEPOSITS—Number is altitude of water level, in feet. Datum is NGVD 29

282 WELL SCREENED IN THE COCKFIELD FORMATION—Number is altitude of water level, in feet. Datum is NGVD 29

Figure 7. Altitude of the potentiometric surface of the A1 aquifer, February and March 2000; location of well Sh:U-101 for which continuous water-level data were collected; and Area of Concern (AOC) A model boundary, Naval Support Activity Mid-South, Millington, Tennessee.

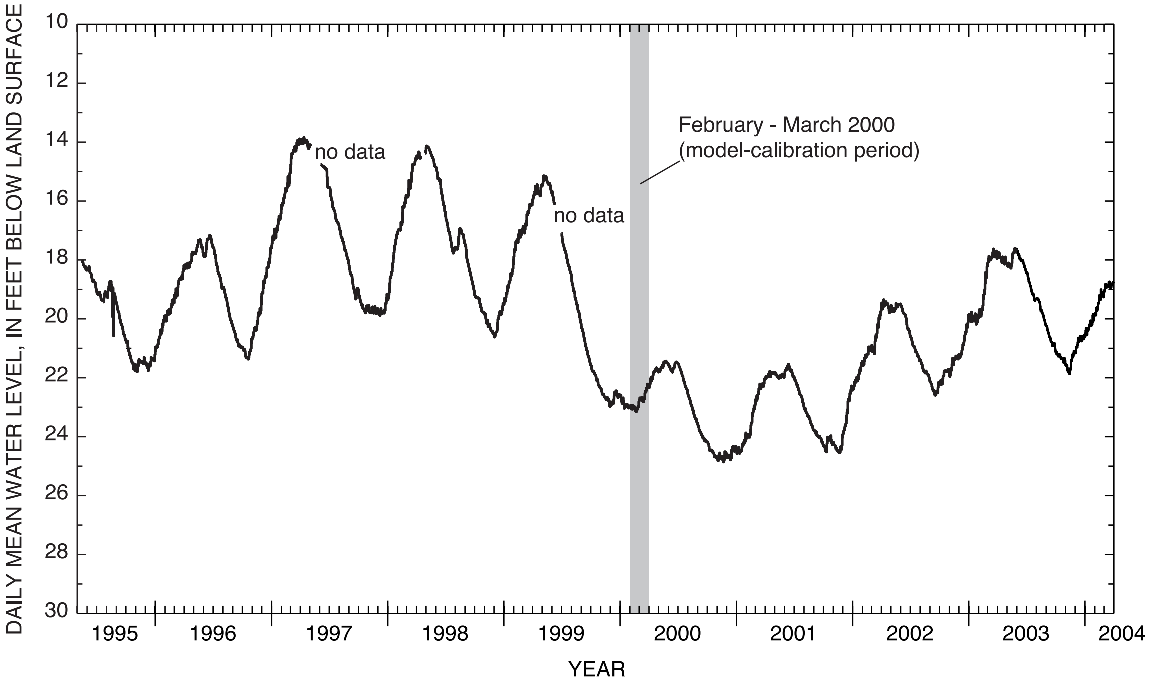


Figure 8. Hydrograph showing water levels recorded in well Sh:U-101 at Naval Support Activity Mid-South, May 1995 through March 2004.

2. The top boundary of the A1 aquifer model is assumed to be the bottom of the loess in the area southwest of the scarp where artesian conditions predominantly exist and the water table in the scarp area and to its northeast where water levels are below the base of the loess.
3. The bottom boundary of the A1 aquifer model is assumed to be the base of the alluvial-fluvial deposits aquifer southwest of the scarp and the base of the upper part of the Cockfield aquifer northeast of the scarp. This boundary, which corresponds to the top of the Cockfield confining unit throughout the model area, is assumed to be a no-flow boundary.
4. The hydraulic properties of the hydrogeologic units are homogeneous within a block of the finite-difference grid.
5. The hydraulic properties are isotropic within a layer.
6. Flow within a layer is horizontal; flow between layers is vertical.

Model Boundaries

The lateral boundaries of the AOC A model correspond to a local ground-water divide, ground-water flow-path lines, and a potentiometric contour (fig. 7). The east-southeastern boundary corresponds to a local ground-water divide and is simulated as a no-flow boundary. The north-northeastern and south-southwestern boundaries correspond to ground-water flow-path lines as defined by the February and March 2000 potentiometric surface of the A1 aquifer and are simulated as no-flow boundaries. The northwestern boundary corresponds to the 225-foot potentiometric contour of February and March 2000 and is simulated as a constant-head boundary. The upper boundary of the model ranges between altitudes of 220 and 285 feet above NGVD 29 and corresponds to the base of the loess southwest of the scarp where artesian conditions exist and to the water table northeast of the scarp where water levels are below the base of the loess (fig. 9). A recharge flux simulating leakage from the loess was applied to the upper boundary. The bottom boundary of the A1 aquifer is the top of the Cockfield confining unit throughout the model area which corresponds to the base of the alluvial-fluvial deposits aquifer southwest of the scarp and to the base of the upper part of the Cockfield aquifer northeast of the scarp (fig. 10). This boundary ranges between altitudes of 160 and 250 ft and is simulated as a no-flow boundary.

Model Construction

The AOC A model grid is approximately a 1.8- by 1.9-mi rectangle consisting of 100- by 100-ft grid cells (fig. 11). The grid is composed of 92 columns and 103 rows. About 2.2 mi^2 of the 3.4-mi^2 model grid is active. Vertically, the total thickness of the A1 aquifer (fig. 12) was divided into three equal layers to model vertical variations in aquifer texture and resulting hydraulic conductivity.

Model parameters, as discussed by Harbaugh and others (2000), were defined for recharge and hydraulic-conductivity zones (table 2). Recharge to the model is from downward leakage from the overlying loess and is constant throughout the area.

Hydraulic-conductivity zones for the AOC A flow model were determined on the basis of geology and well hydraulic-test

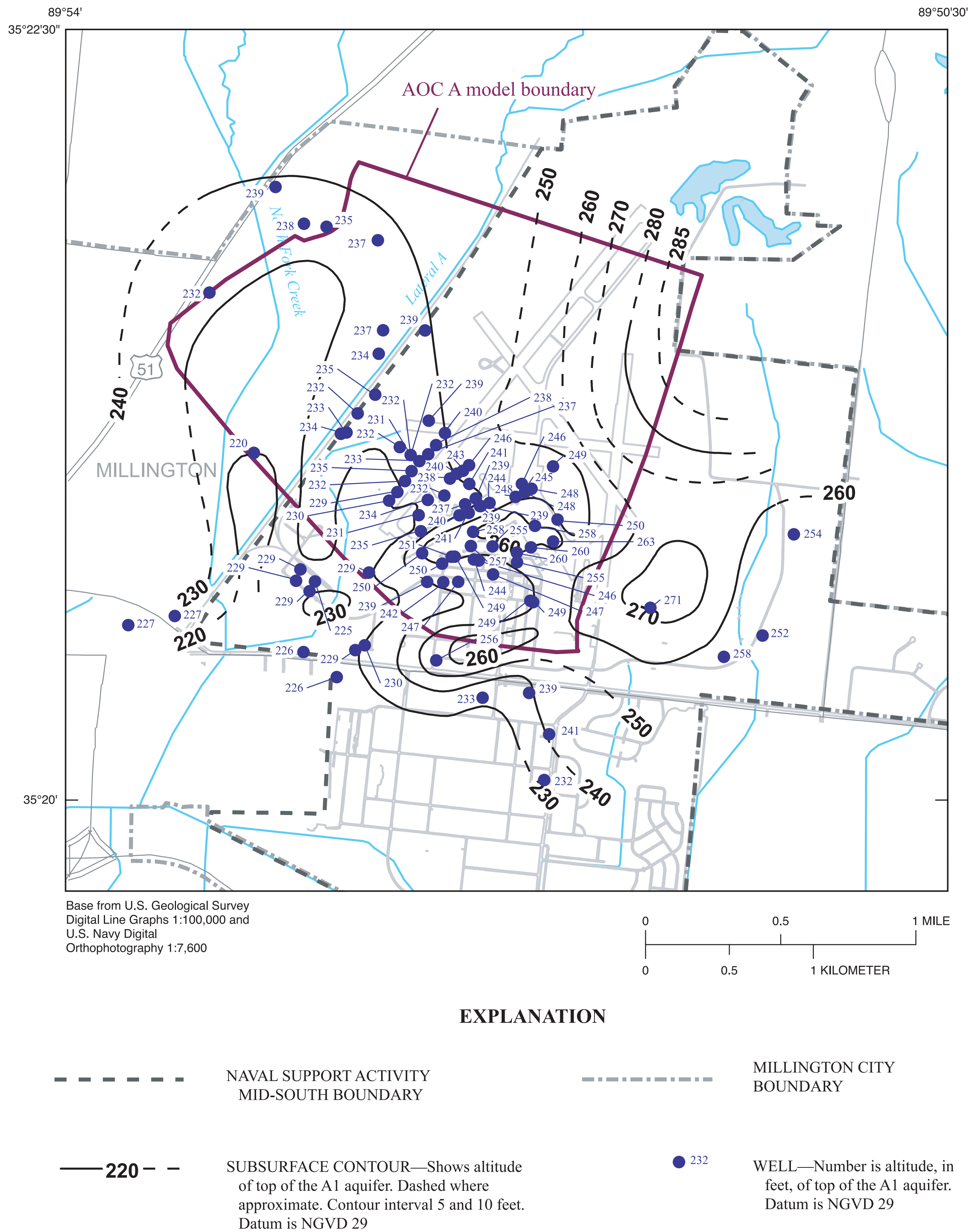
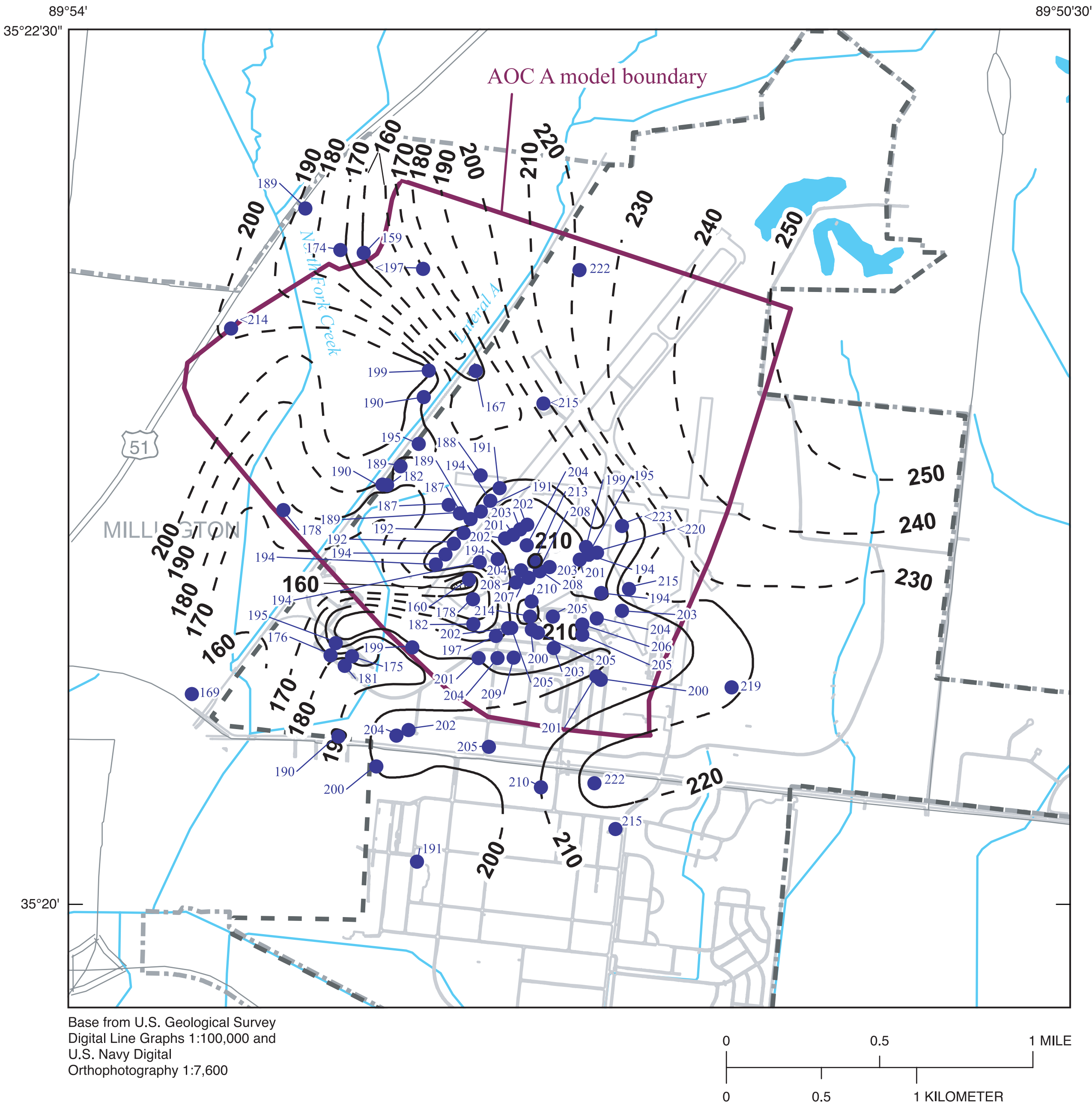


Figure 9. Altitude of the top of the A1 aquifer at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.



EXPLANATION

NAVAL SUPPORT ACTIVITY MID-SOUTH BOUNDARY

MILLINGTON CITY BOUNDARY

220 — SUBSURFACE CONTOUR—Shows altitude of base of A1 aquifer. Dashed where approximate. Hachures indicate depression. Contour interval 10 feet. Datum is NGVD 29

215 WELL—Number is altitude, in feet, of base of A1 aquifer. Datum is NGVD 29

Figure 10. Altitude of the base of the A1 aquifer at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.

Figure 11. Model grid cell types for the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

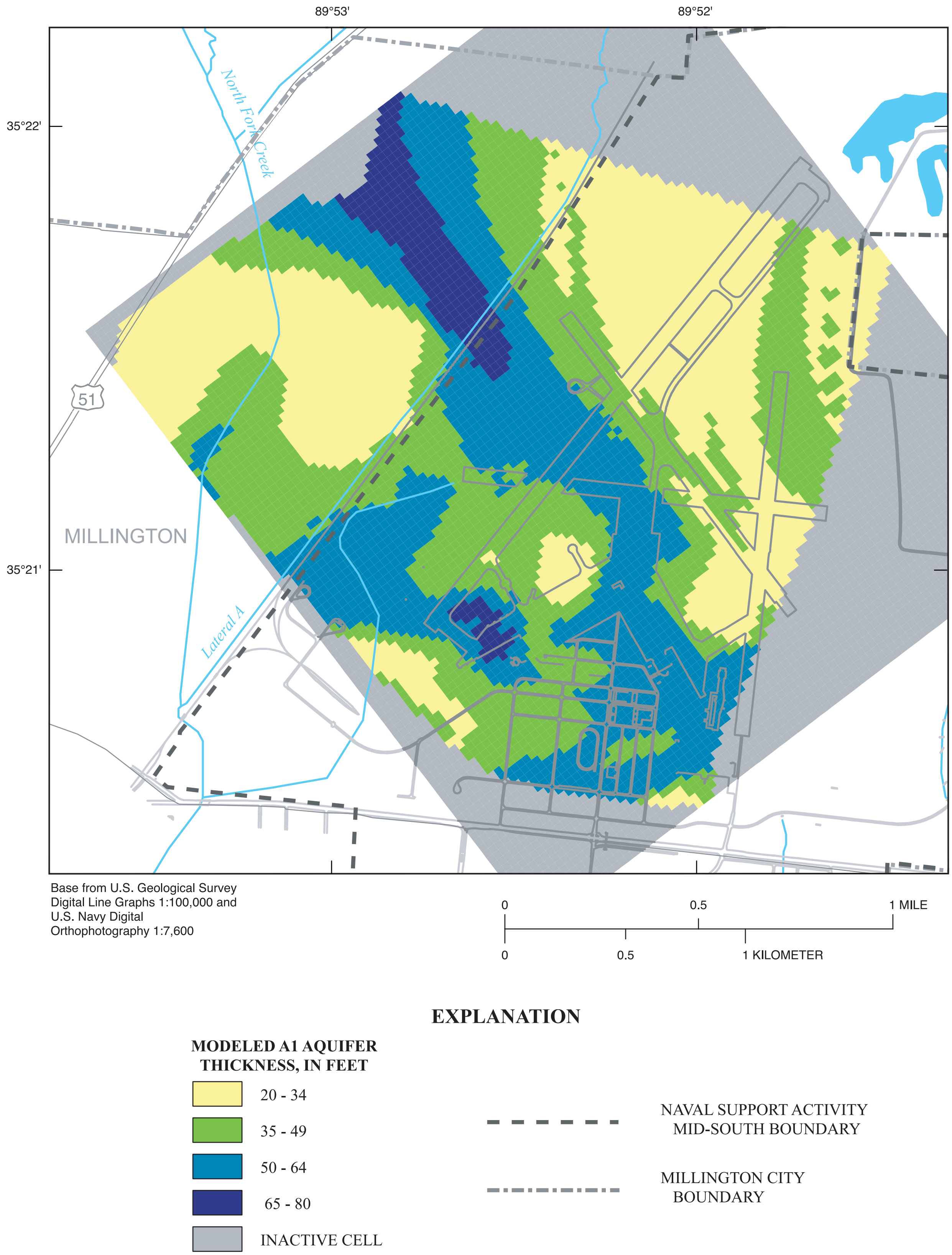


Figure 12. Thickness of the modeled A1 aquifer, Naval Support Activity Mid-South, Millington, Tennessee.

Table 2. Recharge and hydraulic conductivity parameters defined in the Area of Concern A flow model, Naval Support Activity Mid-South

Model parameter	Description
RECH	Recharge rate to the A1 aquifer from leakage from the overlying loess
HK_Average	Hydraulic conductivity in layer 3 for the model area outside the scarp area and southeast of the main runway. The A1 aquifer in this area consists of the alluvial-fluvial deposits aquifer. Hydraulic conductivity of layers 2 and 1 in this area is calculated by multiplying the parameter HK_Average by 0.5 and 0.25, respectively.
HK_High	Hydraulic conductivity in layer 3 for the area outside the scarp area and northwest of the main runway. The A1 aquifer in this area consists of the alluvial-fluvial deposits aquifer. Hydraulic conductivity of layers 2 and 1 in this area is calculated by multiplying the parameter HK_High by 0.5 and 0.25, respectively.
HK_ScarpA	Hydraulic conductivity in layers 1, 2, and 3 for the scarp area. The A1 aquifer in this area consists of the upper part of the Cockfield aquifer.
HK_ScarpB	Hydraulic conductivity in layers 1, 2, and 3 for a transition area near the edge of the scarp. The A1 aquifer in this area consists of both the alluvial-fluvial deposits aquifer and the upper part of the Cockfield aquifer.
VANI	Ratio of the horizontal to vertical hydraulic conductivity

data including aquifer tests, slug tests, and borehole-flowmeter measurements, as well as on supplemental data from pumping rates, drawdown, and water-level recovery during well sampling. Each of the layers contains four hydraulic-conductivity zones (fig. 13). The highest conductivity zone (HK_High) is in the northwestern part of the model area where slug tests and the multiple-well aquifer test conducted by EnSafe, Inc., (written commun., 2000), indicate the highest horizontal hydraulic conductivities for the alluvial-fluvial deposits aquifer at AOC A. Based on 12 measured values, hydraulic conductivities in this zone range from 45 to 68 ft/d with a median value of 61 ft/d. The lowest conductivity zones (HK_ScarpA and HK_ScarpB) are located in the scarp area in the eastern part of the model area. In the HK_ScarpA zone, the aquifer consists of the upper part of the Cockfield aquifer. In the HK_ScarpB zone, the aquifer consists of both the alluvial-fluvial deposits aquifer and the upper part of the Cockfield aquifer. Based on 14 measured values, horizontal hydraulic conductivities in the upper part of the Cockfield Formation range from 0.5 to 3 ft/d with a median value of 1.0 ft/d (Robinson and others, 1997). The other conductivity zone (HK_Average) is located in the center and southern part of the model area where slug tests and a multiple-well aquifer test indicate hydraulic conductivities to be about an order of magnitude lower than the HK_High zone. Based on 10 measured values, horizontal hydraulic conductivities in this zone range from 5 to 40 ft/d (excluding one outlier of 150 ft/d) with a median value of 13 ft/d (Robinson and others, 1997).

Each model layer contains four hydraulic-conductivity zones. The layers are set up such that hydraulic conductivity increases with depth by a factor of two between layers in zones HK_High and HK_Average. Hydraulic conductivity is constant in all layers in zones HK_ScarpA and HK_ScarpB (table 3).

Transmissivity for each cell was calculated by the model using hydraulic-conductivity and layer or saturated thickness data, both of which vary areally. The model layers were assumed to be hydraulically well connected and not separated by confining material. The vertical hydraulic conductivity was modeled as a constant ratio of the horizontal hydraulic-conductivity value.

Model Calibration

The process of adjusting the input variables to produce the best match between simulated and observed water levels and flows is known as calibration. The model developed for this study was calibrated to steady-state conditions as defined by the potentiometric-surface map of the A1 aquifer for February and March 2000 (fig. 7). Because no ground water discharges to surface features within the modeled area, ground-water discharge fluxes could not be used to aid in model calibration. The recharge flux into the model (leakage from the overlying loess) is difficult to measure in the field, so no independent measurements of this flux are available. Therefore, data to calibrate the model are limited to matching observed water levels and measured hydraulic-conductivity values. To provide additional information to help calibrate the model, an advective-flow observation was added (Anderman and Hill, 1997; Hill and others, 2000). An advective-flow observation requires specifying two observation points, the advective travel time between the points, and the aquifer porosity. The starting and ending points for the advective-flow observation were at the southeastern end of the main TCE plume and the northwestern edge of the former Northside property boundary where the TCE plume crosses this boundary (fig. 3). An advective travel time of 40 years was estimated based on ground-water velocities of between 30 and 140 ft/yr determined for two different zones by Ensafe, Inc. (written commun., 2000). This travel time is consistent with the estimated site disposal history. An aquifer effective porosity of 25 percent was assumed (Robinson and others, 1997).

The AOC A model was calibrated using a combination of automated and manual methods to minimize the difference

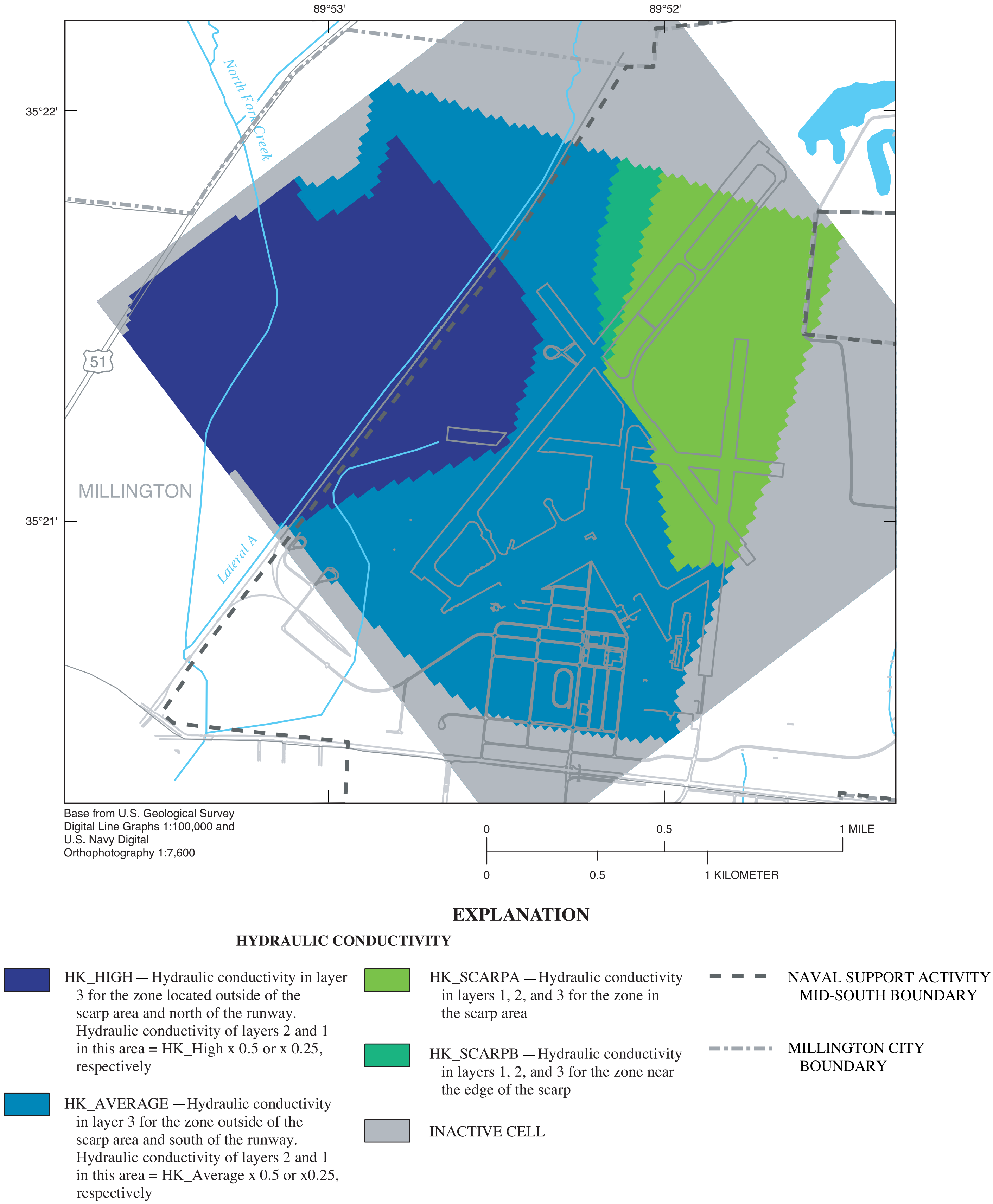


Figure 13. Hydraulic conductivity zones for the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

Table 3. Relation between hydraulic conductivity parameters and hydraulic conductivity by layers for the Area of Concern A flow model, Naval Support Activity Mid-South

	Hydraulic conductivity zone			
	HK_Average	HK_High	HK_ScarpA	HK_ScarpB
Layer 1	0.25 * HK_Average	0.25 * HK_High	HK_ScarpA	HK_ScarpB
Layer 2	0.5 * HK_Average	0.5 * HK_High	HK_ScarpA	HK_ScarpB
Layer 3	HK_Average	HK_High	HK_ScarpA	HK_ScarpB

between simulated and measured water levels, and the simulated and estimated advective travel time. These observations were weighted, as described by Hill (1998), to account for the greater accuracy in the measured water levels and lesser accuracy in the estimated advective travel time. The four most sensitive parameters (HK_High, HK_Average, HK_ScarpA, and RECH) were estimated using the parameter-estimation process in MODFLOW-2000. The two least sensitive parameters, HK_ScarpB and the ratio of horizontal to vertical hydraulic conductivity (VANI), were calibrated manually during the calibration process.

Overall, simulated water levels (fig. 14) agree reasonably well with measured water levels (fig. 7). Water levels were available for comparison at 68 wells. The root mean square error (RMSE) was calculated to compare simulated and measured water levels. The RMSE, in feet, is calculated by

$$RMSE = \sqrt{\left(\sum_{i=1}^{N} \langle h_i^m - h_i^c \rangle^2\right) / N} \qquad (1)$$

where

N is the number of observations;
h_i^m is the measured water level, in feet; and
h_i^c is the simulated water level, in feet.

The RMSE for water levels is 1.1 ft. The average difference between measured and simulated water levels for the calibration model simulation is 0.04 ft. Sixty-two percent of the simulated water levels are within 1 ft of the observed water levels and 96 percent are within 2 ft. The errors or residuals in simulated water levels show no significant spatial pattern; however, in a small area in the southeastern corner of the model, simulated water-levels tended to be consistently higher than observed water levels.

Calibrated horizontal hydraulic conductivities for the AOC A flow model range from 1.2 to 65 ft/d (table 4). These values are comparable to measured values from well hydraulic tests (Robinson and others, 1997, table 3; Ensafe, Inc., written commun., 2000). Calibrated transmissivities for layer 1 vary from 7.9 to 430 ft^2/d (fig. 15) with an average of 110 ft^2/d and a median of 61 ft^2/d. The highest transmissivities in layer 1 are in the northwestern part of the model area where a thick section of the alluvial-fluvial deposits aquifer coincides with higher than average hydraulic-conductivity values. Calibrated transmissivities for layer 2 vary from 7.9 to 870 ft^2/d (fig. 16) with an average of 220 ft^2/d and a median of 120 ft^2/d. Calibrated transmissivities for layer 3 vary from 7.9 to 1,700 ft^2/d (fig. 17) with an average of 430 ft^2/d and a median of 240 ft^2/d. The calibrated hydraulic conductivities used in this model are greater than the conductivities used by Robinson and others (1997) for the basewide flow model. The higher calibrated values for the AOC A model are the result of data collected from additional wells and the EnSafe, Inc., aquifer test that indicates hydraulic conductivities of the alluvial-fluvial deposits aquifer at AOC A are higher than the value of about 5 ft/d assumed to be representative of this aquifer by Robinson and others (1997). Additionally, the areal and vertical distribution of hydraulic conductivities at AOC A are now better understood on the basis of additional data collected since 1997.

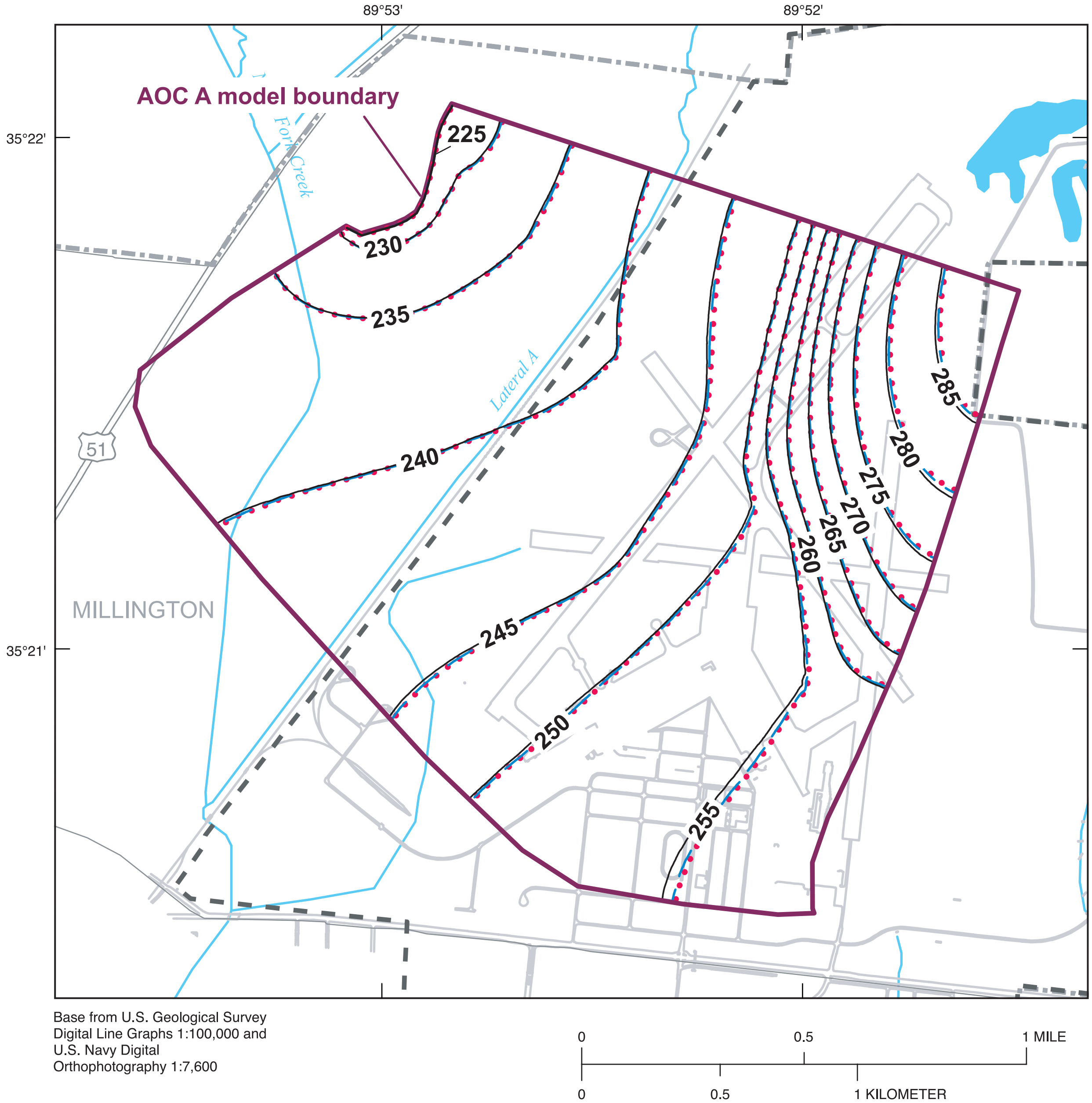
The ratio of horizontal to vertical hydraulic conductivity (VANI) for the calibrated AOC A flow model is 100. This ratio is supported by horizontal and vertical hydraulic-conductivity data presented in Robinson and others (1997, tables 2 and 3).

The AOC A flow model calibrated recharge rate is 1.82 in/yr. This recharge rate is higher than the natural recharge rate of 0.32 in/yr used in the basewide ground-water model by Robinson and others (1997). The basewide model also included anthropogenic recharge in some areas at rates between 0.67 and 1.8 in/yr. The AOC A area, however, had no anthropogenic recharge applied in the basewide model. Differences in these recharge rates are discussed in the section “Model Limitations.” This recharge rate of 1.82 in/yr results in a ground-water flux of 0.31 ft^3/s through the model. This is the total flux through the model because recharge is the only source of water for the model. All water leaves the model through the constant-head boundary near the northwestern edge of the model area.

Many of the estimated parameters for the calibrated AOC A flow model show high correlation coefficients (table 5).

Table 4. Calibrated hydraulic conductivities of the Area of Concern A flow model, Naval Support Activity Mid-South

	Calibrated hydraulic conductivity, in feet per day			
	HK_Average	HK_High	HK_ScarpA	HK_ScarpB
Layer 1	3.6	16	1.2	8.0
Layer 2	7.3	32	1.2	8.0
Layer 3	15	65	1.2	8.0



EXPLANATION

255 — POTENTIOMETRIC CONTOUR—Shows simulated altitude of water level. Contour interval 5 feet. Datum is NGVD 29

- Layer 1
- Layer 2
- Layer 3

NAVAL SUPPORT ACTIVITY MID-SOUTH BOUNDARY

MILLINGTON CITY BOUNDARY

Figure 14. Simulated steady-state water levels for layers 1, 2, and 3 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

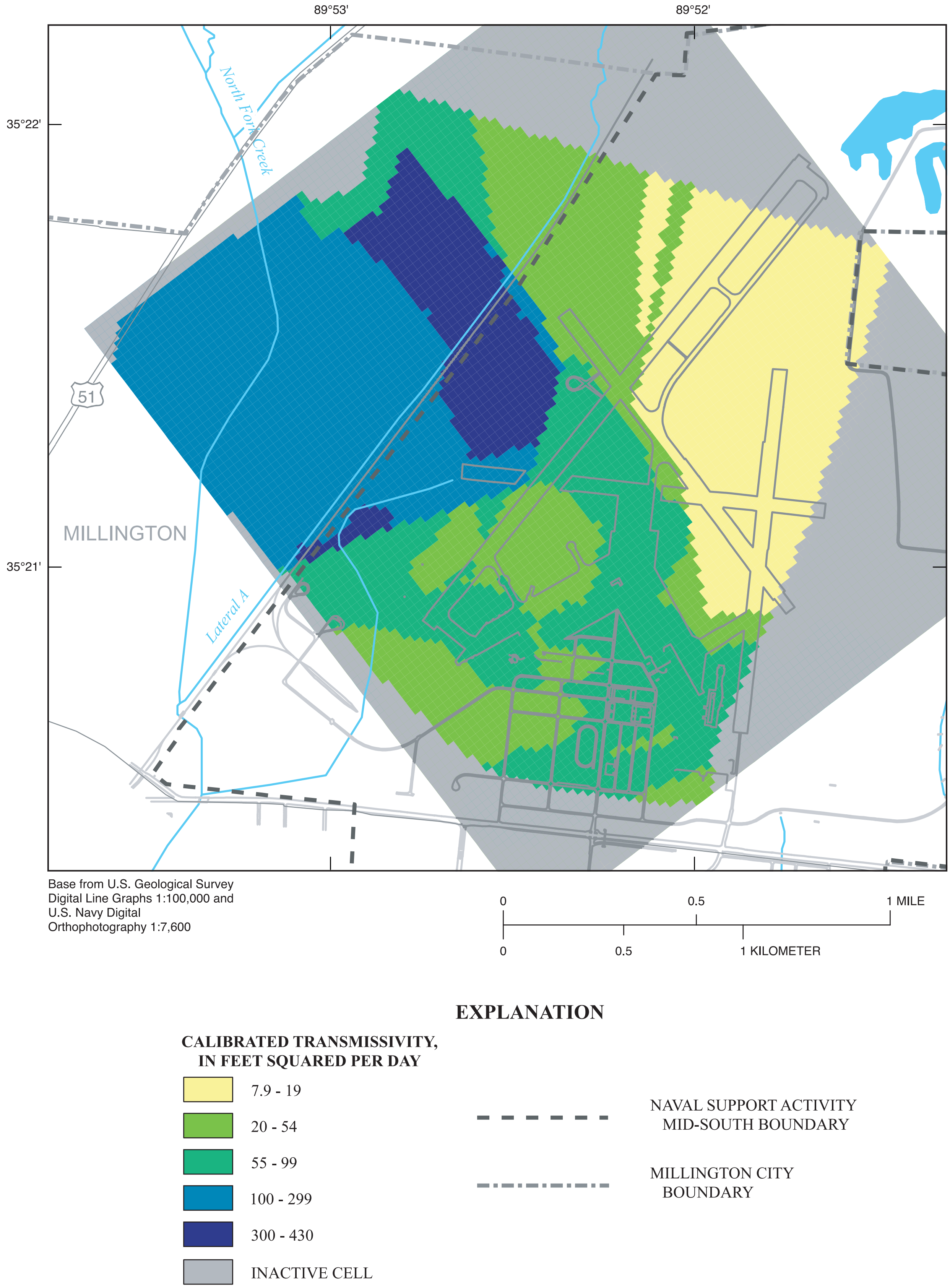


Figure 15. Calibrated transmissivities for layer 1 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

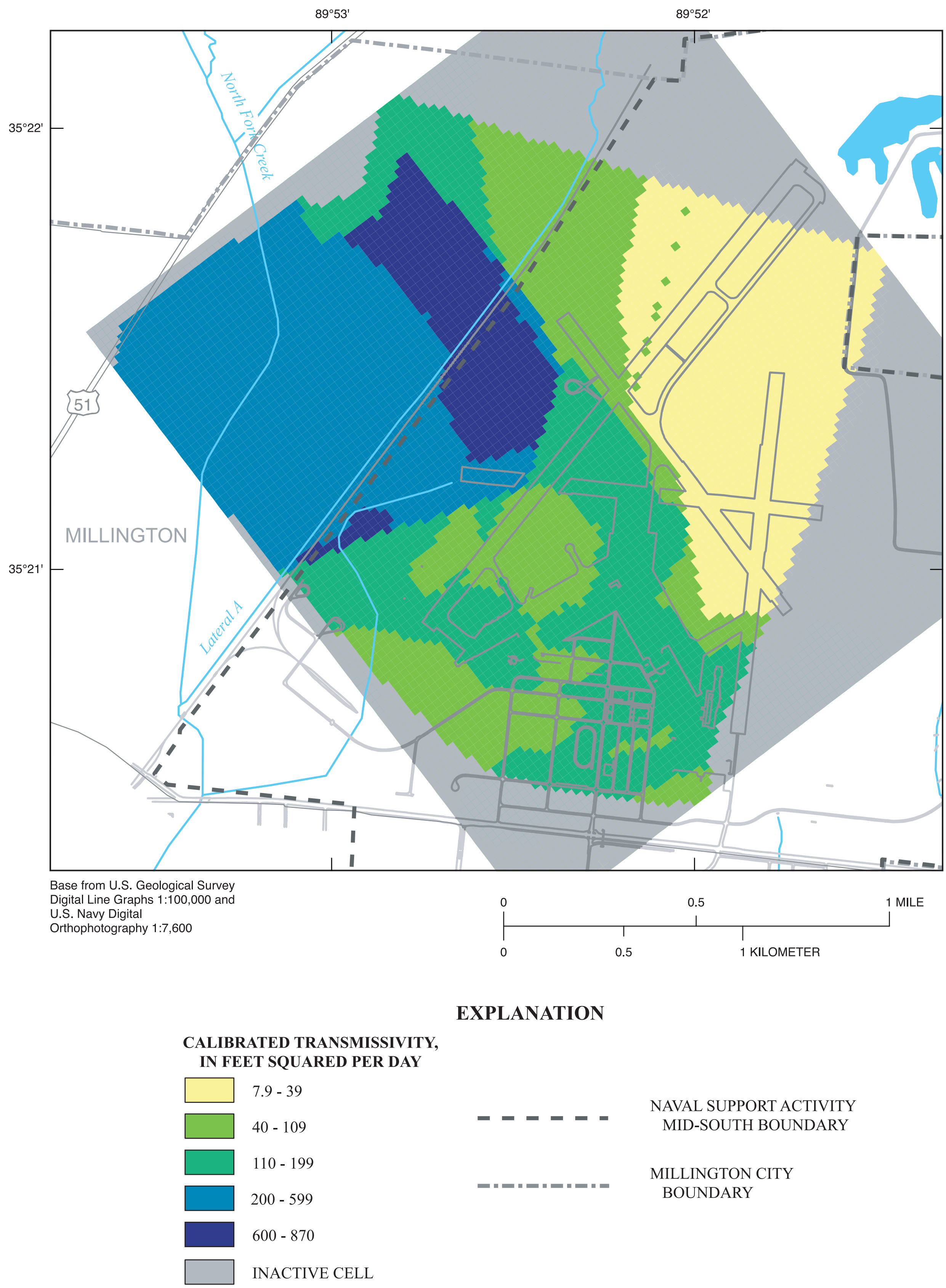


Figure 16. Calibrated transmissivities for layer 2 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

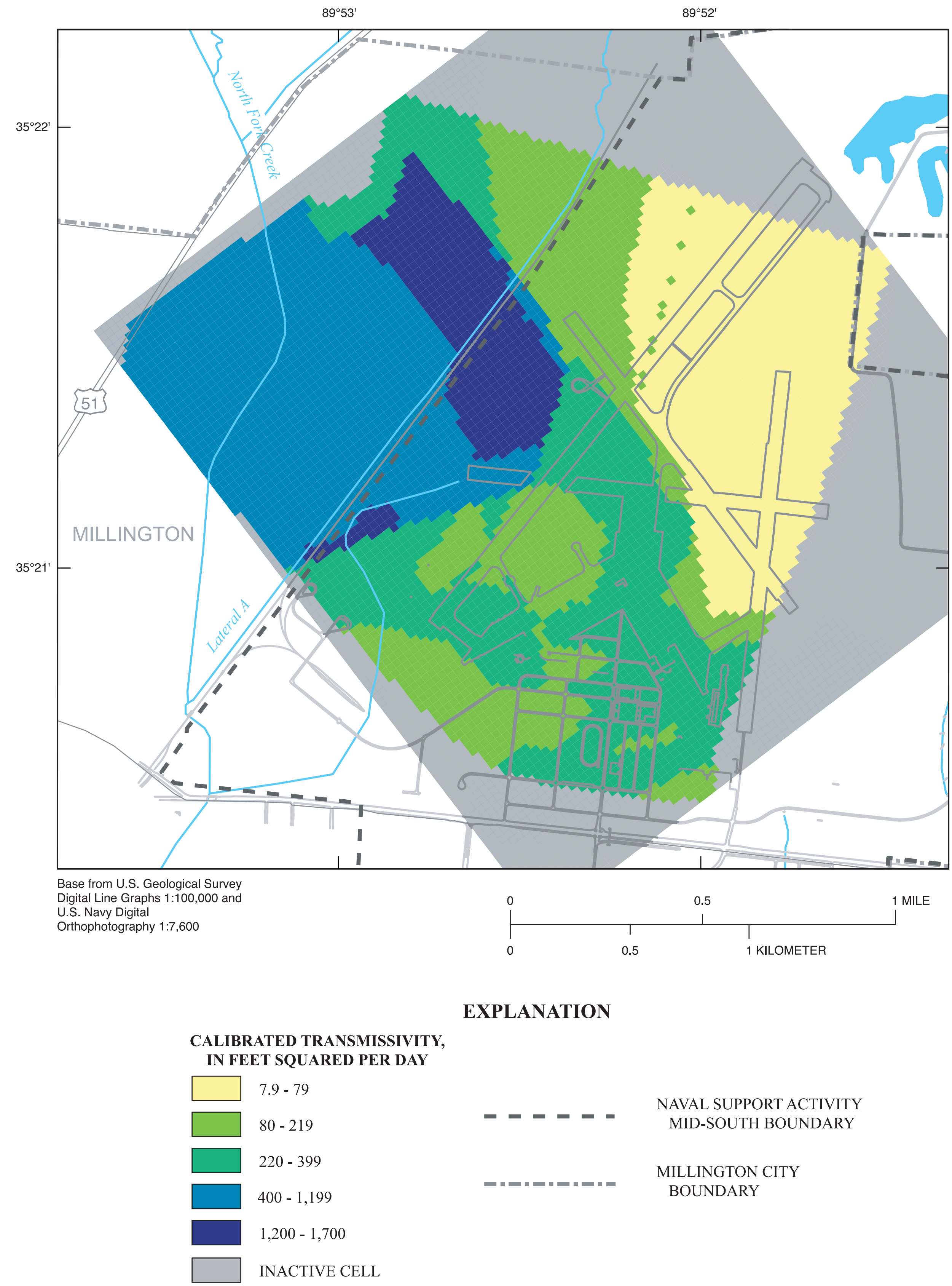


Figure 17. Calibrated transmissivities for layer 3 of the Area of Concern (AOC) A flow model, Naval Support Activity Mid-South, Millington, Tennessee.

Table 5. Correlation coefficients between estimated parameters of the Area of Concern A flow model, Naval Support Activity Mid-South

Estimated parameters	Correlation coefficients			
	RECH	HK_High	HK_Average	HK_ScarpA
RECH	1.00			
HK_High	0.97	1.00		
HK_Average	0.98	0.91	1.00	
HK_ScarpA	0.98	0.95	0.96	1.00

When parameters are correlated, the parameter-estimation process may not have enough information to estimate parameters individually and may estimate only the ratio or sums of parameters. To determine if the parameters were uniquely estimated, the parameter estimation was run from several different sets of starting parameter values. In each case, the regression converged to the same final values. This result indicates that the final values probably were estimated individually. Testing during model calibration indicates that without the advective-flow observation, parameters could not have been estimated individually.

Sensitivity Analysis

Composite scaled sensitivities were calculated for the calibrated AOC A flow model by using the sensitivity process in MODFLOW-2000 for all the hydraulic-conductivity and recharge parameters (fig. 18). Hill and others (2000) describe how sensitivities can be calculated for any of the model parameters discussed by Harbaugh and others (2000). Composite scaled sensitivities can be used to compare the importance of different parameters to the calculation of model simulated water levels and flows (Hill, 1998). Parameters with greater composite sensitivities have greater importance and influence on the model solution. The most sensitive parameter in the AOC A flow model is the recharge rate (RECH). The next most sensitive parameter is the hydraulic conductivity for the average zone (HK_Average), followed by the hydraulic conductivity for the high zone (HK_High). The model is least sensitive to the hydraulic conductivity in the scarp area (HK_ScarpA and HK_ScarpB) and the ratio of horizontal to vertical hydraulic conductivity (VANI).

Model Limitations

The AOC A flow model is calibrated as a steady-state model to water levels measured in the study area in February and March 2000. These measurements are assumed to be representative of long-term average conditions; however, not enough long-term water-level data exist for the study area to define the actual long-term average conditions. The flow paths investigated in the study area are estimated to be about 40 years old, but continuous water-level data are available for only about 9 years at well Sh:U-101 screened in the fluvial deposits at AOC A (fig. 8). If conditions in the aquifer have changed significantly over the past 40 years, the model flow field may not be representative of long-term conditions in the aquifer. The hydrograph shows no obvious trends, increasing or decreasing, in water levels for the period of record. Overall, water levels for the February and March 2000 map are about 3 ft lower than the average of the water levels for April and October 1996 that were used by Robinson and others (1997) to calibrate the basewide model, but the horizontal gradients across the study area are similar. Therefore, the assumption that the aquifer is at steady state is considered adequate to investigate flow paths within the study area.

The AOC A model is consistent with the current conceptual model of ground-water flow and assumed boundary conditions. However, the model, by necessity, is a simplified approximation of the actual ground-water system at AOC A. For example, the model simulates known variations in hydraulic conductivity, both areally and with depth, by using four hydraulic-conductivity zones and three layers, but this representation of the aquifer still is a simplification of the actual spatial variations and patterns of aquifer properties. Similarly, the model uses a uniform recharge rate to simulate water leakage through the loess. The actual recharge rate probably varies spatially, but the processes that control water movement through the loess are poorly understood; therefore, the spatial pattern of recharge was assumed to be uniform. Additionally, the model cannot provide simulations on a scale finer than the grid resolution.

The model provides a reasonable match to measured water levels and gradients (figs. 7 and 14), but no independent check on the model flux (recharge or discharge) is available. This lack of an independent check on model flux is the most important limitation of the flow model. Robinson and others (1997,

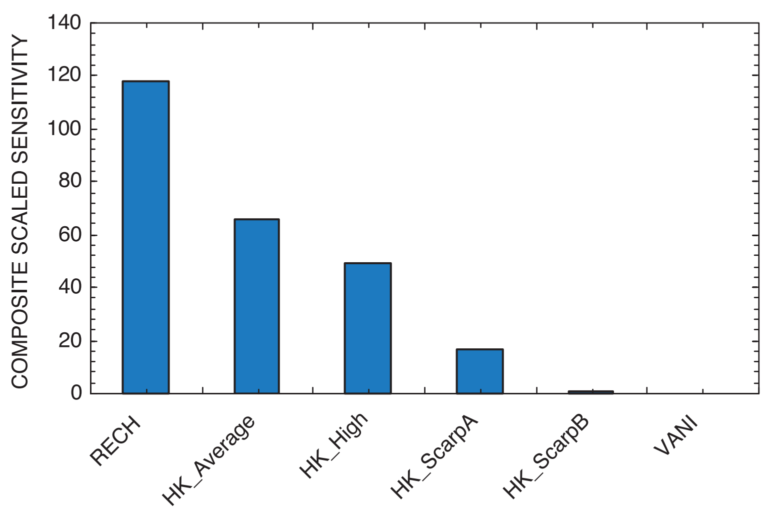


Figure 18. Composite scaled sensitivities for Area of Concern (AOC) A flow model parameters, Naval Support Activity Mid-South, Millington, Tennessee.

p. 45-46) clearly explain this limitation with the basewide model. With no independent measurement of the recharge flux, any constant ratio of recharge flux and hydraulic conductivity will produce the same simulated potentiometric surface. Therefore, in both of these models, the calibrated value of recharge is directly dependent on the values and distribution of hydraulic conductivity. This explains why the AOC A model presented in this report has a higher value of recharge (1.82 in/yr) than that used for the AOC A area of the basewide model (0.32 in/yr) of Robinson and others (1997). The basewide model assumed a constant hydraulic conductivity of about 5 ft/d for the alluvial-fluvial deposits aquifer based on the aquifer test conducted south of the western end of the airfield apron. Additional data and well tests indicated that the hydraulic conductivity in parts of the alluvial-fluvial deposits aquifer at AOC A is higher than 5 ft/d. The basewide model underestimated the hydraulic conductivity at AOC A and therefore underestimated the recharge rate. Given that the hydraulic-conductivity values and distribution have been better defined at AOC A since 1997, the calibrated recharge rate of 1.82 in/yr should be a more realistic estimate of recharge for the area, but this estimate still is limited by the confidence in the hydraulic-conductivity data.

The advective-flow observation helps overcome the lack of ground-water flux data and allows the conductivity and recharge parameters to be estimated individually. Although the mapped contaminant plume clearly defines the advective flow path, the estimate of the advective travel time is uncertain. The exact time when the contaminants were released to the aquifer is unknown. Other factors such as dispersion, retardation, and degradation affect travel times, causing the contaminants to move faster or slower than the ground water. An advective travel time of 40 years used to calibrate the AOC A model is consistent with all known data and results in estimates of parameters that are within expected ranges. If the advective travel time is actually 30 years, then the model would converge to higher parameter values for hydraulic conductivity and recharge, but the ratio of conductivity to recharge remains constant. Similarly, if the advective travel time is actually 50 years, then the model would converge to lower parameter values for hydraulic conductivity and recharge (table 6).

Advective Flow Particle Tracking

Ground-water-flow paths were simulated from two sites at AOC A suspected as being contaminant-plume source areas. The sites simulated as source areas are the “grassy area” and the “north edge of apron” (fig. 19). MODPATH, a particle-tracking program (Pollock, 1994), was used to simulate ground-water-flow directions and times-of-travel from these areas. The particle-tracking analysis does not account for physical and chemical processes such as dispersion, sorption, or degradation that would cause dissolved contaminants to move at velocities different from the average ground-water velocity. A contaminant plume, as the result of dispersion, also would spread out more than the advective flow paths indicated. A uniform effective porosity of 25 percent was assumed for the particle-tracking analysis conducted for this study (Robinson and others, 1997). The flow paths indicated by the particle tracking (fig. 19) agree reasonably well with the interpreted maps of TCE plumes (fig. 3). The time-of-travel plots show that travel times from the north edge of the apron area source to the model boundary are faster than travel times from the grassy area source to the same boundary. Particles originating at the north edge of the apron area source enter the high hydraulic conductivity zone of the A1 aquifer sooner than particles originating from the grassy area source, which decreases their travel time to the boundary. This simulation illustrates how the distribution of hydraulic conductivities can affect travel times.

Table 6. Estimated parameter values using alternate advective travel times, Area of Concern A flow model, Naval Support Activity Mid-South

Parameter	Advective travel times		
	30 years	40 years	50 years
RECH (inches)	2.47	1.86	1.49
HK_High (feet/day)	86.3	65.0	52.0
HK_Average (feet/day)	19.3	14.6	11.6
HK_ScarpA (feet/day)	1.57	1.17	0.929

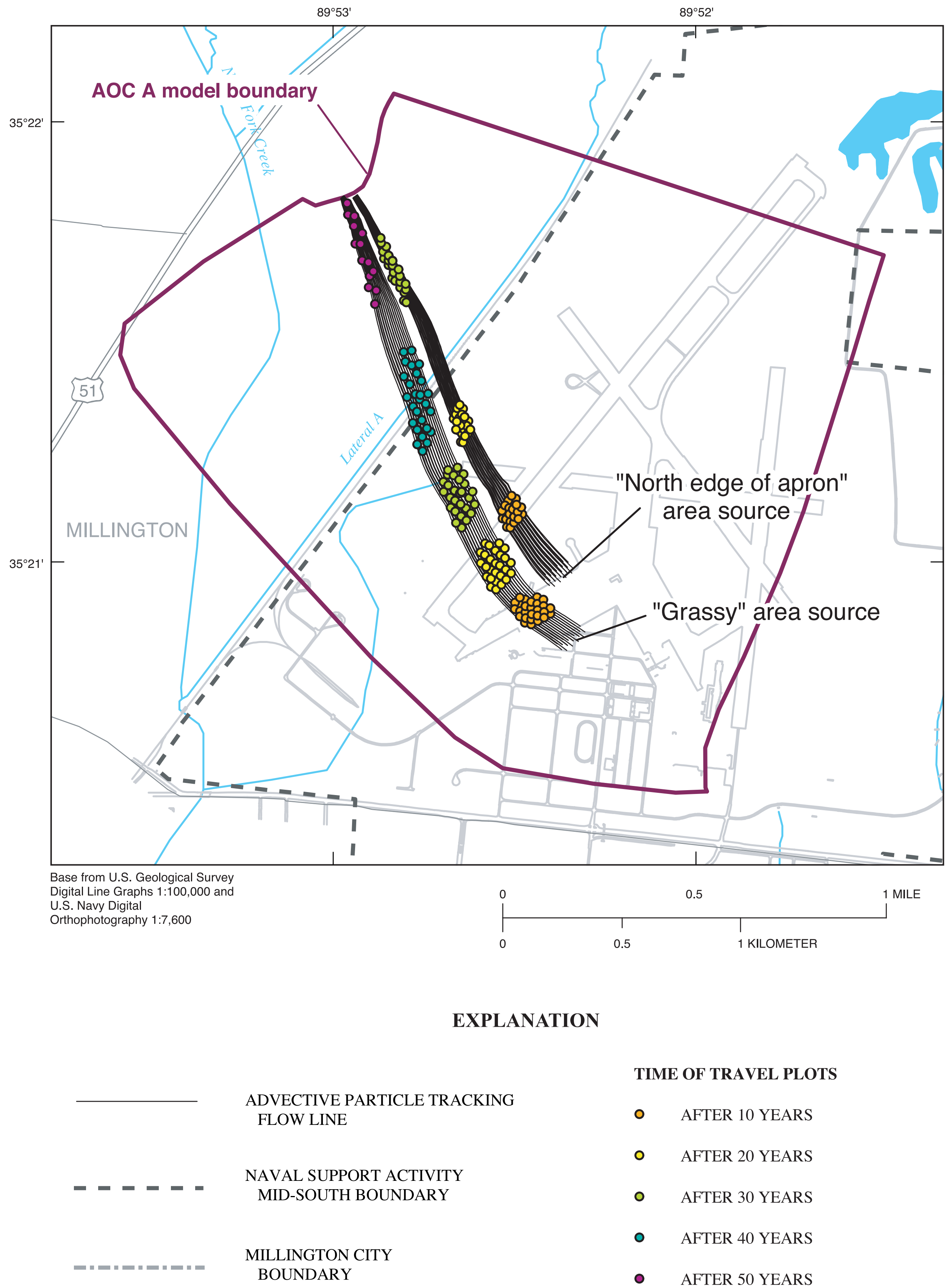


Figure 19. Advective flow path lines from the "grassy" area and "north edge of apron" area at Area of Concern (AOC) A, Naval Support Activity Mid-South, Millington, Tennessee.

Summary and Conclusions

Naval Support Activity (NSA) Mid-South is a Department of the Navy base located in Millington, Tennessee. During environmental investigations at the base, plumes of dissolved chlorinated solvents resulting from past aircraft maintenance and training operations were identified in shallow ground water beneath the airfield area. The area containing the plumes has been designated as Area of Concern (AOC) A. Chlorinated solvents, primarily trichloroethene, are the principal contaminants in the ground water at AOC A. The nature and extent of the primary plumes at AOC A were addressed during a Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI), and selected options for remediation currently (2004) are being implemented under a corrective action program.

Geologic units of primary importance to hydrogeologic investigations conducted under the RFI at AOC A include the alluvium, loess, fluvial deposits, and Cockfield Formation. Saturated and hydraulically connected sections of the lower, coarse-grained part of the alluvium and the fluvial deposits constitute the alluvial-fluvial deposits aquifer, the primary part of the shallow aquifer at NSA Mid-South. Within the AOC A study area, the alluvial-fluvial deposits aquifer is interpreted as comprising only the fluvial deposits because the coarse-grained lower part of the alluvium is absent beneath the middle and upper reaches of the alluvial valleys of North Fork Creek and its tributary Lateral A located in the western part of the area. The upper, fine-grained sections of the alluvium and loess generally retard recharge to and serve as the upper confining unit for the alluvial-fluvial deposits aquifer, and clay in the Cockfield Formation and underlying Cook Mountain Formation serve as the lower confining unit for the aquifer and the upper confining unit for the Memphis aquifer. Discontinuous saturated sand lenses are present locally in the Cockfield Formation and constitute the Cockfield aquifer. Within the AOC A study area, the alluvial-fluvial deposits and Cockfield aquifers are interpreted as hydraulically connected across an erosional scarp in the Cockfield Formation located in the northern part of the area.

Recent investigations at and near the facility have produced new data prompting updates to two USGS reports published in 1997. The updates consist primarily of (1) refinements to geologic structure maps presented in the 1997 reports that show the altitude of the base of the loess or silt and clay in the upper alluvium, and the altitude of the base of sand and gravel in the lower alluvium or fluvial deposits at AOC A on the basis of data collected from new wells at on- and off-base locations; (2) additional hydraulic-conductivity data for the alluvial-fluvial deposits aquifer at AOC A from a multiple-well, 24-hour constant-rate-withdrawal aquifer test conducted by EnSafe, Inc., in 1999; and (3) construction of a potentiometric-surface map of the A1 aquifer for the northern part of the NSA Mid-South area for February and March 2000 water-level conditions. As part of the study, the USGS also developed and calibrated a numerical ground-water-flow model of AOC A.

A steady-state model of the shallow aquifer at AOC A was constructed and calibrated to conditions of February and March 2000. Following model calibration, a particle-tracking simulation was used to analyze ground-water-flow paths and time-of-travel from selected locations suspected as being contaminant source areas within AOC A. The modeled aquifer, designated as the A1 aquifer for a previous modeling study at NSA Mid-South, consists of the alluvial-fluvial deposits aquifer within most of the modeled area and the upper part of the Cockfield aquifer in the scarp area and to the northeast. The A1 aquifer in this study was divided into three layers to simulate vertical variations in lithology and hydraulic conductivity in the fluvial deposits. Horizontal hydraulic conductivity of the alluvial-fluvial deposits aquifer at AOC A increases with depth; therefore, in areas where the A1 aquifer consists of the alluvial-fluvial deposits aquifer, layer 1 has the lowest hydraulic conductivity and layer 3 has the highest hydraulic conductivity. In the scarp area and to the northeast, where the alluvial-fluvial deposits are unsaturated and the A1 aquifer consists of the upper part of the Cockfield aquifer, hydraulic conductivity is assumed to be constant with depth. Recharge to the modeled aquifer occurs as leakage from the overlying loess. Ground water does not discharge to streams or springs anywhere in the model area. Ground water leaves the modeled area through a constant head boundary at the 225-ft potentiometric contour that defines a depression in the potentiometric surface in the alluvial-fluvial deposits aquifer. This constant-head boundary is near an area where the alluvial-fluvial deposits aquifer thickens and the Cockfield Formation thins. Downward leakage of water locally occurs from the alluvial-fluvial deposits aquifer through the Cockfield and Cook Mountain confining units and is indicated by observed water levels in the alluvial-fluvial deposits aquifer in this depression that are approximately equal in altitude to water levels in the Memphis aquifer in this area.

The model developed for this study was calibrated to steady-state conditions as defined by the potentiometric-surface map for February and March 2000. The model was calibrated to observed water levels and measured hydraulic-conductivity values. To provide additional information to help calibrate the model, an advective-flow observation was added. Overall, simulated water levels agree reasonably well with measured water levels. Water levels were available for comparison at 68 wells. The RMSE for water levels is 1.1 ft. The average difference between measured and simulated heads for the calibrated model is 0.04 ft.

Calibrated horizontal hydraulic conductivities for the AOC A flow model range from 1.2 to 65 ft/d. The calibrated hydraulic conductivities used in the AOC A model are greater than the value of 5.3 ft/d used for the "basewide" model of NSA Mid-South calibrated in 1996. The higher calibrated values for the AOC A model are the result of data from the 1999 aquifer test that indicate hydraulic conductivities in parts of the alluvial-fluvial deposits aquifer at AOC A are higher than previously determined.

The AOC A flow model calibrated recharge rate is 1.82 in/yr. This recharge rate is higher than the natural recharge rate of 0.32 in/yr used in the basewide ground-water model. The higher recharge rate also is the result of hydraulic conductivity values being higher in the AOC A study area than previously determined.

The model provides a reasonable match to measured water levels and gradients, but no independent check on the model flux (recharge or discharge) is available. This lack of an independent check on model flux is the most important limitation of the flow model. With no independent measurement of the recharge flux, any constant ratio of recharge flux and hydraulic conductivity will produce the same simulated potentiometric surface. Given that the hydraulic conductivity values and distribution have been better defined within AOC A, the calibrated recharge rate of 1.82 in/yr should be a more realistic estimate of recharge for the area, but this estimate still is limited by the confidence in the hydraulic-conductivity data.

Many of the estimated parameters for the calibrated AOC A flow model show high correlation coefficients. Testing during model calibration indicates that without the advective-flow observation, parameters could not have been estimated individually. The advective-flow observation helps overcome the lack of ground-water flux data and allows the hydraulic conductivity and recharge parameters to be estimated individually. The most sensitive parameter in the AOC A flow model is the recharge rate (RECH). The next most sensitive parameter is the hydraulic conductivity for the average zone (HK_Average), followed by the hydraulic conductivity for the high zone (HK_High).

Ground-water-flow paths were simulated from two suspected contaminant-plume source areas at AOC A. The sites simulated as source areas are the “grassy area” and the “north edge of apron” area. The flow paths indicated by the particle tracking agree reasonably well with the interpreted maps of TCE plumes. The time-of-travel plots show that travel times from the north edge of the apron source to the model boundary are faster than travel times from the grassy area source to the same boundary.

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