U.S. Department of the Interior
U.S. Geological Survey

Hydrogeology and Ground-Water Flow of the Shallow Aquifer System at the Naval Surface Warfare Center, Dahlgren, Virginia

Water-Resources Investigations Report 99-4149

Prepared in cooperation with the

SAFETY AND ENVIRONMENTAL OFFICE
NAVAL SURFACE WARFARE CENTER
DAHLGREN, VIRGINIA

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By Barry S. Smith

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Richmond, Virginia
1999

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CONVERSION FACTORS, ABBREVIATIONS, VERTICAL DATUM, AND HYDRAULIC CONDUCTIVITY

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09290	square meter
square inch (in^2)	6.452	square centimeter
square mile (mi^2)	2.590	square kilometer
	Volume	
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day

Temperature in degrees Celsius (C) may be converted to degrees Fahrenheit (F) as follows: $°F = (1.8 \times °C) + 32$

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

Altitude, as used in this report, refers to distance above or below sea level.

Hydraulic conductivity: Hydraulic conductivity is reported in foot per day (ft/d), a mathematical reduction of the unit square foot per day per foot of thickness [(ft^2/d)/ft].

Hydrogeology and Ground-Water Flow of the Shallow Aquifer System at the Naval Surface Warfare Center, Dahlgren, Virginia

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ABSTRACT

The possible migration of contaminants by ground-water flow at the Naval Surface Warfare Center (NSWC) at Dahlgren, Va., is a concern of the U.S. Navy. Ground water in the Dahlgren area flows through a layered sedimentary system of aquifers and intervening confining units. The hydrogeologic units of the shallow aquifer system at the NSWC are the surficial aquifer, the upper confining unit, the upper confined aquifer, the Nanjemoy-Marlboro confining unit, and the Aquia aquifer.

Maps and data defining the geometry of the aquifers and confining units at the NSWC were assimilated from previous investigations, expanded, and refined. Medians were determined for water levels measured in 64 observation wells at the NSWC from 1992 and 1994 through the spring of 1998. Median and geometric means were determined for horizontal hydraulic conductivities from published single-well aquifer (slug) tests at the NSWC. Medians and geometric means were determined for vertical hydraulic conductivities from published falling-head permeameter tests at the NSWC.

A steady-state, three-dimensional ground-water flow model was used to analyze the shallow aquifer system in the Dahlgren area. The model was calibrated by minimizing the root mean square error between simulated water levels and the medians of measured water levels at the NSWC. The calibrated model was then used to determine the ground-water budget, to depict ground-water flow vectors, and to delineate general flow paths and ground-water traveltimes for selected areas of the NSWC.

The shallow aquifer system of the Dahlgren area is recharged by local precipitation, most of which also is discharged from the surficial aquifer. Ground-water discharge from the shallow aquifer system seeps out of the banks of streams and ditches or leaks upward to the rivers, wetlands, and estuaries of the Dahlgren area. Water levels in the upper confined aquifer are similar to those of the surficial aquifer, but the levels are lower beneath the interstream areas and slightly higher beneath the rivers, wetlands, and estuaries than those of the surficial aquifer. Ground water generally leaks downward and flows outward from higher ground in the west or from central interstream areas beneath the flat terrace plain and then outward and upward to discharge through the intervening upper confining unit to the streams, wetlands, and estuaries.

Ground water flows through the Aquia aquifer from the northwest toward the southeast because of regional ground-water withdrawals. The Aquia is separated from the shallower aquifers by a relatively thick and continuous confining unit, the Nanjemoy-Marlboro Clay.

Ground-water flow in the surficial aquifer at the Open Burn and Open Detonation area of the NSWC is toward the north, east, and south, as indicated by vectors of the calibrated model. Flow velocities are slow beneath the flat ground of the Open Burn and Open Detonation area.

Ground-water flow paths in the surficial aquifer diverge radially from the airfield at the NSWC and imply a wide range in possible directions and traveltimes for the advective flow of potential contaminants. If the hydraulic properties of the shallow aquifer system are consistent, as simulated by the ground-water flow model, the

potential spread of contaminants by advective ground-water flow at any particular site at the NSWC would depend on the location of the site with respect to the interstream areas and the discharge areas.

Ground-water traveltimes through the upper confining unit and the upper confined aquifer are measured in hundreds of years. Such slow traveltimes imply that contamination of the upper confined aquifer would not yet be expected if it is assumed that the confining unit is continuous, which is indicated by the available data and simulated by the ground-water flow model.

Ground-water traveltimes through the Nanjemoy-Marlboro confining unit and through the Aquia aquifer are measured in thousands of years. Such slow traveltimes imply that contamination of the Aquia aquifer from the NSCW is unlikely if it is assumed that the confining units are continuous, which is indicated by the available data and simulated by the ground-water flow model.

INTRODUCTION

The possible migration of contaminants by ground-water flow at the Naval Surface Warfare Center (NSWC) at Dahlgren, Va., is a concern of the U.S. Navy. Since 1992, the U.S. Geological Survey (USGS) has worked in cooperation with the Safety and Environmental Office at the NSWC in support of the Navy's environmental program. A three-dimensional ground-water flow model of the Dahlgren area was needed to incorporate and analyze data collected by the USGS during previous studies of the shallow aquifer system. A calibrated ground-water flow model with a particle-tracking component was needed to better define potential ground-water flow paths and traveltimes for selected areas at the NSWC.

Background

The U.S. Naval Proving Ground was established in 1918 on the western shore of the Potomac River in Virginia (fig. 1). In the following year, the proving ground was named after Rear Admiral John Adolphus Dahlgren, a commander during the Civil War, best known for designing a cast-iron gun also called a Dahlgren.

In 1959, the Dahlgren Naval Proving Ground was renamed the Dahlgren Naval Laboratory. In 1974, the laboratory became a part of the Naval Surface Weapons Center and in 1987, the weapons center was renamed the Naval Surface Warfare Center. Following the Base Closure and Realignment Act of 1991, the warfare center was realigned as the Naval Surface Warfare Center, Dahlgren Division, which includes a naval facility at Panama City, Fla. The NSWC, Dahlgren Division, has become the Navy's principal civilian research laboratory for surface ship combat systems.

The primary mission of the NSWC has been to test guns and ammunition for fleet operations. Shells are test-fired from a gun range at the shore of the Mainside of NSWC down the Potomac River. A more remote area, the Explosive Experimental Area (EEA) of the NSWC, south of upper Machodoc Creek, is used exclusively for testing and evaluating naval ordnance by burning and detonation.

Purpose and Scope

The hydrogeology and ground-water flow of the shallow aquifer system in and around the NSWC are described in this report. Maps defining the geometry of aquifers and confining units are presented and hydrogeologic data from previous USGS studies are analyzed. The design, calibration, and use of a three-dimensional ground-water flow model of the shallow aquifer system also is described.

The calibrated ground-water flow model was used to determine: (1) the ground-water budget of the Dahlgren area, (2) general directions and rates of ground-water flow in the shallow aquifer system in the Dahlgren area, and (3) ground-water flow paths and times of travel for advective ground-water flow from selected areas at the NSWC.

Analyses of the hydrogeology, ground-water flow, and computer simulations described in this report are intended to contribute knowledge for the wise use of the shallow ground-water resources in the Dahlgren area and to provide technical insights for the prudent management of the Navy's hazardous materials operations at the NSWC.

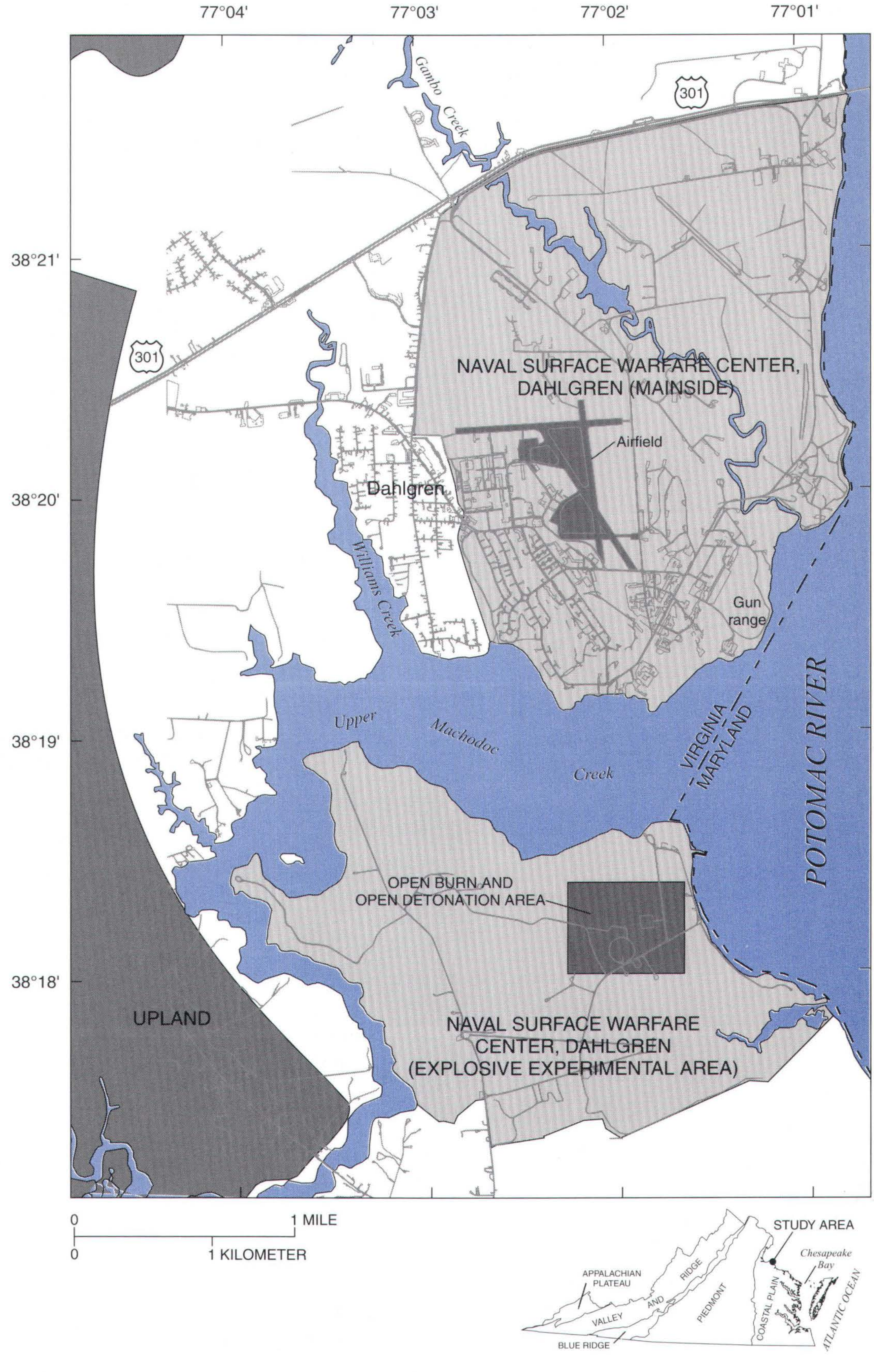


Figure 1. Location of the study area, Dahlgren, Virginia.

Methods of Study

A steady-state, three-dimensional ground-water flow model of the shallow aquifer system in the Dahlgren area was used to incorporate, evaluate, and refine existing USGS hydrogeologic data.

The computer program Visual MODFLOW version 2.7.1© 1995-1997 by Waterloo Hydrogeologic, Inc. was used to simulate and depict ground-water flow for this study (Guiguer and Franz, 1994, p. 3). Visual MODFLOW is an extension of MODFLOW, the USGS three-dimensional, finite-difference, ground-water flow model (Harbaugh and McDonald, 1996). Visual MODFLOW also includes the USGS particle-tracking program MODPATH (Pollock, 1994), a vector plotting post-processor, and the USGS volumetric budget calculator ZONEBUDGET (Harbaugh, 1990), as well as a statistical calibration program and other graphic post-processors that were used in this study.

The ground-water flow model was calibrated by minimizing the Root Mean Square Error (RMSE) of simulated water levels to the medians of measured water levels. RMSE's of simulated to measured water levels also were used to test the sensitivity of the model to changes in hydraulic properties. The calibrated ground-water flow model was then used to determine the ground-water budget and general directions and rates of ground-water flow in the shallow aquifer system, as well as ground-water flow paths and times of travel for advective ground-water flow from selected areas at the NSWC.

Hydrogeologic data from USGS Water-Resources Investigations Reports and from Water Data Reports and information from ongoing projects of the USGS at the NSWC were incorporated in the model. Maps and data defining the geometry of aquifers and confining units were assimilated from the previous reports, expanded, and refined. Medians were determined for water levels measured in 64 USGS wells (fig. 2) from 1992 and 1994 through the spring of 1998. Medians and geometric means were determined for horizontal hydraulic conductivities from previous single-well aquifer (slug) tests of 47 wells in the surficial aquifer, 7 wells in the upper confined aquifer, 4 wells in the Nanjemoy-Marlboro confining unit, and 3 wells in the Aquia aquifer (Bell, 1996, p. 13; Harlow and Bell, 1996, p. 21 and 22). Medians and geometric means also were determined for vertical hydraulic conductivities from previous falling-head permeameter tests of 20 Shelby-tube samples from 18 sites in the surficial aquifer, 30 samples from 24 sites in the upper confining unit, 2 samples from 2 sites in the upper confined aquifer, and 18 samples from 14 sites in the Nanjemoy-Marlboro confining unit (Bell, Bolles, and Harlow, 1994, p. 34; Hammond and Bell, 1995, p. 23).

Description of the Study Area

The NSWC is located on the west bank of the Potomac River adjacent to the town of Dahlgren, Va., in King George County (fig. 1). The main facilities of the NSWC, including office space, housing, laboratories, machine shops, the gun range, a sewage treatment plant, some testing areas, and an airfield are on the Mainside north of upper Machodoc Creek. A few structures are scattered around the Explosive Experimental Area (EEA) south of upper Machodoc Creek.

The NSWC and the town of Dahlgren are about 20 ft above sea level on a relatively flat flood plain formed on a Pleistocene terrace. A steep bluff of exposed Tertiary sediments (Chesapeake group) rises about 100 ft to the west and south of Dahlgren. The sides of the bluff curve in a smooth arc indicating that an ancestral river had cut into and exposed the sediments.

The Upper Machodoc Creek meanders in a narrow valley along the west side of the bluff. The creek cuts through the bluff just to the south of Dahlgren and from there the creek meanders up the east side of the bluff before it opens into the tidal Potomac River. Two smaller streams, Williams Creek and Gambo Creek, flow across the flood plain and drain the terrace deposits north of upper Machodoc Creek. Both streams are tide-affected south of Highway 301.

Previous Studies

An initial assessment of hazardous materials at the NSWC begun in 1981 identified 36 potentially contaminated sites. None of the sites posed an immediate threat to human health or to the environment, but seven sites on the Mainside posed a potential threat and warranted further investigations (Fred C. Hart Associates, 1983, p. 3-1). Confirmation studies of the NSWC in 1983 and 1984 recommended ground-water monitoring at five of those seven sites on

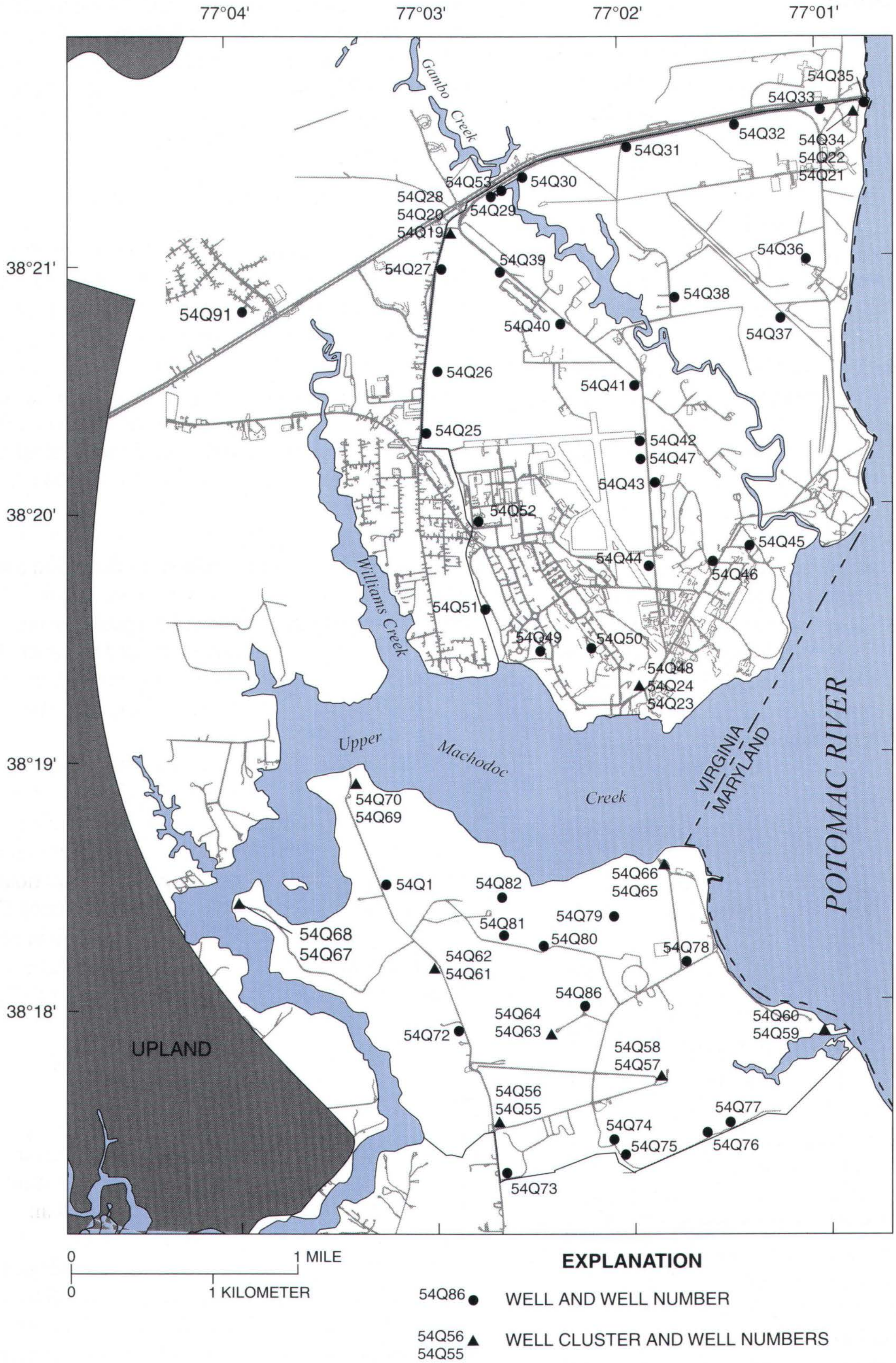


Figure 2. Location of observation wells at the Naval Surface Warfare Center, Dahlgren, Virginia.

the Mainside (O'Brien and Gere Engineers, 1986, p. i and ii). In 1992, however, the U.S. Environmental Protection Agency (USEPA) added the NSWC to the National Priorities (Superfund) List and identified 129 solid-waste management units at Dahlgren and 26 areas of concern. From this list, the USEPA determined that 67 units needed further study (Halliburton, 1995, p. 1-6).

In 1992, the USGS began the first of several investigations to define the hydrogeology of the shallow aquifer system in support of the Navy's environmental program at the NSWC. From 1992 through 1998, the USGS drilled more than 70 test holes; installed numerous piezometers, a tide gage, and more than 60 observation wells; maintained a ground-water monitoring network, including 14 continuous recorders; sampled surface- and ground-water quality; conducted single-well aquifer (slug) tests; and defined the hydrogeologic framework, first at Mainside and then at the EEA.

The hydrogeology and general ground-water chemistry of the shallow aquifers at NSWC are documented in four USGS reports. The hydrogeology and general ground-water chemistry of the Mainside (north of upper Machodoc creek) are described by Harlow and Bell (1996), and the data for that study are documented by Bell and others (1994). The hydrogeology and general ground-water chemistry of the EEA (south of upper Machodoc Creek) are described by Bell (1996) and the data are documented by Hammond and Bell (1995).

HYDROGEOLOGY

The NSWC is located entirely within the Coastal Plain of Virginia. Sediments beneath the Coastal Plain of Virginia form a layered sequence of aquifers and intervening confining units. Sand, gravel, and shell deposits of sufficient saturated thickness to yield significant quantities of water have been defined as aquifers. Continuous clay and silt deposits of low permeability have been defined as confining units (Meng and Harsh, 1988, p. C11).

The hydrogeologic framework of the shallow aquifer system beneath the Mainside at the NSWC was defined by Harlow and Bell (1996, p. 8) on the basis of data from test drilling and installation of 29 shallow wells, 3 wells of "medium depth," and 3 "deep" wells (fig. 2). The deepest well bore was drilled to about 200 ft below land surface (Bell and others, 1994, p. 11). The shallow aquifer system beneath the EEA was defined by Bell (1996, p. 8) on the basis of data from test drilling and installation of 28 wells, the deepest of which was about 100 ft. The previous investigators defined the hydrogeologic units at Dahlgren by interpreting geophysical logs, analyzing split-spoon and Shelby-tube samples, observing drill cuttings, and, in some instances, by analyzing pollen grains and invertebrate fossils.

Hydrogeologic Framework

Three aquifers and two confining units have been identified at the NSWC as the shallow aquifer system (fig. 3). From the land surface downward they are the surficial aquifer, commonly called the Columbia aquifer in the Coastal Plain of Virginia; the upper confining unit of Pleistocene age; the upper confined aquifer, also of Pleistocene age; the Nanjemoy-Marlboro confining unit, a continuous and relatively thick regional confining unit in the Dahlgren area; and the Aquia aquifer, which is also a regional aquifer of the Coastal Plain of Virginia (Meng and Harsh, 1988, p. 18 and 19).

Surficial Aquifer

The surficial aquifer encompasses a composite of variously colored pebble, gravel, sand, silt, and clay sediments deposited and then reworked by recent (Holocene) or older (Pleistocene) streams, rivers, and estuary currents. The surficial aquifer is generally unconfined; however, the aquifer can be locally or partially confined where silt and clay deposits are more prevalent near the top of the aquifer than sand and gravel deposits. The surficial aquifer of the Coastal Plain of Virginia has been formally named the Columbia aquifer, but it correlates with the surficial aquifers of Maryland and North Carolina (Meng and Harsh, 1988, p. C52).

The top of the surficial aquifer (fig. 4) was drawn by contouring median water levels from USGS wells at the NSWC and by estimating water levels in perennial streams as delineated on the Dahlgren, Va.-Md. 7.5-minute topographic map of 1968, photorevised in 1983. The median water levels were calculated from water levels measured from the date of well construction to March 1998. Water levels measured in the wells at the

<table>
<tr><th>SERIES</th><th>GEOLOGIC UNIT</th><th>HYDROGEOLOGIC UNIT</th><th>MODEL LAYER</th></tr>
<tr><td>Holocene</td><td>Alluvial, paludal, and fill deposits</td><td rowspan="2">Surficial aquifer</td><td rowspan="2">1</td></tr>
<tr><td rowspan="3">Pleistocene</td><td>Tabb Formation</td></tr>
<tr><td rowspan="2">Pleistocene deposits, undifferentiated</td><td>Upper confining unit</td><td>2</td></tr>
<tr><td>Upper confined aquifer</td><td rowspan="2">3</td></tr>
<tr><td>Eocene</td><td>Nanjemoy Formation</td><td rowspan="2">Nanjemoy-Marlboro confining unit</td></tr>
<tr><td rowspan="2">Paleocene</td><td>Marlboro Clay</td><td>4</td></tr>
<tr><td>Aquia Formation</td><td>Aquia aquifer</td><td>5</td></tr>
</table>

Figure 3. Geologic units, hydrogeologic units, and model layers of the shallow aquifer system at Dahlgren, Virginia. (Modified from Bell, 1996, p. 9, and Harlow and Bell, 1996, p. 9)

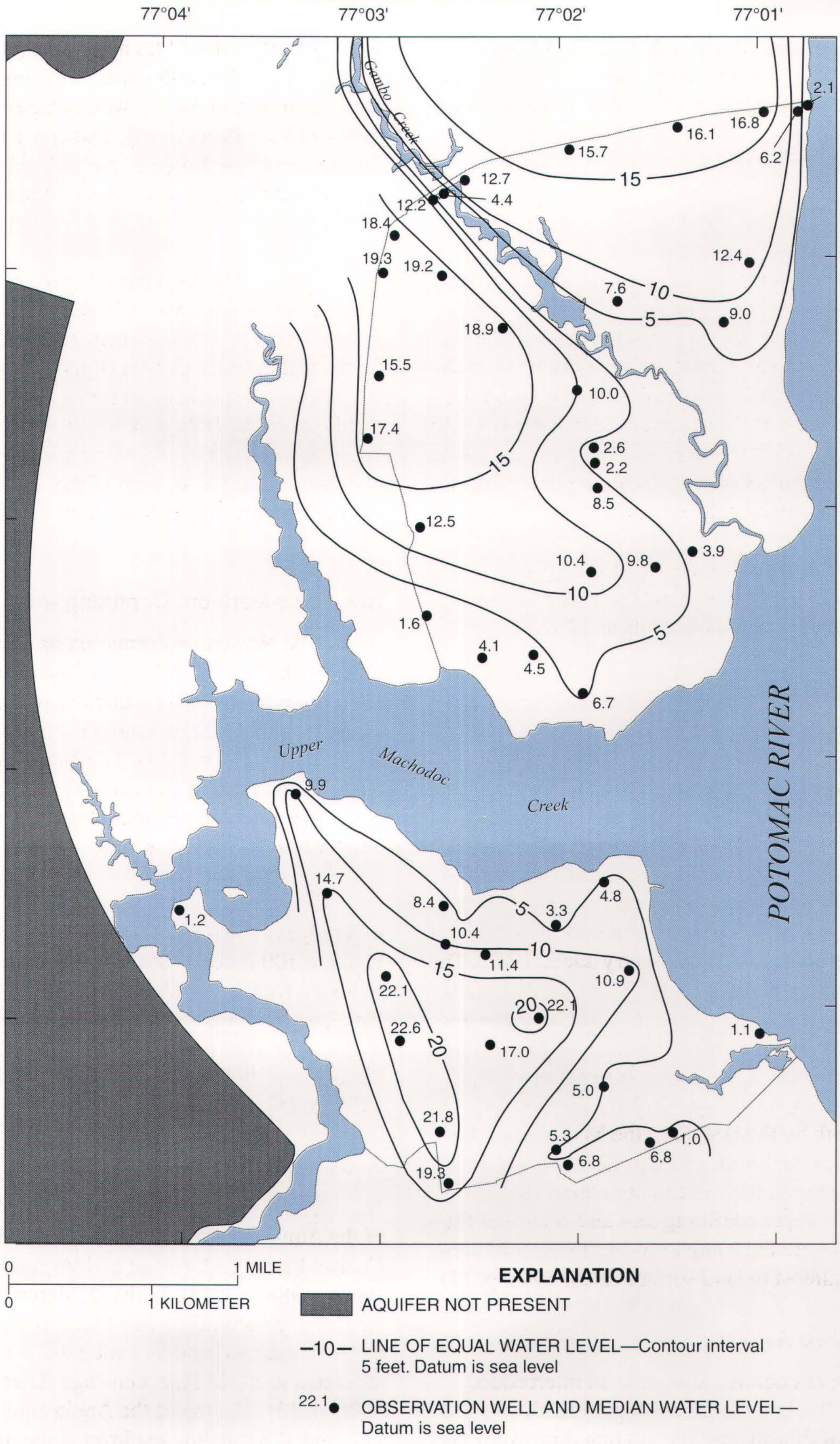


Figure 4. Median water levels of the surficial aquifer at the Naval Surface Warfare Center, Dahlgren, Virginia.

NSWC were published with other wells in King George County in the annual ground-water data reports of the USGS, Virginia District for Water Years 1993 through 1998.

The topography of the land surface has a profound influence on the configuration of the top of the surficial aquifer because most of the ground water flowing in the aquifer is recharged by local precipitation and is in turn discharged to local streams, wetlands, and shorelines. The water levels are higher and may be mounded in interstream areas, but are lowered by loss of pressure at and near discharge areas.

The bottom of the surficial aquifer rests on the undulating surface of the upper confining unit beneath the Mainside of NSWC and beneath parts of the EEA, while the Nanjemoy-Marlboro confining unit marks the bottom of the surficial aquifer beneath the higher ground near the west central part of the EEA (fig. 5). The undulating surface of the top of the upper confining unit was formed by paleochannels eroded into the surface by ancient streams and rivers.

Upper Confining Unit

The upper confining unit is a gray to olive-gray clay, silty clay, clayey sand, and fine sand deposit of Pleistocene age. The unit contains organic material and wood fragments (Bell, 1996, p. 11). The top of the upper confining unit ranges from about 5 ft above sea level to probably less than 20 ft below sea level as extrapolated beneath the Potomac River, taking into account bathymetric contours of the Dahlgren 7.5-minute topographic map (bathymetry added 1982). The thickness of the upper confining unit probably ranges from less than 10 ft beneath the Potomac River to a little more than 50 ft in some areas.

The upper confining unit was penetrated, although not completely, by every well drilled to sufficient depth by the USGS on the Mainside of the NSWC (Harlow and Bell, 1996, p. 12). This indicates that the confining unit is continuous across the Mainside. The upper confining unit also underlies the EEA except where the Nanjemoy-Marlboro confining unit extends almost to land surface (Bell, 1996, p. 11).

Upper Confined Aquifer

The upper confined aquifer is an interbedded glauconitic, olive-gray to greenish gray sand, silt, and clay deposit of Pleistocene age grading downward into sand, gravel, and pebbles at its base (Harlow and Bell, 1996, p. 12). The confined aquifer contains abundant organic matter, including wood fragments and tree stumps (Bell, 1996, p. 15). The upper confined aquifer was probably deposited in paleochannels. The aquifer is confined above and below by continuous and relatively thick units composed mostly of clay and fine sand.

The altitude of the top of the upper confined aquifer ranges from about 20 ft below sea level to more than 60 ft below sea level beneath the upper Machodoc Creek and Potomac Rivers (fig. 6). The aquifer ranges in thickness from about 10 ft to about 30 ft based on 11 test holes in the Dahlgren area that are documented in site files and working files of the USGS office in Richmond, Va. The bottom of the aquifer rests unconformably on the Nanjemoy-Marlboro confining unit.

Nanjemoy-Marlboro Confining Unit

The Nanjemoy Formation of Eocene age, and at its base, the Marlboro Clay of Paleocene age form a continuous and relatively thick regional confining unit in the Coastal Plain of Virginia and Maryland (Meng and Harsh, 1988, p. C44). The Nanjemoy Formation is a glauconitic, dark greenish-gray clay and silt with some fine sand and abundant bivalve shells. The Marlboro is a light brown clay at Dahlgren (Harlow and Bell, 1996, p. 12).

The top of the Nanjemoy-Marlboro confining unit ranges from about 10 ft above sea level at the EEA to about 100 ft below sea level near the shore of the Potomac River (Bell, 1996, p. 19). The thicknesses of the Nanjemoy-Marlboro confining unit on the Mainside of the NSWC were 75, 117, and 143 ft in the three "deep" holes drilled in 1992 (Harlow and Bell, 1996, p. 15).

Aquia Aquifer

The Aquia aquifer is composed of the sand facies of the Aquia Formation and is a regional aquifer in the Coastal Plain of Maryland and Virginia (Meng and Harsh, 1988, p. C43). In the Dahlgren area, the Aquia aquifer is glauconitic, olive-black to olive-gray, fine- to medium-grained sand and silt containing beds of indurated shells of Paleocene age (Harlow and Bell, 1996, p. 12). The top of the Aquia aquifer was 147, 177, and 178 ft below sea level at the three deep wells

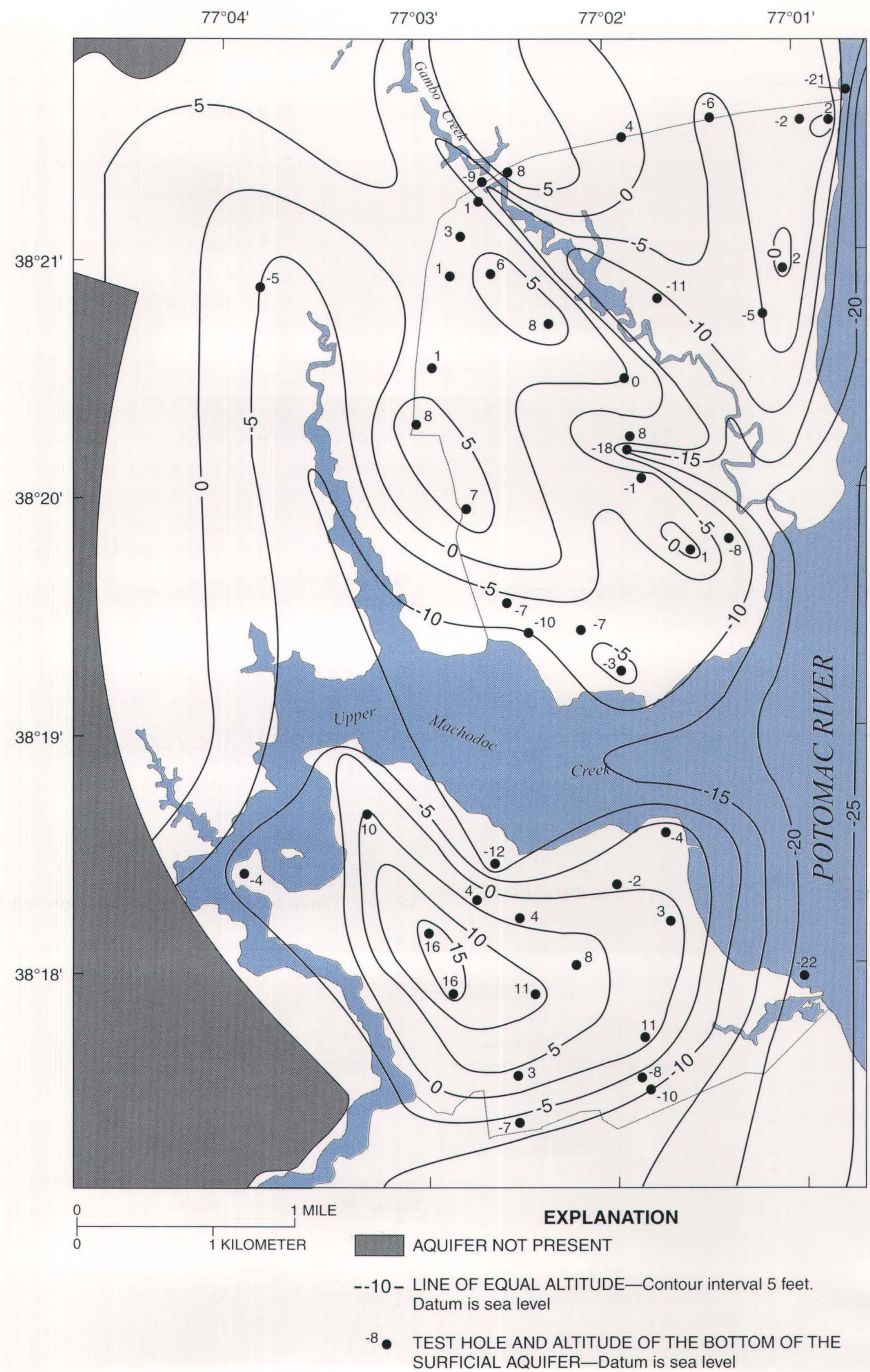


Figure 5. Altitude of the bottom of the surficial aquifer at Dahlgren, Virginia.

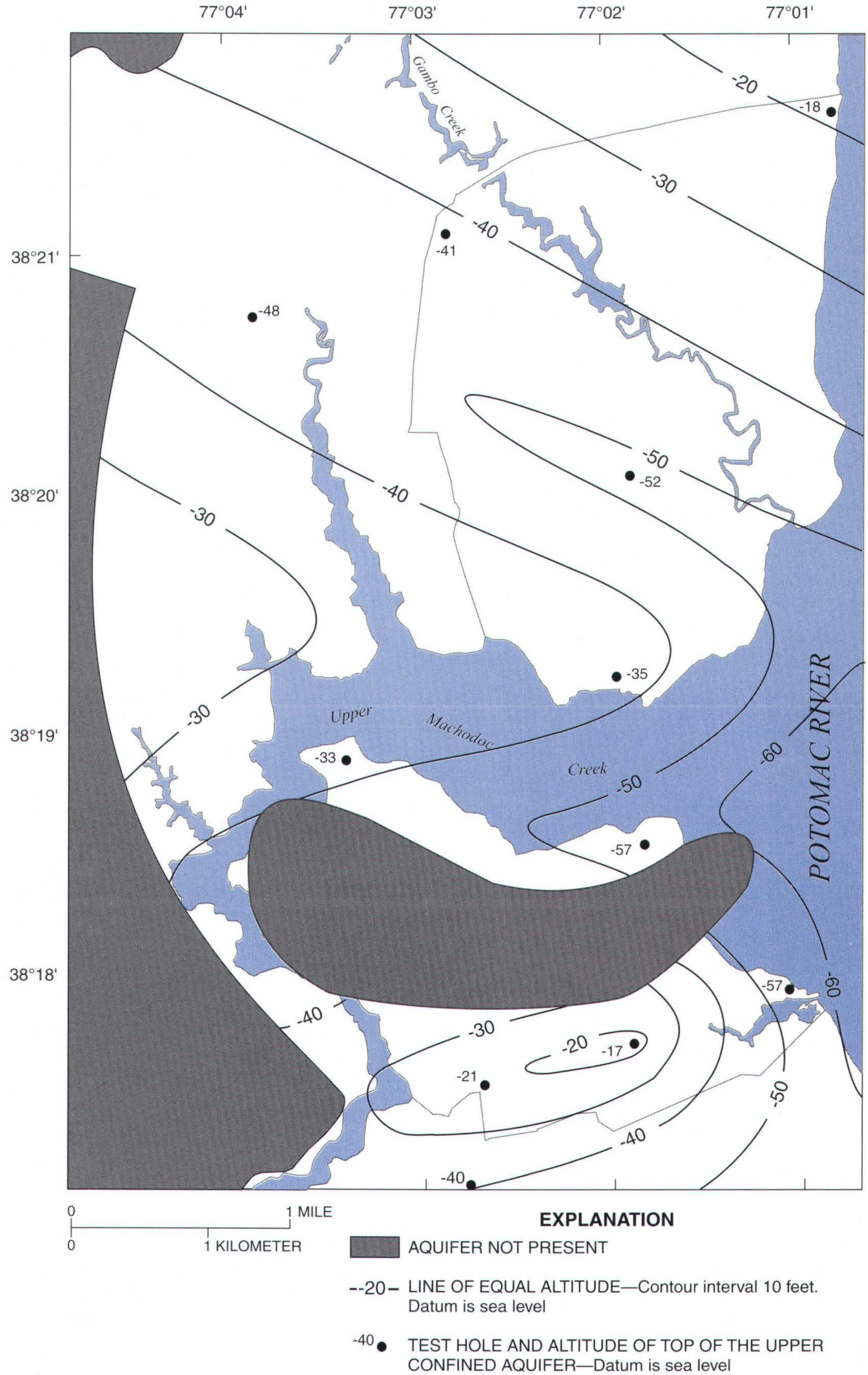


Figure 6. Altitude of top of the upper confined aquifer at Dahlgren, Virginia.

at the NSWC. The upper 50 ft of the Aquia aquifer was penetrated by the deepest test hole on the Mainside (Harlow and Bell, 1996, p. 12). The Aquia, however, is probably at least 100 ft thick in northern Virginia (Meng and Harsh, 1988, p. C44).

Ground-Water Hydrology

Ground water in the Dahlgren area flows through a layered system of aquifers and intervening confining units. The hydraulic conductivities of the aquifers are typically higher than those of the confining units. Water tends to flow horizontally through the aquifers and vertically through the confining units of such a layered, heterogeneous system (Freeze and Cherry, 1979, p. 172).

Water-Level and Temperature Fluctuations

The surficial aquifer is generally unconfined, and the water level in a well open to an unconfined aquifer is free to equilibrate to atmospheric pressure. Water levels in wells open to the shallow-aquifer system in the Dahlgren area rise and then decline after recharge events (fig. 7a). Water levels also tend to rise gradually with continued precipitation following the end of the growing season in autumn when the trees become dormant, leaves fall, and evapotranspiration decreases. The rise can continue through the winter if precipitation is forthcoming, but with the return of the growing season and the new leaves of spring, ground-water levels generally begin a long decline that continues through the summer.

Water levels in wells open to the upper confined aquifer are under pressure from the confining units above and beneath. Water levels in these wells near the tidal rivers fluctuate with the pressure loading of the tides but also show a subdued response to large precipitation events and small cyclic seasonal fluctuation caused by pressure loading of the units above (fig. 7b).

Water levels in the aquifers also respond to periods of prolonged drought or precipitation, but when viewed over the course of a normal year or over the course of several years, the water levels can be seen to fluctuate above and below a common average, indicating a steady state. Water levels in the surficial and upper confined aquifers at the NSWC have been observed long enough to define a steady-state trend, in which the amount of recharge to the aquifer is equal to the amount of discharge. Water levels in wells open to the Aquia aquifer in the Dahlgren area, however, are slowly declining (White and Powell, 1997, p. 147 and 149); these water level declines are caused by withdrawals of ground water at pumping centers 30 miles away in southern Maryland (Curtin and others, 1997).

The annual ground-water temperature fluctuates about 6° Celsius in the surficial aquifer and about 2° Celsius in the upper confined aquifer. Water temperature extremes in both the surficial aquifer and the upper confined aquifer lag behind seasonal air temperature extremes (July and January) by several months (fig. 7). The lag time is in proportion to the depths of the well openings below the land surface. Seasonal temperature fluctuations are regular, but ground-water temperatures tend to decrease faster than they increase, which is particularly evident in the record of the surficial aquifer (fig. 7a).

Recharge and Discharge

Ground-water recharge is that part of precipitation that reaches the surficial aquifer. In the Coastal Plain of Virginia, annual ground-water recharge and discharge varies from 7.5 to 12.5 in/yr and averages 10.8 in/yr based on base-flow separation of stream flow hydrographs for 16 gaging stations with at least 10 years of record (Richardson, 1994, p. 14). The annual ground-water discharge for any area of the Coastal Plain averages 9.9 in/yr based on a regional regression of ground-water discharge at those 16 stations and the hydrogeologic characteristics of those watersheds. The annual ground-water recharge and discharge for the Potomac River drainages, including the Dahlgren area, was also 9.9 in/yr based on the regional hydrogeologic analyses (Richardson, 1994, p. 5).

Ground-Water Flow

A median water level was determined for each of 64 wells at the NSWC. The median was calculated from numerous periodic water-level measurements of each well at the NSWC from the time of construction in 1992 or 1994 until the spring of 1998. A map of the top of the surficial aquifer was drawn using those median water levels.

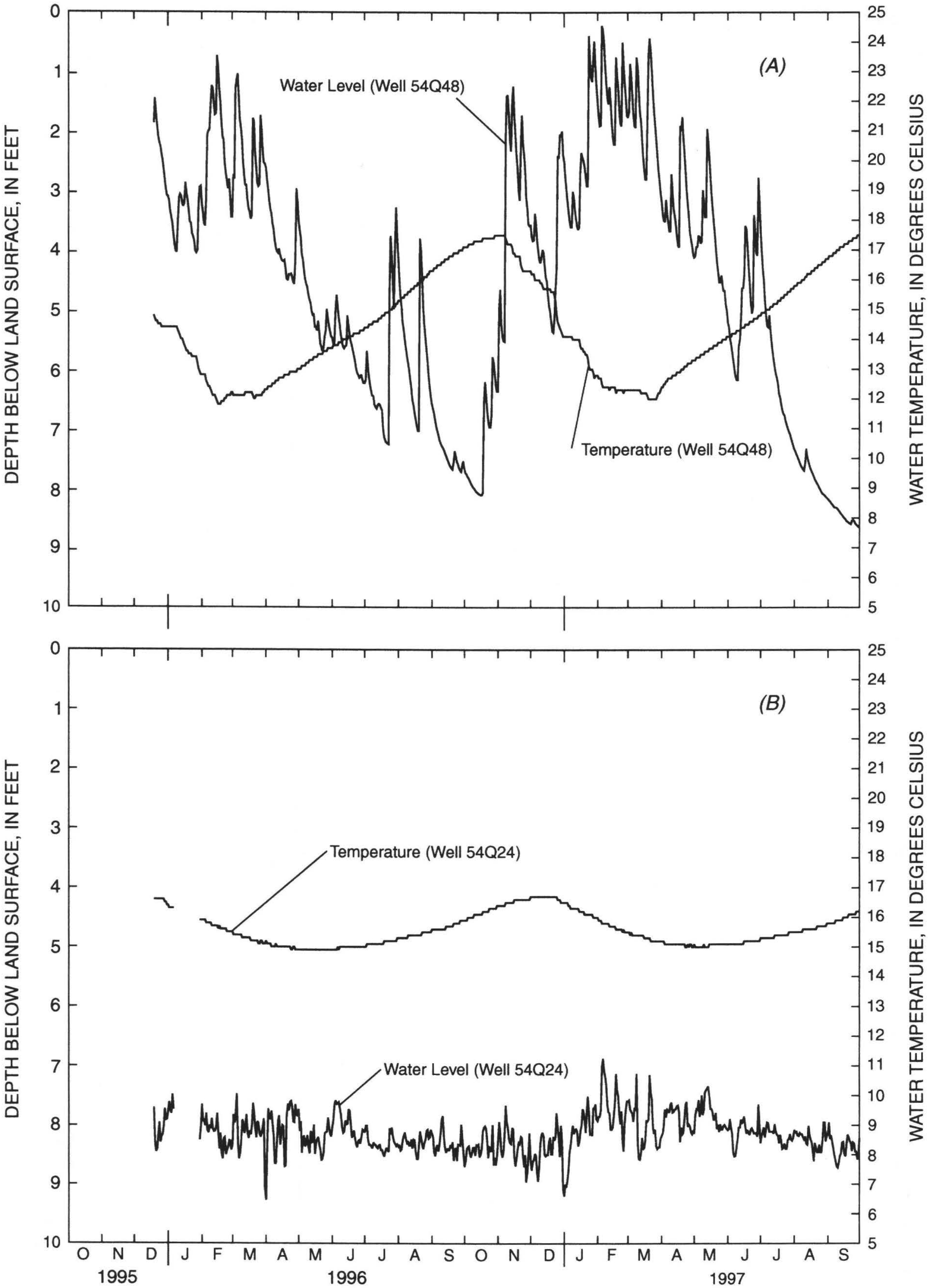


Figure 7. Ground-water temperature and water levels in a well open to the surficial aquifer *(A)* and in a well open to the upper confined aquifer *(B)* at Dahlgren, Virginia. See figure 2 for well locations.

From the top of the surficial aquifer, ground water flows slowly downward and outward through the interconnected openings between the sediments and rocks that form the framework of the aquifer. Wherever water percolates to the top of the surficial aquifer faster than it can flow away, it tends to mound. Ground-water mounds are common in areas far from rivers, streams, marshes, and shorelines, which are commonly sinks (depressions) where ground water tends to discharge. Ground-water levels are lowered near streams, rivers, and shorelines because hydraulic pressures are reduced in the immediate area of these sinks. Because of such mounds and sinks, the topography of the land surface has a profound influence on the water levels of the surficial aquifer. In addition, human activities that change the topography, such as redirection of streams or construction of ditches, ponds, lakes, and filled areas can alter the water levels of the surficial aquifer and thereby change the directions and velocities of ground-water flow.

Ground water generally flows horizontally in the surficial aquifer, and lines drawn perpendicular to the water-level contours from higher altitudes toward lower altitudes would indicate the general directions of ground-water flow (fig. 4). In the Dahlgren area, ground water flows from higher hydraulic heads beneath the interstream areas radially outward toward ditches, streams, wetlands, and the shorelines of the tidal Potomac River and upper Machodoc Creek. Ground water discharges to those surface waters by upward leakage through the bottom sediments. Where the water levels are almost flat and the hydraulic gradients are low, such as beneath the airfield, the velocities of ground-water flow tend to be slower than where the hydraulic gradients are steep, such as near the incised stream banks of Gambo Creek.

Hydraulic Properties

Distributions of hydraulic conductivity for the shallow aquifer system at the NSWC were estimated by single-well aquifer (slug) tests and by falling-head permeameter tests of Shelby tube samples (Bell and others, 1994, p. 5, and Hammond and Bell, 1995, p. 4 and 5). Median values from these tests were calculated and used as the values for hydraulic conductivities in the initial run of the ground-water flow model of the Dahlgren area. The median value was used rather than average values because hydraulic conductivities are nonparametric (not normal) distributions. The geometric means of the hydraulic conductivity distributions also were calculated to confirm that the medians were close approximations to the central tendencies of the distribution.

Surficial Aquifer

Slug tests of 47 wells in the surficial aquifer indicated a range in horizontal hydraulic conductivities from 1.0×10^{-2} ft/d to 21 ft/d at the NSWC. The median horizontal hydraulic conductivity of the 47 tests was 1 ft/d (table 1) and the geometric mean was 0.9 ft/d.

Falling-head permeameter tests of 20 samples from 18 test holes in the surficial aquifer indicated a range in vertical hydraulic conductivities from 3.6×10^{-5} ft/d to 5.1 ft/d. The median of the 20 samples was 2.5×10^{-2} ft/d (table 1) and the geometric mean was 2.1×10^{-2} ft/d.

Upper Confining Unit

No data were available for the horizontal hydraulic conductivity of the upper confining unit. The median value was assumed to be 10 times the median of the vertical hydraulic conductivities, because most aquifers of water-deposited sediments are stratified and, therefore, are anisotropic (Jacob, 1963, p. 274). Falling-head permeameter tests of 30 samples from 24 test holes in the upper confining unit indicated a range in vertical hydraulic conductivities from 2.7×10^{-6} to 7.1×10^{-1} ft/d. The median of the 30 samples was 1.6×10^{-4} ft/d (table 1) and the geometric mean was 5.4×10^{-4} ft/d.

Upper Confined Aquifer

Slug tests of seven wells open to the upper confined aquifer indicated a range in horizontal hydraulic conductivities from 8×10^{-2} to 23 ft/d. The median hydraulic conductivity of the seven tests was 3.3 ft/d (table 1) and the geometric mean was 2.5 ft/d.

Table 1. Hydraulic conductivities of the shallow aquifer system at the Naval Surface Warfare Center, Dahlgren, Virginia

Unit	Median hydraulic conductivities (feet per day) (number of samples)		Model-calibrated hydraulic conductivities (feet per day)	
	Horizontal	Vertical	Horizontal	Vertical
Surficial Aquifer	1.0 (47)	0.025 (20)	30	0.025
Upper Confining Unit	0.0016[1] (0)	0.00016 (30)	1.6	0.016
Upper Confined Aquifer	3.3 (7)	0.0029 (2)	3.3	0.0029
Nanjemoy-Marlboro Confining Unit	0.017 (4)	0.0069 (18)	0.017	0.000069
Aquia Aquifer	0.04 (3)	0.004[1] (0)	4.0	0.004

[1] No data. Horizontal hydraulic conductivity was assumed to be 10 times the vertical.

Falling-head permeameter tests of two samples from two different test holes in the upper confined aquifer indicated vertical hydraulic conductivities of 7.8×10^{-5} and 5.7×10^{-3} ft/d. The median of the two samples was 2.9×10^{-3} ft/d (table 1) and the geometric mean was 6.7×10^{-4} ft/d.

Nanjemoy-Marlboro Confining Unit

Slug tests of four wells open to the Nanjemoy-Marlboro confining unit indicated a range in horizontal hydraulic conductivities from 3.2×10^{-3} ft/d to 4.3×10^{-2} ft/d. The median hydraulic conductivity of the four tests was 1.7×10^{-2} ft/d (table 1) and the geometric mean was 1.0×10^{-2} ft/d.

Falling-head permeameter tests of 18 samples from 14 test holes in the Nanjemoy-Marlboro confining unit indicated a range in vertical hydraulic conductivities from 6.0×10^{-5} ft/d to 1.6×10^{-1} ft/d. The median of the 18 samples was 6.9×10^{-3} ft/d (table 1) and the geometric mean was 4.6×10^{-3} ft/d.

Aquia Aquifer

Slug tests of three wells open to the Aquia aquifer indicated a range in horizontal hydraulic conductivities from 4×10^{-3} ft/d to 3×10^{-1} ft/d. The median hydraulic conductivity of the three tests was 4×10^{-2} ft/d (table 1) and the geometric mean also was 4×10^{-2} ft/d. No data were available for the vertical hydraulic conductivity of the Aquia aquifer at Dahlgren. The horizontal hydraulic conductivity of the Aquia was assumed to be 10 times the vertical because most aquifers of water-deposited sediments are stratified and, therefore, are anisotropic (Jacob, 1963, p. 274).

GROUND-WATER FLOW SIMULATION

A deterministic ground-water flow model is a system of governing process equations that numerically relate measured data and conceptual information about an aquifer system by simulation. Data and information about the geometries and hydraulic characteristics of the aquifers, confining units, and surface-water bodies; ground-water recharge and discharge rates; and ground-water levels can be incorporated into the system of equations. Hydrogeologic information and ground-water flow concepts related to a particular set of objectives can be evaluated, compared, and refined quantitatively by analyses of digital ground-water-flow simulations.

A steady-state, three-dimensional ground-water flow model of the shallow aquifer system in the Dahlgren area was devised and used to incorporate, evaluate, and refine existing USGS hydrogeologic data. The ground-water flow model was calibrated by minimizing the Root Mean Square Error (RMSE) of measured to simulated water levels. The sensitivity of the calibrated model to changes in hydraulic properties also was evaluated. The calibrated model was then used to determine the ground-water budget, general directions and rates of ground-water flow, and ground-water flow paths and traveltimes from selected sites at the NSWC.

Model Design and Assumptions

Visual MODFLOW version 2.7.1© 1995-1997, the Waterloo Hydrogeologic, Inc. extension of the USGS three-dimensional, finite-difference, ground-water flow model MODFLOW (Harbaugh and McDonald, 1996), was used to simulate and depict ground-water flow for this study. Visual MODFLOW also includes the USGS particle-tracking program MODPATH (Pollock, 1994) and the USGS volumetric budget calculator ZONEBUDGET (Harbaugh, 1990), as well as a statistical calibration program and other visual aids that were used in this study.

MODFLOW simulates laminar (non-turbulent), advective flow of ground water that is assumed to be uniform in temperature, concentration, and density. Temperature fluctuations in the shallow ground-water system at Dahlgren are small. Advective flow implies that any solutes in the ground water are entrained and travel with the bulk ground-water motion and are not dispersed or diffused. Simulations based on these assumptions give an approximation of the potential movement of inert contaminants in ground water and are valid for the objectives of this study.

Model Grid, Layers, and Boundaries

The finite-difference method requires that a rectangular grid be defined for the model area. The hydrogeologic properties of the aquifer system are then assigned to the corresponding cells and layers of the grid. A simple rectangular grid of 5 layers, 70 rows and 48 columns was designed to cover the NSWC and the adjacent area (fig. 8). Each cell of the grid is 400 ft^2, which is small enough to reasonably represent shorelines, streams, and drainage ditches throughout the surficial aquifer, as well as individual well points in the aquifer.

The model covers the NSWC and the adjacent area from the arcuate bluff in the west and south to the Potomac River in the east. The surficial aquifer, the upper confining unit, and the upper confined aquifer end at the bluff and the Potomac River acts as a wide discharge area for the aquifers. A partial stream divide to the north of NSWC, where ground-water flow in the surficial aquifer is primarily east and west, was selected as the northern extent of the modeled area.

The aquifers and confining units of the shallow aquifer system were assigned to five corresponding layers (fig. 9). The layers and units are continuous to the edges of the model except at the bluff, where the top three layers are truncated, and beneath the EEA, where the Nanjemoy-Marlboro confining unit protrudes from layer 4 up and into layer 3. The zone in layer 3 beneath the EEA corresponding to the Nanjemoy-Marlboro confining unit was assigned the same aquifer properties as layer 4 and the surrounding zone of layer 3 was assigned the hydraulic conductivity representing the upper confined aquifer. Layers 1, 2, and 3 of the model varied in thickness. A paucity of data precluded any meaningful variation in thickness for the bottom two layers.

No-flow boundaries were assumed at the bluff and elsewhere at the extent of the model grid for layers 1, 2, and 3 because virtually no water was expected to flow into or out of the aquifers and confining units at those extremities. No-flow boundaries also were assumed at the outer extent of the model for layer 4, the Nanjemoy-Marlboro confining unit. Constant-head boundaries were assigned at the edges of the Aquia aquifer (layer 5) because a flow proportional to the head gradients at those extremities was expected. The constant heads in the Aquia were extrapolated from a water-level map derived from the three observation points in the aquifer. The bottom of the Aquia aquifer was assumed to be an impermeable boundary at approximately 250 ft below sea level to give the Aquia a thickness of 100 ft, as indicated by Meng and Harsh (1988, p. C44).

Constant heads of sea level were assigned to layer 1 to represent the upper Machodoc Creek and Potomac River estuaries. Constant heads can accurately represent the estuaries in the model area because the time scale of the model is a steady state, simulating long-term average conditions. The mean range of the tide is 1.6 ft but the average is at or near sea level.

Because the estuary water is shallow, density differences between assuming a freshwater head rather than a saline water equivalent are negligible. The difference between a freshwater column and, in the extreme case, a seawater column in the deeper parts of the estuaries (about 20 ft maximum) would be the ratio of the density of freshwater to that of seawater times the depth, or 1/40 of 20 ft, which is 0.5 ft. The estuaries are not as saline as seawater and are generally less than 20 feet deep in the model area; therefore, the difference

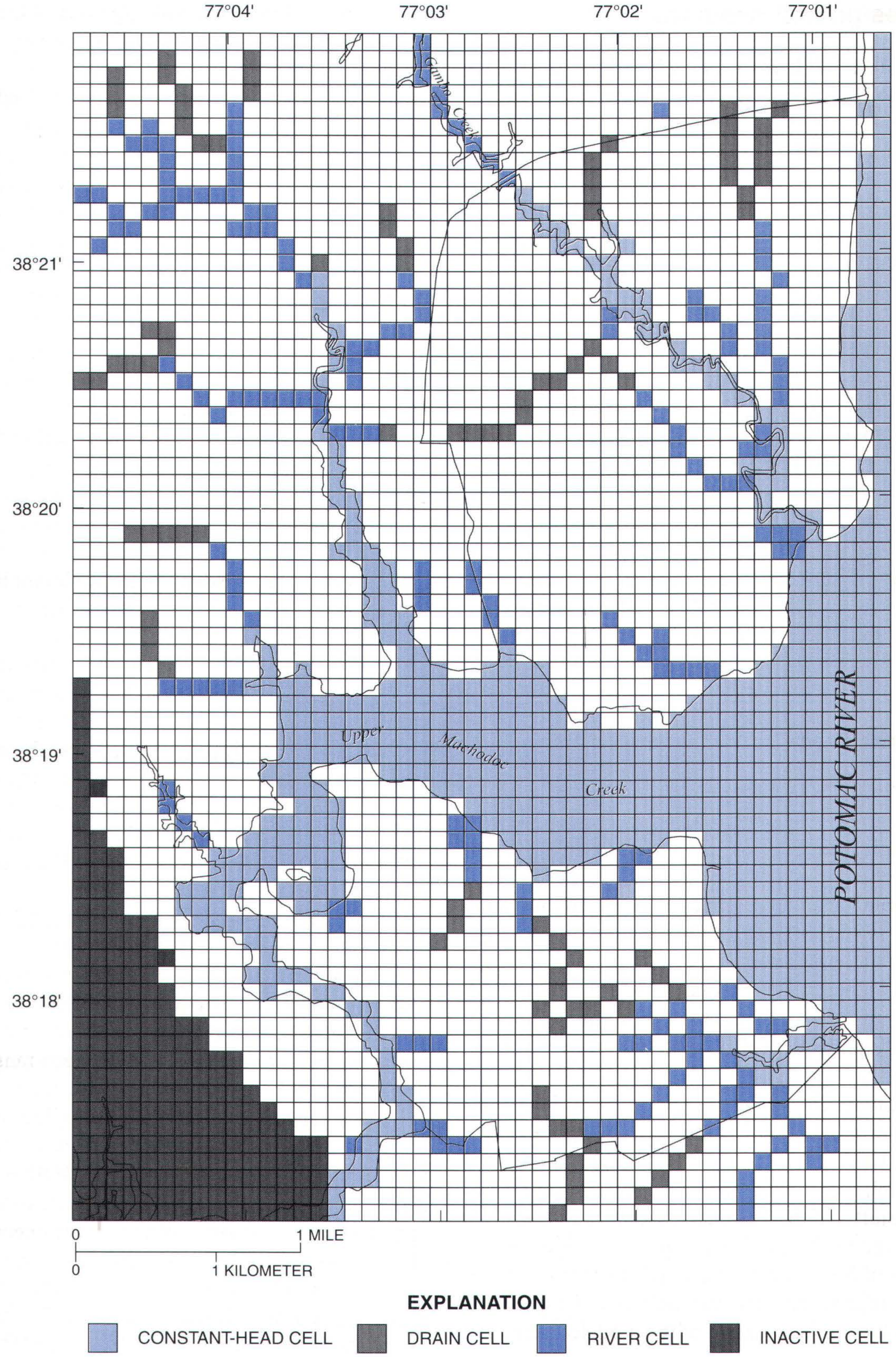


Figure 8. Grid, river, drains, and constant heads of layer 1 of the Dahlgren area model.

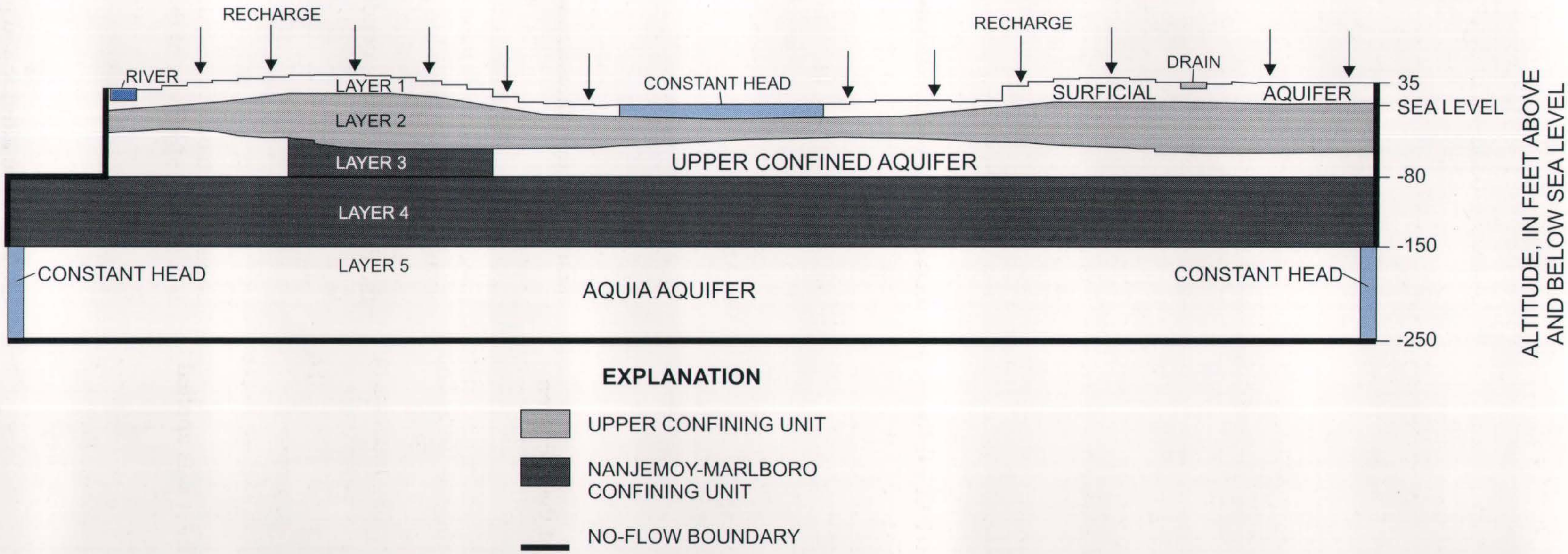


Figure 9. Layers and boundaries of the Dahlgren area ground-water flow model.

in simulated heads caused by density variations would be much less than 0.5 ft for nearly all of the area representing the estuaries.

River nodes were assigned to the perennial reaches of the streams that drain the surficial aquifer. The stage of the river nodes and the points where the streams were designated as being perennial were taken from the Dahlgren 7.5-minute quadrangle (1968, photorevised 1983). Streams and ditches that are marked as intermittent on the Dahlgren quadrangle were designated as drains. The drain bottoms were set to the altitude of land surface that was indicated by interpolation of the topographic contours crossing the center of the corresponding cell. The stream and drain bottoms were assumed to be 1 ft thick and the hydraulic conductivities of the bottoms were assumed to be 1 ft/d.

The Strongly Implicit Procedure (SIP) was selected to solve the system of ground-water flow equations for the Dahlgren area model. The head change criterion for closure was set to 0.001 ft for calibration and sensitivity analysis. The calibrated model was re-run with a head change criterion for closure of 0.0001 for a more precise budget analysis. Five iteration parameters were selected. The acceleration parameter was 0.5 and a user-defined seed of 0.001 was chosen for calculating iteration parameters (Harbaugh and McDonald, 1996, p. 37).

Model Calibration

The ground-water flow model of the Dahlgren area was calibrated to steady-state conditions based on median water levels calculated from observation wells measured from 1992 or 1994 to the spring of 1998. The model was calibrated by minimizing the RMSE of simulated water levels to the corresponding medians of water levels measured in 64 observation wells at the NSWC. Most of the observation wells were open to the surficial aquifer. Six wells were open to the upper confined aquifer, and only three wells were open to the Aquia aquifer.

An annual recharge rate of 10 in/yr was applied to the top layer of the model, which represents the unconfined surficial aquifer. This recharge rate is from the annual ground-water discharge rate for the Potomac River drainages in Virginia, which includes the Dahlgren area. An annual ground-water discharge rate of 9.9 in/yr was calculated for the area by streamflow separations of long-term hydrographs, as well as regional hydrogeologic analyses based on soil drainage and surficial geology (Richardson, 1994, p. 5 and 12). Annual ground-water discharge rates are assumed to be equal to recharge rates in this steady-state model.

An initial computer simulation using the median hydraulic conductivities from previous USGS reports (table 1) resulted in simulated water levels that were much higher than the medians of the measured water levels and resulted in an RMSE of 83 ft. For the next simulation, the horizontal hydraulic conductivity of layer 1, the surficial aquifer, was changed from the initial value of 1 ft/d to 10 ft/d, which resulted in much lower water levels for the model and an RMSE of 8 ft. The initial value of 1 ft/d was the median value derived from slug tests in 47 wells (table 1); the values from those tests ranged from 0.01 to 21 ft/d. A hydraulic conductivity larger than 1 ft/d probably is more appropriate for simulation of ground-water flow at the scale of the Dahlgren area. Research on hydraulic conductivities derived from laboratory analyses, slug tests, multiple-well aquifer tests, and ground-water flow modeling has indicated that larger values are commonly derived from the larger-scale (aquifer-and-model) tests than from the smaller (slug-and-laboratory) tests (Bradbury and Muldoon, 1990, p. 141).

The hydraulic conductivities of the aquifers and confining units were tested and adjusted by additional model runs. The hydraulic conductivity of the Aquia aquifer was adjusted by directly comparing and minimizing the simulated water levels to the measured water levels at the corresponding cells for the three Aquia wells. Similarly, hydraulic conductivities of the upper confined aquifer and the intervening confining units were tested and adjusted by comparing simulated water levels to the measured, as well as by minimizing the RMSE. Hydraulic conductivities that resulted in significant reductions in the RMSE were used for the calibrated model (table 1).

The calibration process resulted in a final RMSE of 3.86 ft. Differences between measured and simulated water levels of the calibrated model were less than 5 ft for most of the observations (fig. 10). No pattern is evident in the differences (residuals) between measured and simulated water levels indicating the errors are distributed random.

Simulated water levels for the surficial aquifer are similar in altitude and pattern to measured water levels (fig. 11). In the Dahlgren area, ground water flows from higher hydraulic heads beneath the interstream areas radially outward toward ditches, streams, wetlands, and the shorelines of the tidal Potomac River and upper Machodoc Creek. Ground water discharges to those surface waters by upward leakage through the confining units and the bottom sediments.

Simulated water levels in the upper confined aquifer (fig. 12) are similar to those of the surficial aquifer, but the levels are lower beneath the interstream areas and slightly higher beneath the rivers, wetlands, and estuaries than those of the surficial aquifer. Ground water can leak downward from the surficial aquifer through the upper confining unit to the upper confined aquifer in the interstream areas because of the downward hydraulic gradient. Ground water can leak upward beneath the streams, wetlands, and river estuaries where there is an upward gradient between the aquifers.

Simulated water levels in the Aquia aquifer are below sea level and do not reflect the water-level patterns of the shallower aquifers (fig. 13). The Aquia is separated from the shallow aquifers by a relatively thick regional confining unit, and water levels in the Aquia are affected by pumping toward the southeast, which was simulated by assigning appropriate constant heads around the perimeter of the model in layer 5.

Model Sensitivity

RMSE's of measured to simulated water levels were used to test the sensitivity of the model to changes in aquifer system properties. Changes in the hydraulic properties of only the surficial aquifer are presented, because most of the ground-water flow and most of the water-level data were from wells completed in the surficial aquifer.

RMSE's for changes in recharge rate and horizontal hydraulic conductivity of the surficial aquifer were plotted and contoured on the same graph (fig. 14). The smallest RMSE's, less than 3.9 ft, follow a narrow but widening upward trend through the middle of the graph, indicating that a change in one property could be compensated for by an appropriate change in the other. The horizontal hydraulic conductivity of the surficial aquifer could range from 20 to 40 ft/d and still be considered calibrated if the recharge rate was between 7.5 and 12.5 in/yr—the range likely to be encountered in the Coastal Plain of Virginia (Richardson, 1994, p. 14). Such a result is said to be non-unique and is common for many ground-water flow models.

The sensitivity of the model to changes in anisotropy of the surficial aquifer also was tested. The horizontal and vertical hydraulic conductivities of the surficial aquifer were varied through reasonable ranges, and RMSE's were calculated for each change. The RMSE's of horizontal to vertical hydraulic conductivity of the surficial aquifer were plotted on a log-log graph and contoured (fig. 15). The graph indicates that the model was more sensitive to changes in horizontal hydraulic conductivity than to changes in vertical hydraulic conductivity. The model was not sensitive to changes in vertical hydraulic conductivity greater than 0.0025 ft/d. The model also was not sensitive to changes in horizontal hydraulic conductivity between 25 and 45 ft/d when the vertical hydraulic conductivity was greater than 0.0025 ft/d, but was sensitive to changes beyond those values.

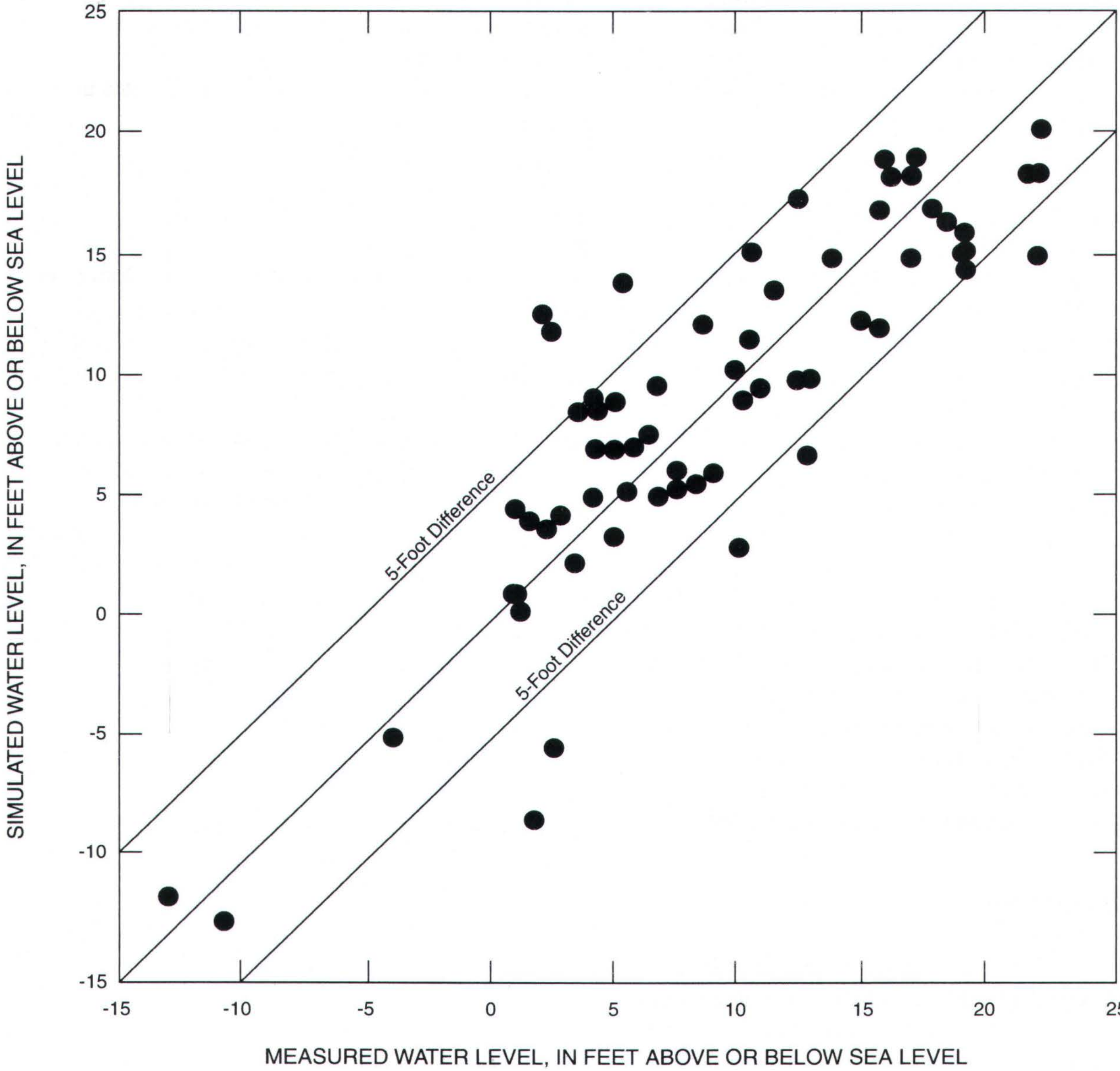
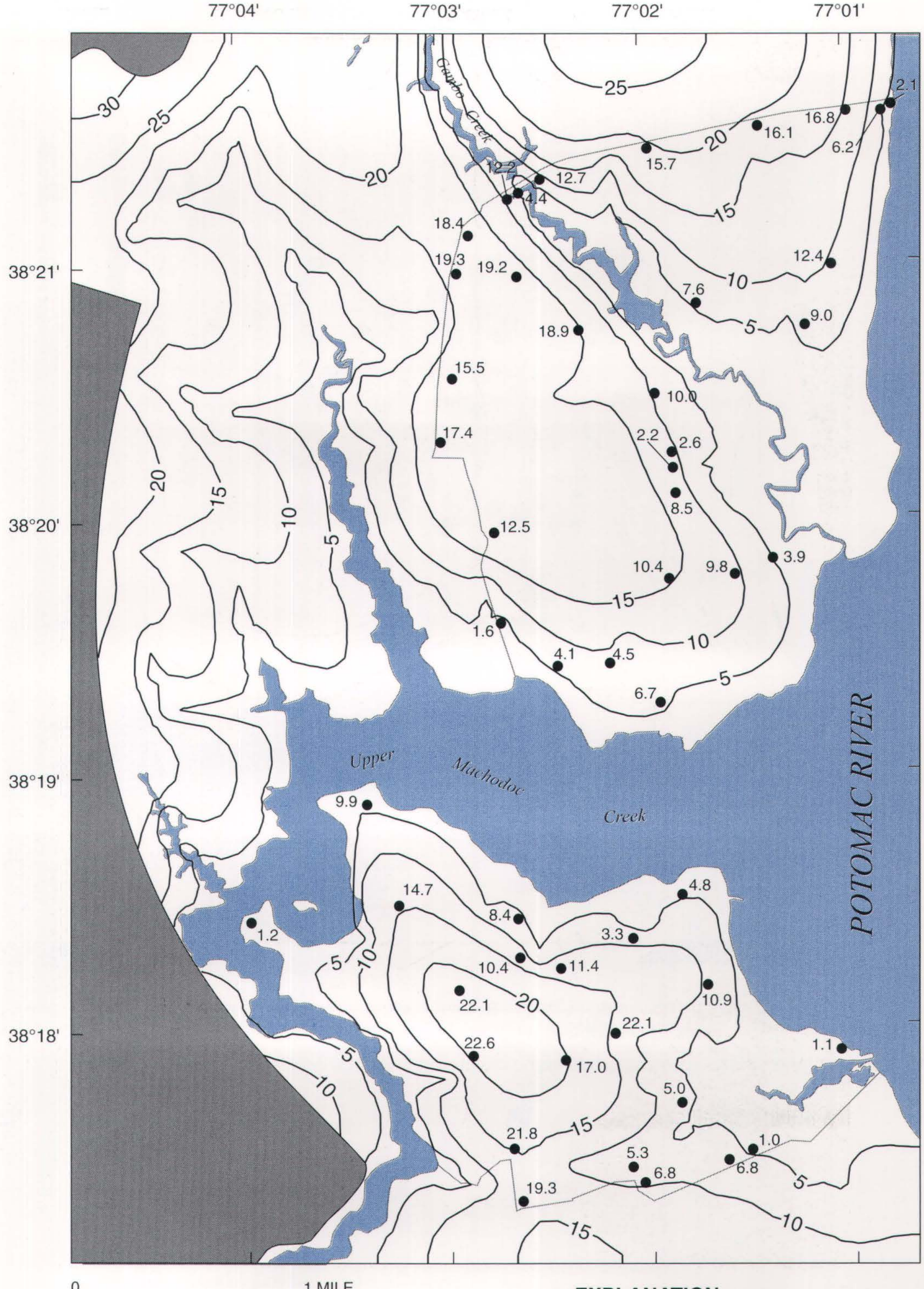


Figure 10. Measured and simulated water levels of the calibrated Dahlgren area ground-water-flow model.



0 1 MILE

0 1 KILOMETER

EXPLANATION

AQUIFER NOT PRESENT

—10— LINE OF EQUAL SIMULATED WATER LEVEL—Contour interval 5 feet. Datum is sea level

22.1● OBSERVATION WELL AND MEDIAN WATER LEVEL—Datum is sea level

Figure 11. Measured and simulated water levels of the surficial aquifer at Dahlgren, Virginia.

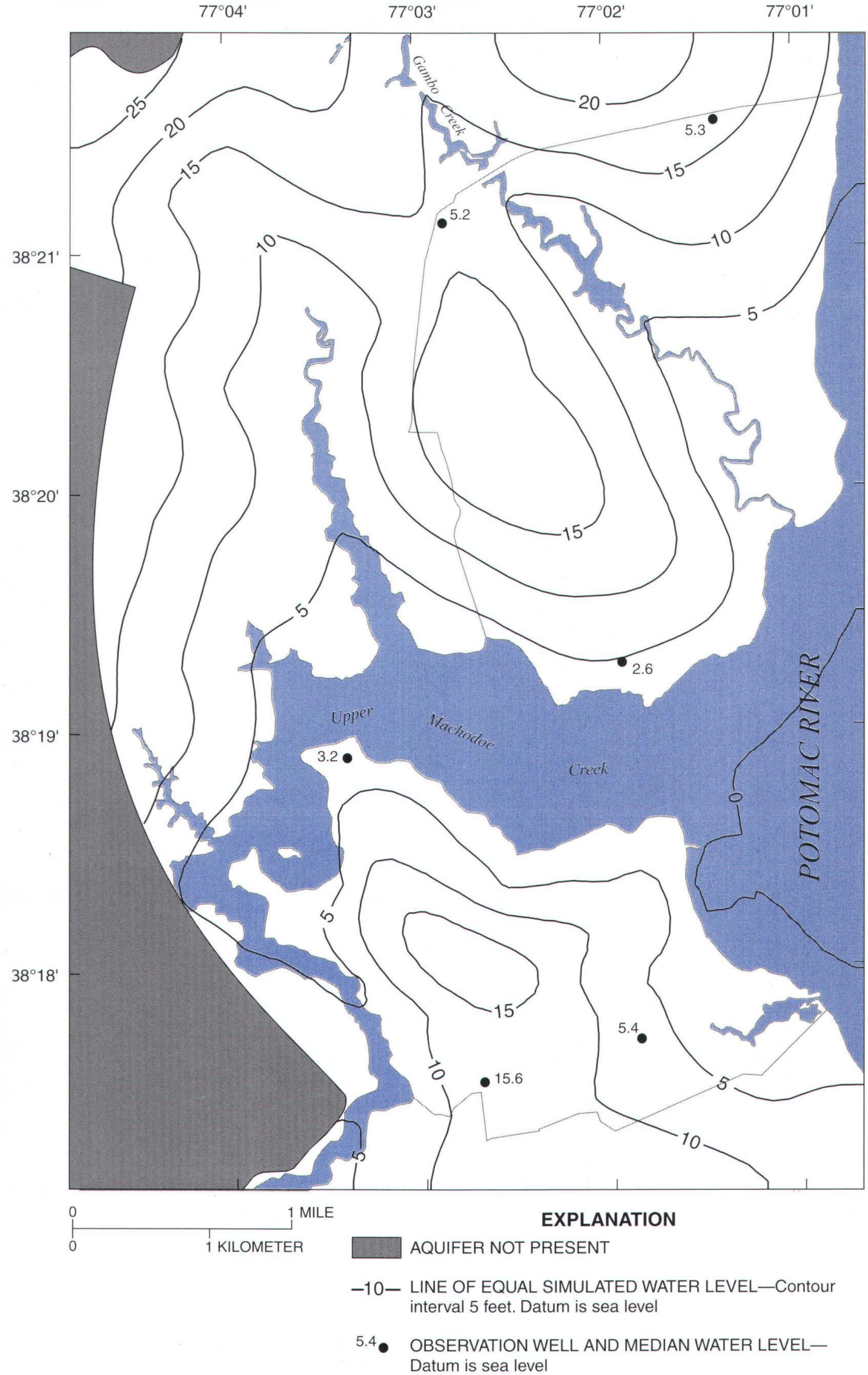


Figure 12. Measured and simulated water levels of the upper confined aquifer at Dahlgren, Virginia.

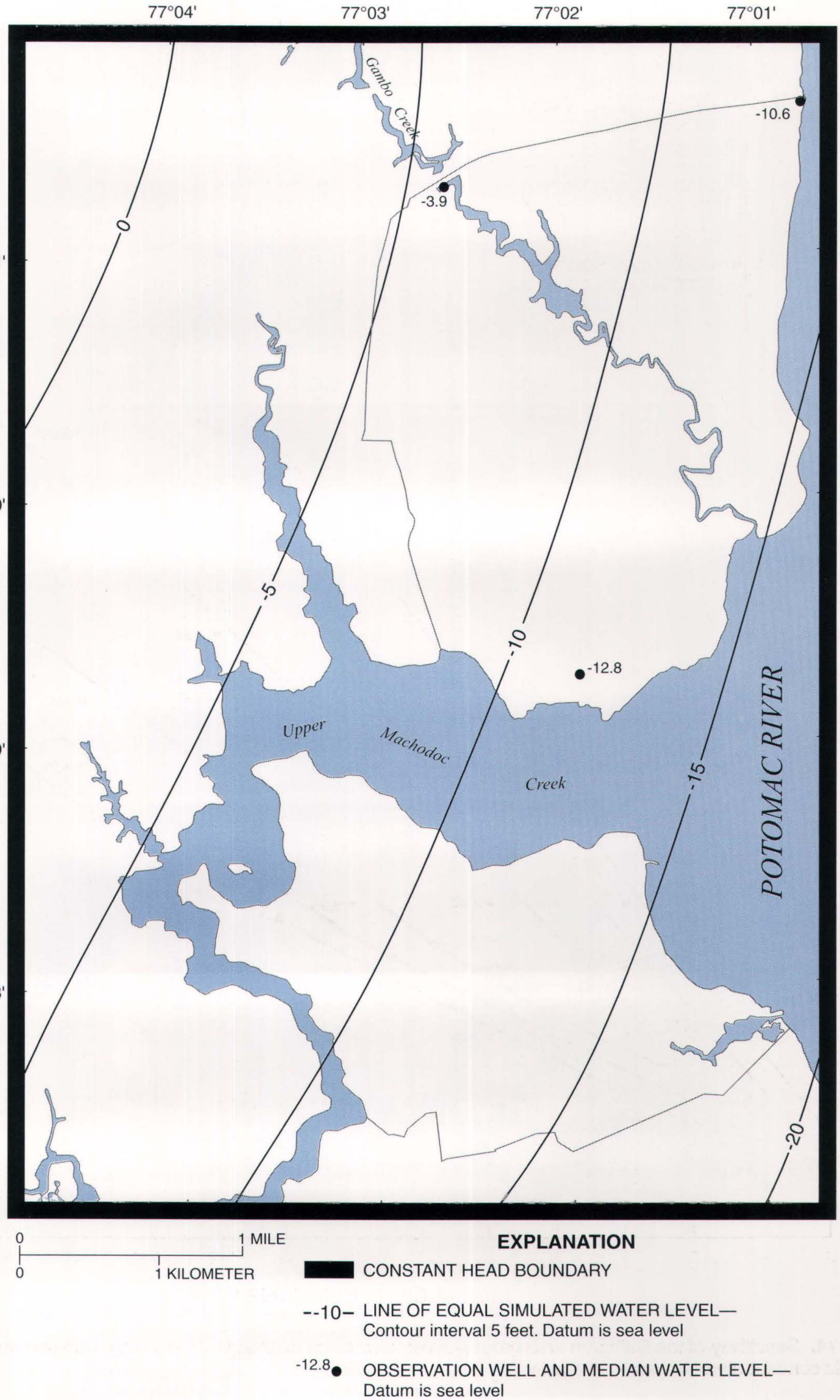


Figure 13. Measured and simulated water levels of the Aquia aquifer at Dahlgren, Virginia.

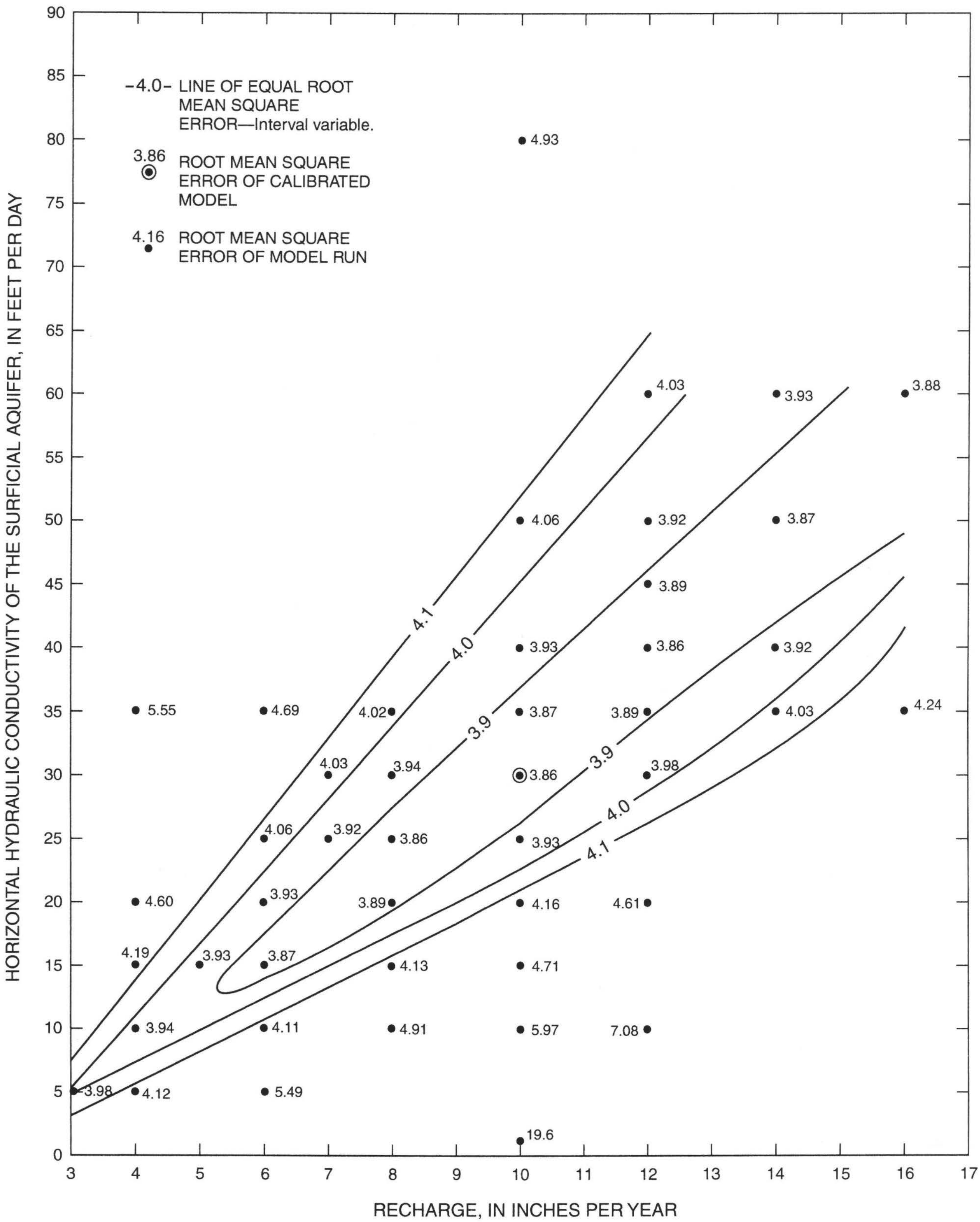


Figure 14. Sensitivity of the Dahlgren area ground-water flow model to changes in recharge rate and horizontal hydraulic conductivity of the surficial aquifer.

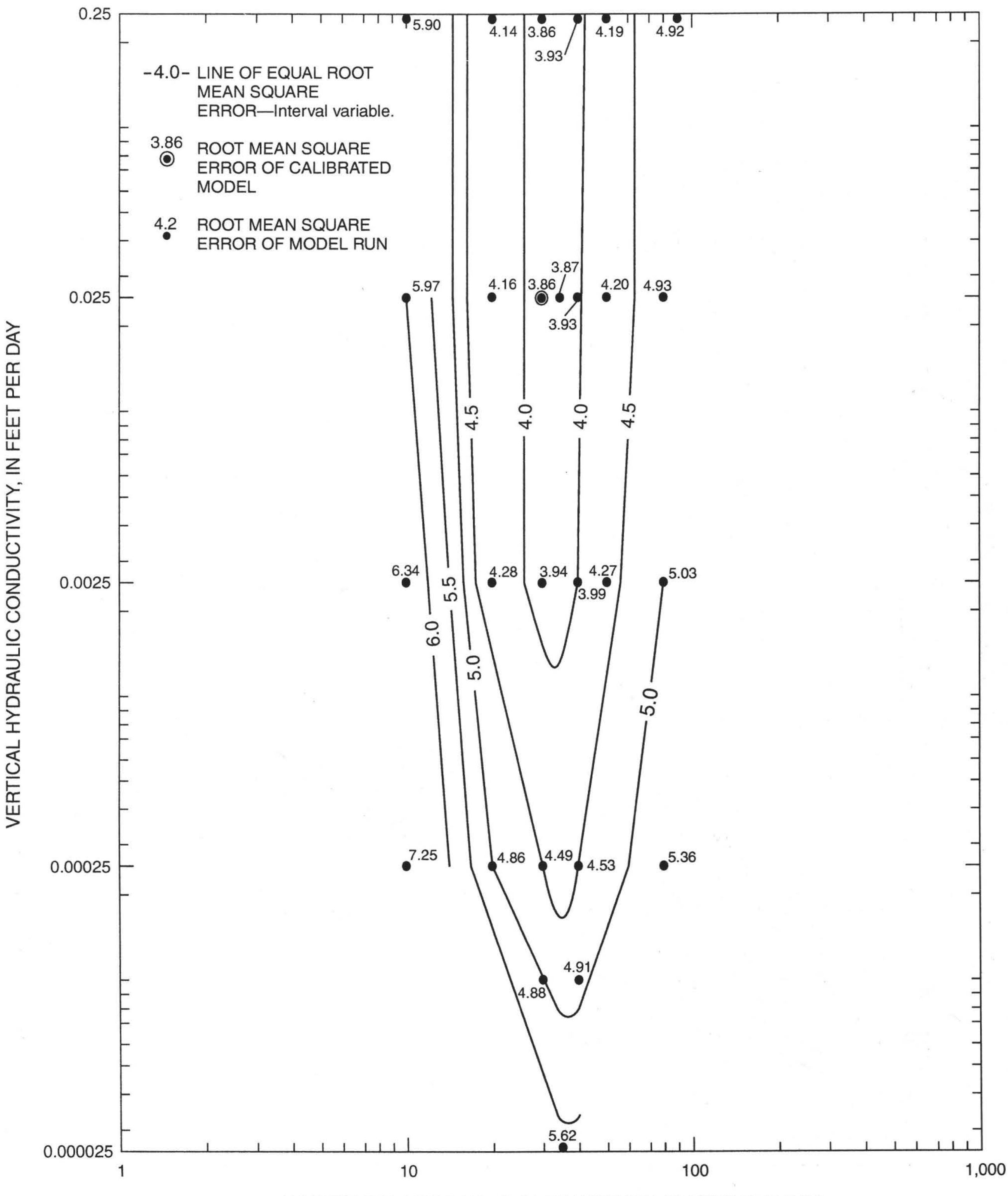


Figure 15. Sensitivity of the Dahlgren area ground-water flow model to changes in horizontal and vertical hydraulic conductivity of the surficial aquifer.

GROUND-WATER FLOW ANALYSES

The calibrated ground-water flow model of the Dahlgren area was analyzed to gain insights about the shallow aquifer system. The ZONEBUDGET subroutine and the interactive graphics output of Visual MODFLOW were used to determine and display the ground-water budget for the shallow aquifer system. Vector plots from Visual MODFLOW were used to depict ground-water flow directions and relative velocities for the shallow aquifers, and the MODPATH component of Visual MODFLOW was used to define general flow paths and ground-water traveltimes for selected areas at the NSWC.

Ground-Water Budget

The shallow aquifer system of the Dahlgren area is recharged by local precipitation, most of which is also discharged from the surficial aquifer. A recharge rate of 0.00228 ft^3/d, equal to 10 in/yr, was applied to each active cell of layer 1, which represents the surficial aquifer. The result was a simulated inflow from recharge of 905,132 ft^3/d, or 95 percent of all ground-water inflows, which totalled 947,833 ft^3/d (table 2 and fig. 16). Less than 4 percent of the inflows, 34,878 ft^3/d, came from river cells in the model. Less than 1 percent of inflows, 7,823 ft^3/d, came from constant-head cells, most of which were located at upgradient boundaries of layer 5, which represents the Aquia aquifer.

The inflows between each layer of the calibrated model are depicted in the last column of figure 16; the volumetric flow of water into and out of each layer also was determined and is depicted in fig. 17. A relatively small amount of ground water flowed from the surficial aquifer to deeper units, according to the volumetric budget of the calibrated model (fig. 17). About 115, 217 ft^3/d (12 percent of the total ground-water inflow) leaked down into layer 2, which primarily represented the upper confining unit. Most of this water (107,191 ft^3/d) returned to layer 1. About 46,475 ft^3/d (5 percent of all inflows) leaked down to layer 3, and about 38,449 ft^3/d returned to layer 2. Only 8,026 ft^3/d (less than 1 percent of all inflows) leaked down through layer 4, the Nanjemoy-Marlboro confining unit, to layer 5, the Aquia aquifer.

Ground-water discharge from the shallow aquifer system seeps out of the banks of streams and ditches or leaks upward to the rivers, wetlands, and estuaries of the Dahlgren area. About 412,583 ft^3/d or 44 percent of all of the outflows of the calibrated model (947,838 ft^3/d) discharged from layer 1, the surficial aquifer, through the river cells (fig. 18). About 393,241 ft^3/d (41 percent of all outflows) discharged from layer 1 through the constant-head cells, representing the Potomac River and upper Machodoc Creek estuaries and 126,304 ft^3/d (13 percent of the total outflows of the model discharged from layer 1 through the drains.

Only 15,746 $ft^{3/}d$, 2 percent of the total outflows from the ground-water model, discharged from constant-head cells at the down-gradient boundaries of layer 5, the Aquia aquifer. A little more than half of this ground water (8,026 $ft^{3/}d$) had leaked downward from the surficial aquifer through the confining units, while a little less than half (7,645 $ft^{3/}d$) had entered from the upgradient boundaries of the aquifer.

Table 2. Ground-water budget of the Dahlgren area model

Component	Inflows (cubic feet per day)	Component	Outflows (cubic feet per day)
Recharge	905,132	Recharge	0
Rivers	34,878	Rivers	412,583
Constant heads	7,823	Constant heads	408,951
Drains	0	Drains	126,304
Total in	947,833	Total out	947,838
Total in-out	-5	Difference	0.0005%

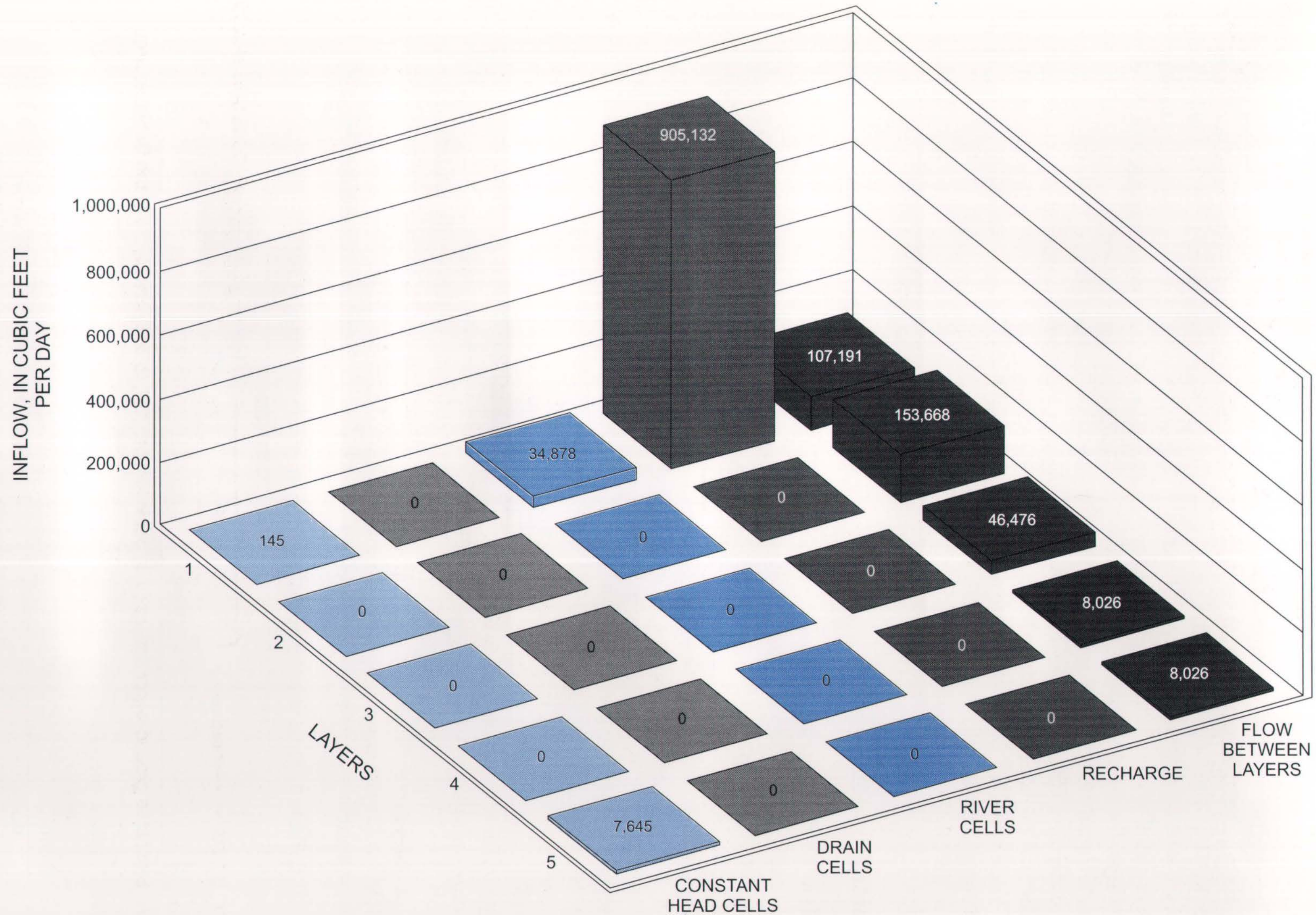


Figure 16. Simulated ground-water inflow rates for layers of the Dahlgren area model.

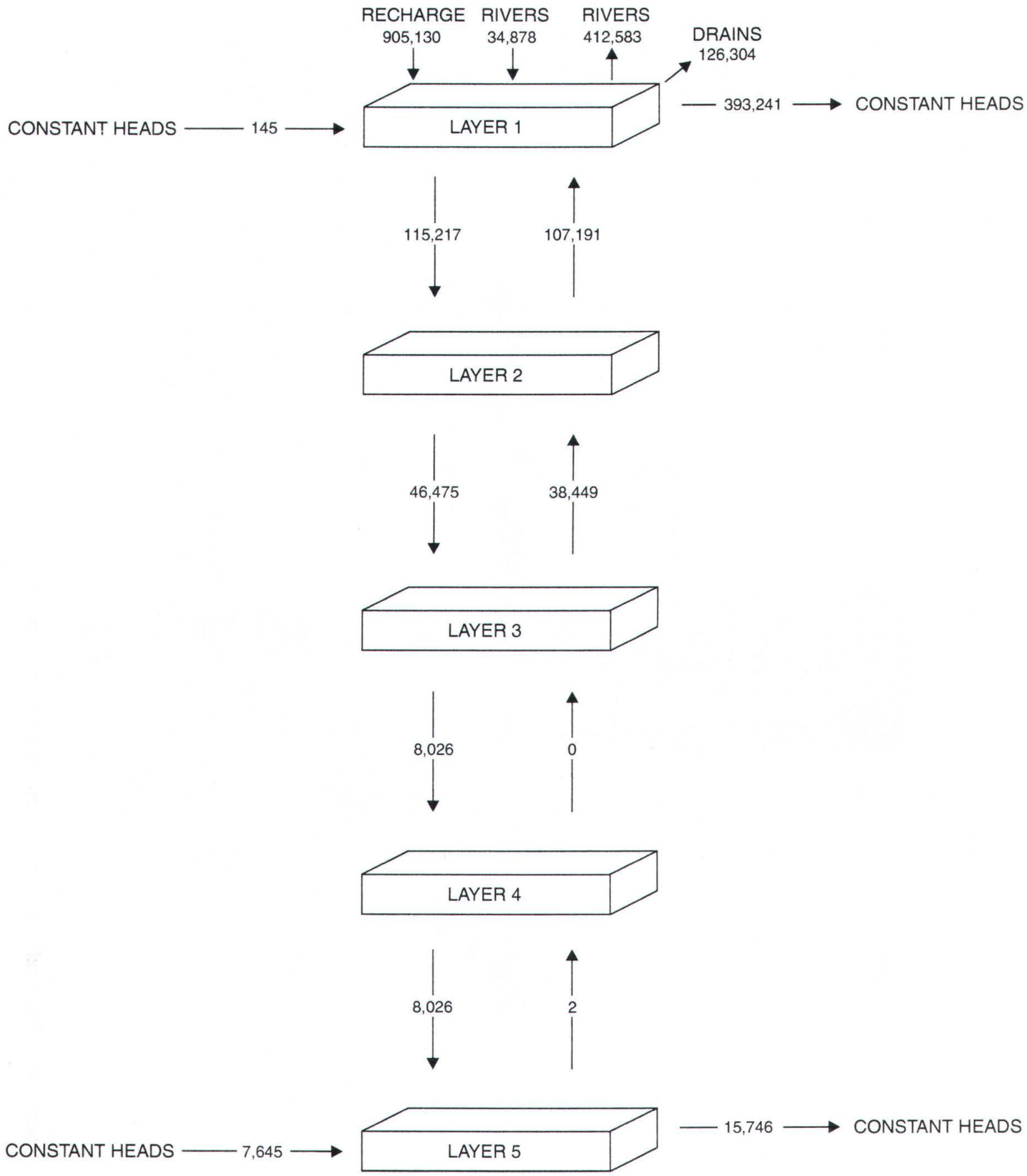


Figure 17. Simulated ground-water flow rates, in cubic feet per day, to and from layers of the Dahlgren area model.

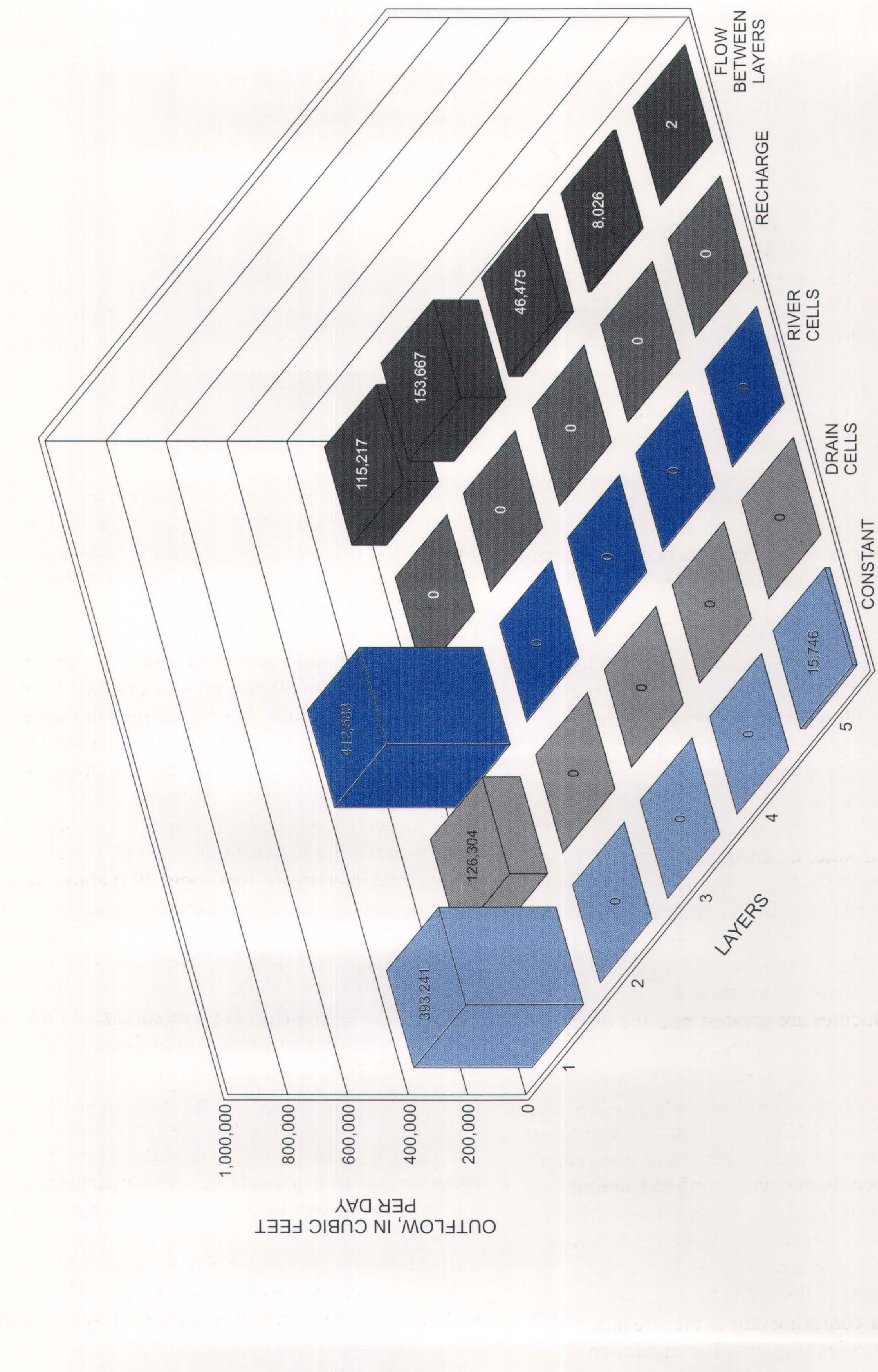


Figure 18. Simulated ground-water outflow rates for layers of the Dahlgren area model.

Ground-Water Flow Vectors

The vectors calculated from a ground-water flow model can be used to display the general directions and relative velocities of advective ground-water flow through an aquifer system. Porosity is required for velocity calculations of ground-water flow; however, no information on the porosity of the shallow aquifer system at the NSWC has been published. An effective porosity of 30 percent was assumed for the shallow aquifer system at Dahlgren by previous investigations (Harlow and Bell, 1996, p. 21 and Bell, 1996, p. 25) and also was assumed for this ground-water flow model.

Thirty percent is near the low end of the range in porosity for sand and gravel deposits, which tends to range from 25 to 50 percent but is generally lower than the range for silt and clay, which is 35 to 70 percent (Freeze and Cherry, 1979, p. 37). If a higher porosity were assumed, the velocities resulting from the following simulations would decrease because porosity is in the denominator of the equation for average linear velocities of ground-water.

Ground-water flow in the surficial aquifer in and around the Open Burn and Open Detonation (OB/OD) area, a flat area of the EEA at the NSWC, is a concern of the U.S. Navy. Flow vectors displayed as arrows from the calibrated ground-water flow model indicate that the directions of ground-water flow in the surficial aquifer at the OB/OD area are generally toward the north, east, and south of the area (fig. 19). A small amount of ground water enters the OB/OD area from slightly higher ground to the southwest, but most of the ground water probably originates as local recharge. The velocities of flow are relatively slow in and around the center of the OB/OD area but increase outward as the gradients increase to the north, east, and south. The gradients and velocities are greatest near the ditches, streams, and the shorelines, where ground water from the OB/OD area eventually discharges. The maximum velocities from the surficial aquifer were 2 ft/d, as calculated by the vector plot, but the small vectors near the flat, open areas were only a fraction of that velocity.

Ground water in the upper confined aquifer generally leaks downward and flows outward from higher ground in the west or from central interstream areas beneath the flat terrace plain and then moves outward and upward to discharge through the intervening upper confining unit to the streams, wetlands, and estuaries (fig. 20). The maximum ground-water velocity simulated for the upper confined aquifer was 0.05 ft/d (18 ft/yr). The upper confined aquifer is not present beneath the central parts of the EEA, where rates of ground-water flow through the confining units are nil.

Ground water flows through the Aquia aquifer in the Dahlgren area from the northwest toward the southeast (fig. 21) because of regional ground-water withdrawals. The Aquia is separated from the shallower aquifers by the relatively thick and continuous Nanjemoy-Marlboro confining unit, and is only partly affected by local recharge. The maximum ground-water velocities simulated for the Aquia aquifer were 0.015 ft/d (5 ft/yr).

Ground-Water Flow Paths

Ground-water flow paths and traveltimes from selected cells in the calibrated ground-water flow model were delineated to highlight typical behavior expected for the shallow aquifer system. Particles for the flow paths were started at the center of the selected cells and were stopped when the particles entered an internal sink or had traveled for a specified period of time. A porosity of 30 percent was assumed for the shallow aquifer system. If a higher porosity were assumed, the velocities resulting from the following simulations would decrease and the traveltimes would increase in proportion to the change.

Ground-water flow paths in the surficial aquifer in and around the airfield at the NSWC, a relatively flat, central interstream area about 20 ft above sea level, are typical for most of the Dahlgren area. Fifty particles, each placed in the middle of a cells in the center of the airfield of layer 1 were tracked forward by 10-year increments for 100 years and plotted by projection to layer 1 (fig. 22). The simulated flow paths were generally downward and radially outward from the airfield. The distances between the 10-year increments were large in the surficial aquifer because traveltimes are relatively fast. The minimum traveltime was about 4 years, probably representing the short route northward to a local ditch. Other particles took longer, but less than 10 years, to reach the streams to the south and east; however, some particles followed deeper paths that reached the upper confining unit where the velocities slowed considerably. Those paths took much longer to travel, as indicated by the short

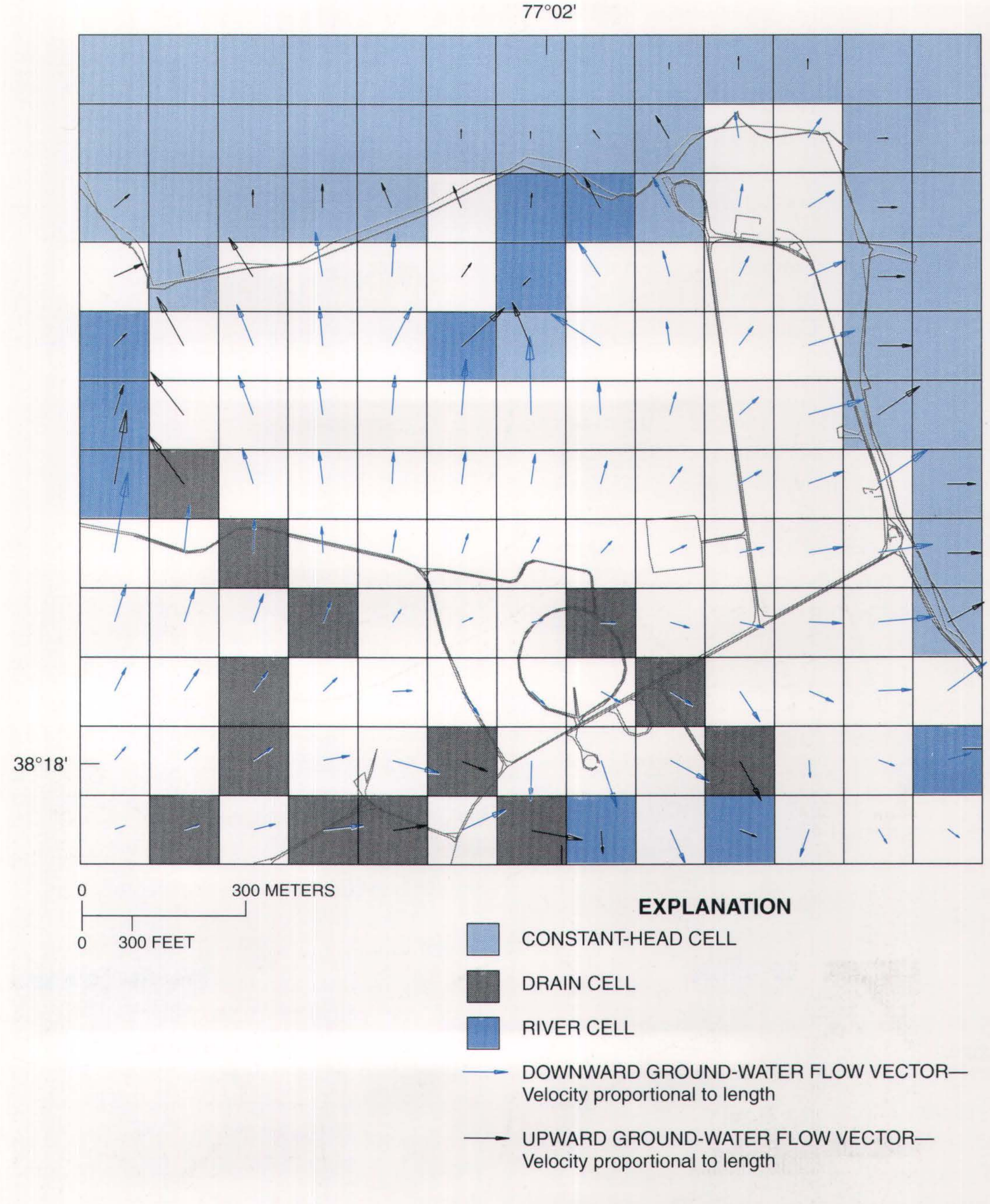
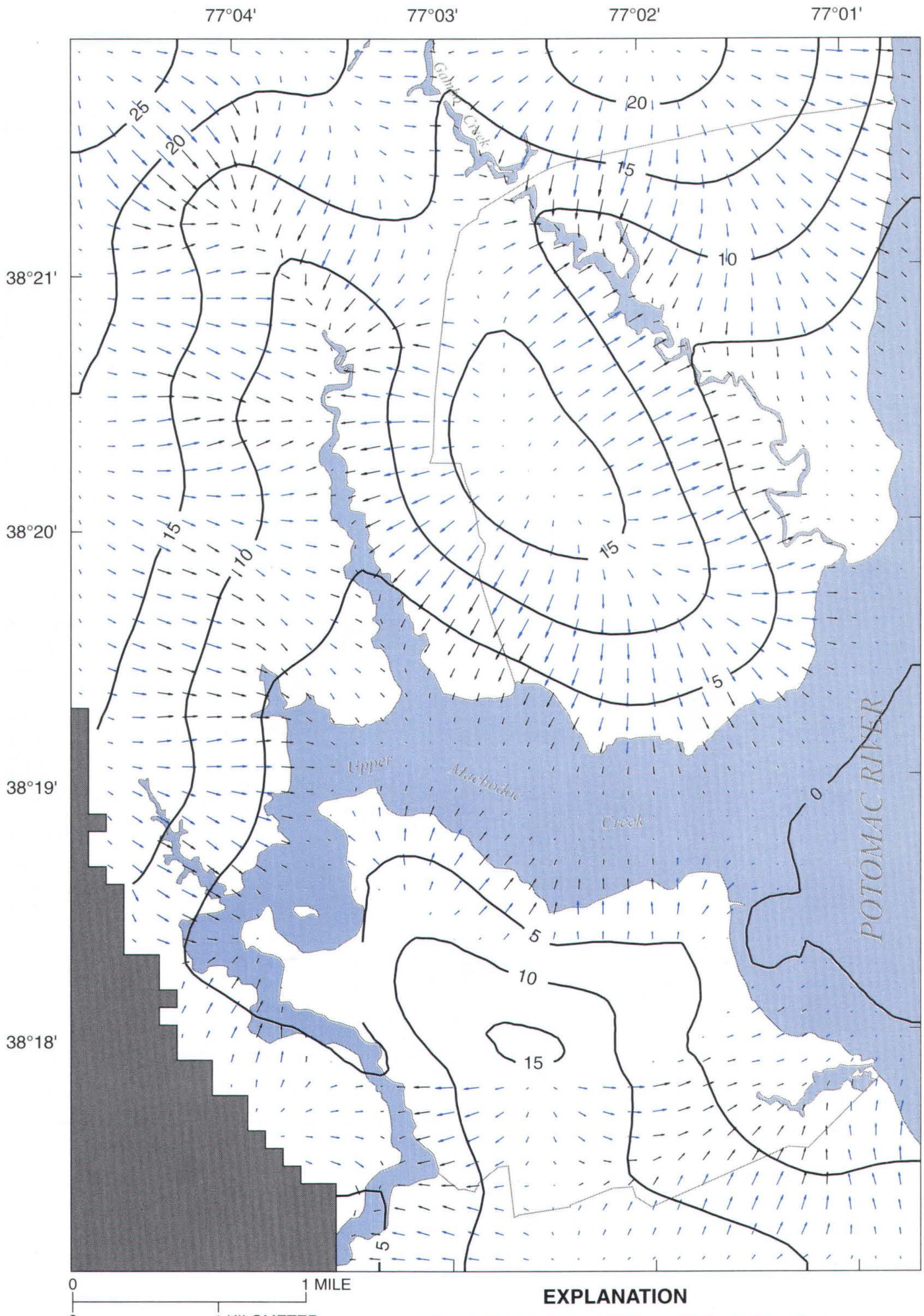


Figure 19. Vectors simulated for the surficial aquifer in and around the Open Burn and Open Detonation sites of the Naval Surface Warfare Center, Dahlgren, Virginia.



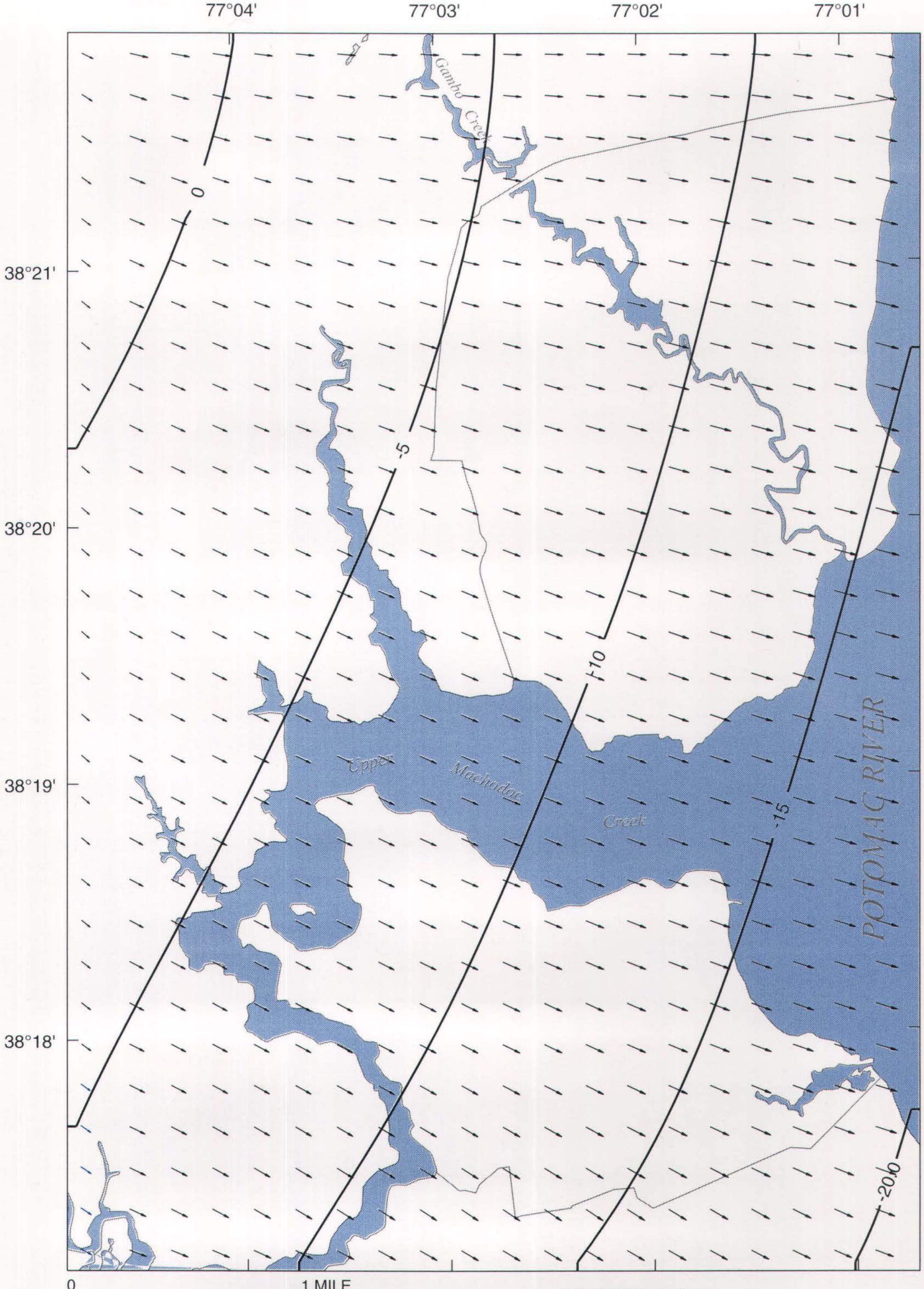
EXPLANATION

—5— LINE OF EQUAL SIMULATED WATER LEVEL—Contour interval 5 feet. Datum is sea level

DOWNWARD GROUND-WATER FLOW VECTOR—Velocity proportional to length

UPWARD GROUND-WATER FLOW VECTOR—Velocity proportional to length

Figure 20. Vectors simulated for the upper confined aquifer by the Dahlgren area model.



EXPLANATION

—-5— LINE OF EQUAL SIMULATED WATER LEVEL—Contour interval 5 feet. Datum is sea level

DOWNWARD GROUND-WATER FLOW VECTOR—Velocity proportional to length

UPWARD GROUND-WATER FLOW VECTOR—Velocity proportional to length

Figure 21. Vectors simulated for the Aquia aquifer by the Dahlgren area model.

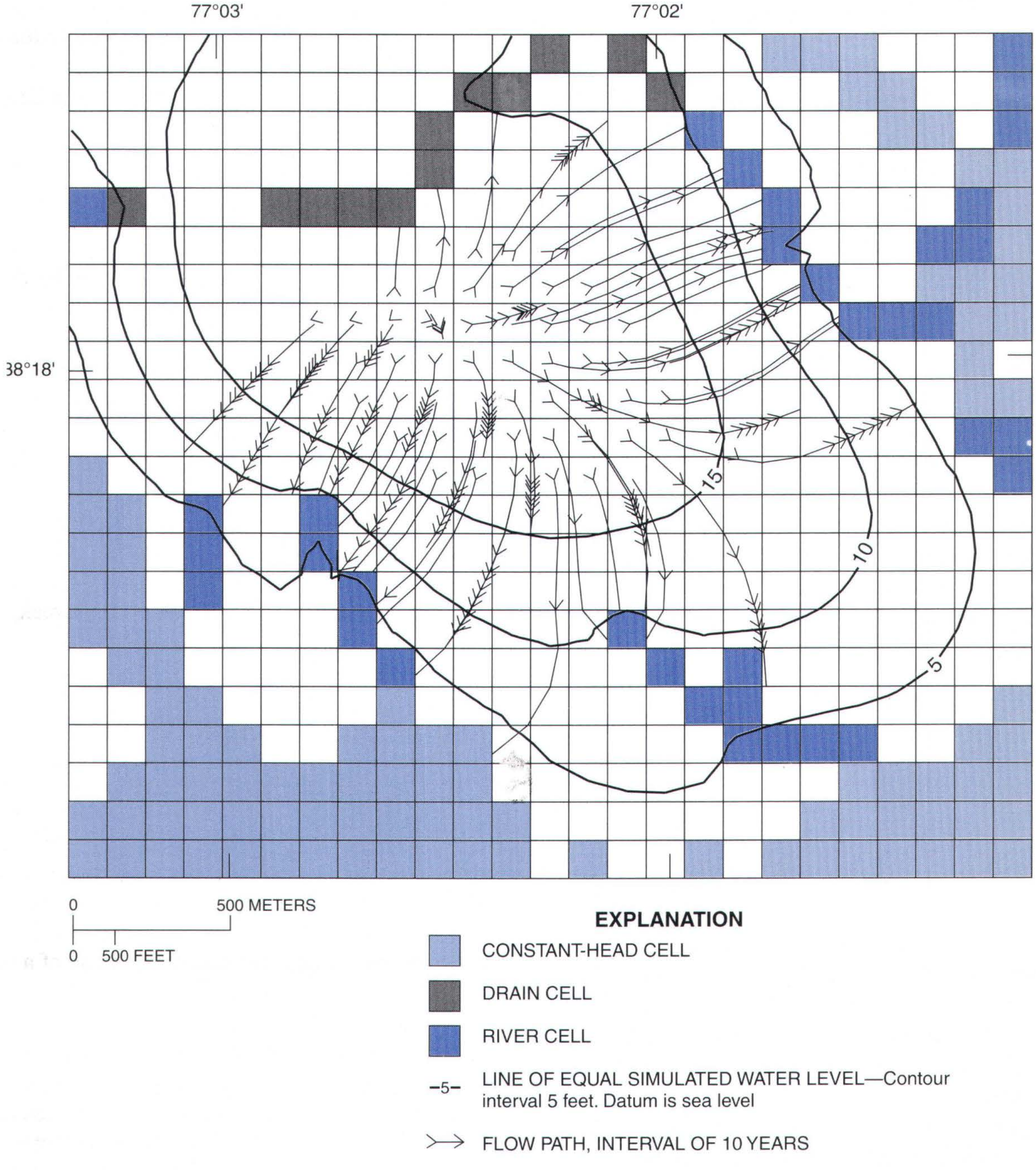


Figure 22. Simulated paths and traveltimes for advective ground-water flow from the airfield of the Naval Surface Warfare Center, Dahlgren, Virginia.

distance between the arrows. None of the particles traveled entirely through the upper confining unit in the 100 years allotted.

The diverse flow paths simulated for this area typical of the surficial aquifer imply a wide range in possible directions and traveltimes for the advective ground-water flow. If the hydraulic properties of the shallow aquifer system are consistent, as simulated by the ground-water flow model, the potential spread of contaminants by ground-water flow at any particular site at the NSWC would depend on the location of the site with respect to the interstream areas and discharge areas.

To depict other possible flow paths and traveltimes through the upper confined aquifer, six particles were placed near the bottom of the surficial aquifer beneath the airfield in column 27 of layer 1 and tracked forward. The flow paths were projected to column 27 and are depicted in a vertically exaggerated section (fig. 23). The particle following the deepest path traveled downward slowly for 100 years through the upper confining unit and then traversed the upper confined aquifer for another 400 years before entering the Nanjemoy-Marlboro confining unit, where it traveled downward slowly for thousands of years before eventually entered the Aquia aquifer. The next deepest particle also traveled about 100 years downward through the upper confining unit and in a little more than 400 years traversed the upper confined aquifer; it then entered the upper confining unit and traveled upward for another 100 years before discharging to upper Machodoc Creek. The third particle traveled about 100 years through the upper confining unit and skimmed the top of the upper confined aquifer in less than 100 years before traveling upward again through the upper confining unit and returning to the surficial aquifer. The next two particles traveled similar, but consecutively shorter paths through the upper confining unit, never reaching the upper confined aquifer before returning to the surficial aquifer, but the last particle moved horizontally near the bottom of the surficial aquifer.

Ground-water traveltimes through the upper confining unit and the upper confined aquifer are measured in hundreds of years. Such slow traveltimes imply that contamination of the upper confined aquifer would not yet be expected if it is assumed that the confining unit is continuous, which is indicated by the available data and simulated by the ground-water flow model.

Traveltimes through the Aquia aquifer are measured in thousands of years. A particle was placed in the middle of each cell of column 48 of layer 5, the downgradient boundary of the Aquia aquifer, and tacked backward to indicate possible sources for ground water leaving the Dahlgren area. The backward tracks indicate long, slow paths marked by 1,000-year increments (fig. 24). The paths travel backwards toward the northwest for 4,000 or more years to entry points in the west from layer 4, the Nanjemoy-Marlboro confining unit. Such slow traveltimes imply that contamination of the Aquia aquifer from the NSCW is unlikely if it is assumed that the confining units are continuous, which is indicated by the available data and simulated by the ground-water flow model.

SUMMARY

The possible migration of contaminants by ground-water flow at the Naval Surface Warfare Center, Dahlgren, Va. (NSWC) is a concern of the U.S. Navy. The U.S. Geological Survey (USGS) has worked in cooperation with the Safety and Environmental Office at Dahlgren since 1992 to investigate the hydrogeology and water quality of the shallow aquifer system.

Ground water in the Dahlgren area flows through a layered system of aquifers and intervening confining units. The shallow aquifer system is comprised of the surficial aquifer, the upper confining unit, the upper confined aquifer, the Nanjemoy-Marlboro confining unit, and the Aquia aquifer.

Maps and data defining the geometry of the aquifers and confining units at the NSWC were assimilated from previous investigations, expanded, and refined. Medians were determined for water levels measured in 64 observation wells from 1992 and 1994 through the spring of 1998. Medians and geometric means were determined for horizontal hydraulic conductivities from published single-well aquifer (slug) tests at Dahlgren. Median and geometric means also were determined for vertical hydraulic conductivities from published falling-head permeameter tests at the NSWC.

A steady-state, three-dimensional ground-water flow model was devised and used to incorporate and evaluate USGS data collected from previous and on-going studies of the shallow aquifer system. The

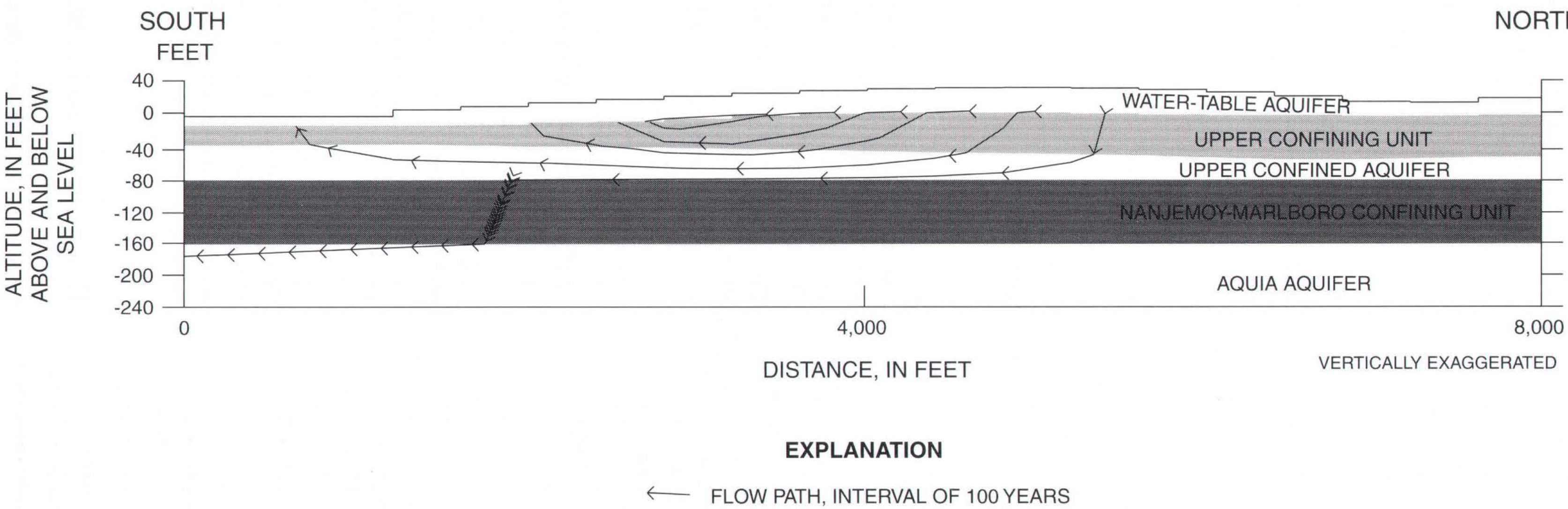


Figure 23. Simulated paths and traveltimes for advective ground-water flow from the bottom of the surficial aquifer beneath the airfield of the Naval Surface Warfare Center, Dahlgren, Virginia.

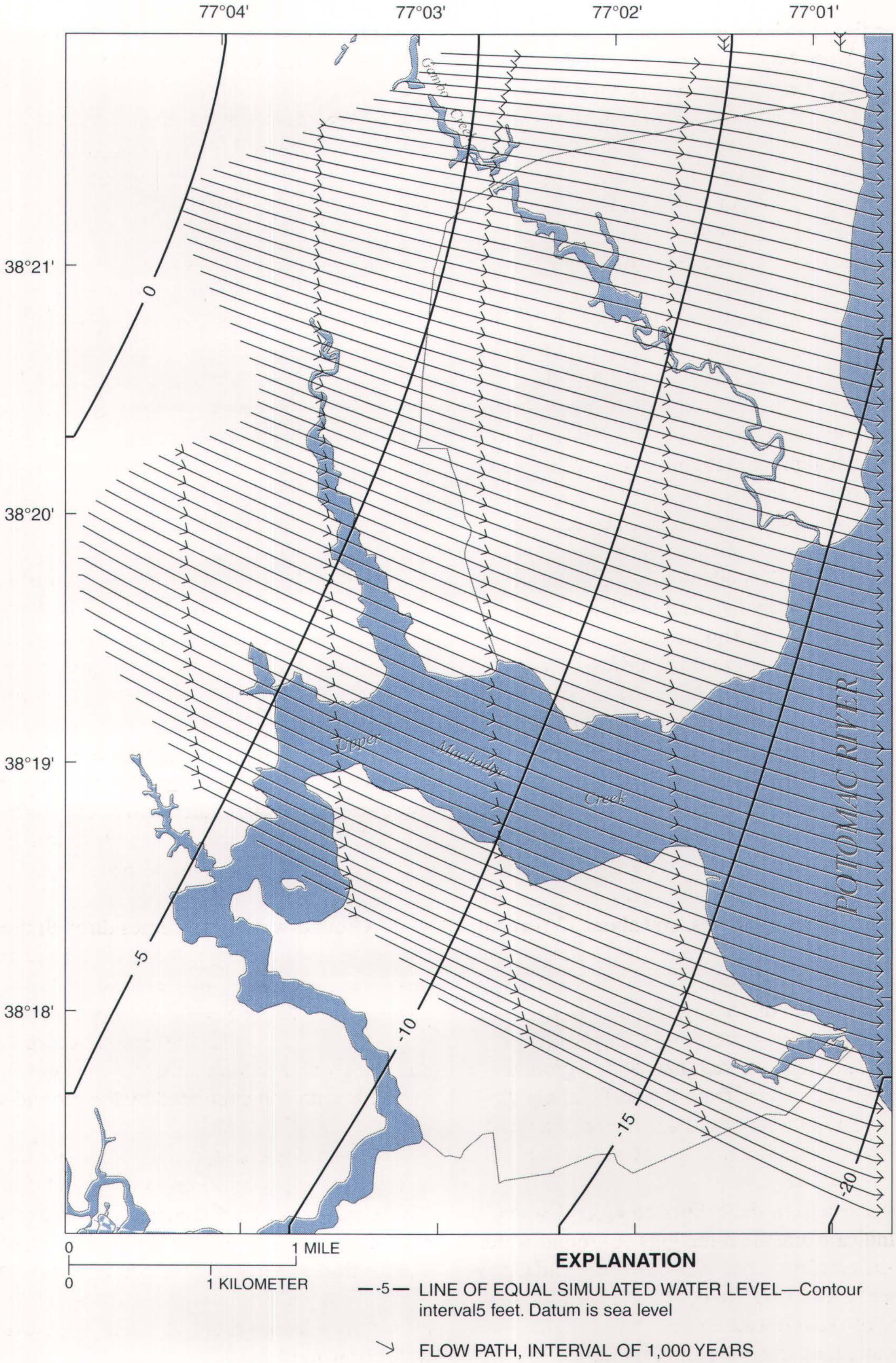


Figure 24. Simulated paths and traveltimes of ground-water particles tracked backwards from the downgradient boundary of the Aquia aquifer at Dahlgren, Virginia.

ground-water flow model was calibrated by minimizing the Root Mean Square Error (RMSE) between simulated water levels and the medians of measured water levels in observation wells at the NSWC. Median horizontal hydraulic conductivities from single-well aquifer tests and median vertical hydraulic conductivities from permeameter tests were used as initial values in the ground-water flow model. Some of the median hydraulic conductivity values were adjusted to calibrate the model. The calibrated model was then used to calculate the ground-water budget, to depict ground-water flow vectors, and to delineate ground-water flow paths and traveltimes for selected areas at the NSWC.

The shallow aquifer system of the Dahlgren area is recharged by local precipitation, most of which also is discharged from the surficial aquifer. A relatively small amount of ground water, only 12 percent of all inflows, leaked from the surficial aquifer to deeper units, as simulated by the model. Only 5 percent of all inflows reached the upper confined aquifer, and less than 1 percent reached the Aquia aquifer.

Ground-water discharge from the shallow-aquifer system seeps out of the banks of streams and ditches or leaks upward to the rivers, wetlands, and estuaries of the Dahlgren area. About 44 percent of all of the outflows simulated by the calibrated model discharged from layer 1, the surficial aquifer, to the river cells of the model. About 41 percent of all outflows discharged from layer 1 to the constant-head cells of the model, representing the Potomac River and upper Machodoc Creek estuaries, and about 13 percent of the total outflows discharged from layer 1 to the simulated drains. Only 2 percent of the total outflows simulated by the model discharged from constant-head cells at the downgradient boundaries of layer 5, the Aquia aquifer. A little more than half of this ground water had leaked downward from the surficial aquifer through the confining units while a little less than half had entered from the upgradient boundaries of the aquifer.

Flow vectors from the calibrated ground-water flow model indicate that the directions of ground-water flow in the surficial aquifer at the Open Burn and Open Detonation area are toward the north, east, and south. A small amount of ground water enters the Open Burn and Open Detonation area from slightly higher ground to the southwest. The velocities of flow are slow in and around the center of the Open Burn and Open Detonation area, but increase outward as the gradients increase.

Water levels in the upper confined aquifer are similar to those of the surficial aquifer, but the levels are lower beneath the interstream areas and slightly higher beneath the rivers, wetlands, and estuaries than those of the surficial aquifer. Ground water generally leaks downward and flows outward from higher ground in the west or from central interstream areas beneath the flat terrace plain and then outward and upward to discharge through the intervening upper confining unit to the streams, wetlands, and estuaries.

Ground water flows through the Aquia aquifer from the northwest toward the southeast because of regional ground-water withdrawals some distance away. The Aquia is separated from the shallower aquifers by the relatively thick and continuous Nanjemoy-Marlboro confining unit.

Ground-water flow paths in the surficial aquifer diverge radially from the airfield at the NSWC. The diverse flow paths simulated for this typical area of the surficial aquifer imply a wide range in possible directions and traveltimes for advective ground-water flow. If the hydraulic properties of the shallow aquifer system are consistent, as simulated by the ground-water flow model, the potential spread of contaminants by advective ground-water flow at any particular site at the NSWC would depend on the location of the site with respect to the interstream areas and discharge areas.

Ground-water traveltimes through the upper confining unit and the upper confined aquifer are measured in hundreds of years. Such slow traveltimes imply that contamination of the upper confined aquifer would not yet be expected if it is assumed that the confining unit is continuous, which is indicated by the available data and simulated by the ground-water flow model.

Ground-water traveltimes through the Nanjemoy-Marlboro confining unit and through the Aquia aquifer are measured in thousands of years. Such slow traveltimes imply that contamination of the Aquia aquifer from the NSCW is unlikely if it is assumed that the confining units are continuous, which is indicated by the available data and simulated by the ground-water flow model.

Analyses of the hydrogeology, ground-water flow, and computer simulations described and depicted in this report are intended to provide knowledge for the wise use of the ground-water resources of the Dahlgren area and to provide technical insights for the prudent management of the Navy's hazardous materials operations at the NSWC.

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