

Hydrogeology and Water Quality of the Shallow Aquifer System at the Mainside, Naval Surface Warfare Center, Dahlgren Site, Dahlgren, Virginia

By George E. Harlow, Jr., and Clifton F. Bell

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 96-4055

Prepared in Cooperation with the

SAFETY AND ENVIRONMENTAL OFFICE
NAVAL SURFACE WARFARE CENTER,
DAHLGREN SITE

Richmond, Virginia

1996



U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey

For additional information write to:

District Chief
U.S. Geological Survey
3600 West Broad Street
Room 606
Richmond, VA 23230-4916

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286, Mail Stop 517
Denver Federal Center
Denver, CO 80225-0046

CONTENTS

Abstract.....	1
Introduction	1
Purpose and scope	3
Previous investigations	3
Methods of study	5
Well installation and collection of lithologic data	5
Borehole geophysics.....	5
Water-level measurements.....	5
Single-well aquifer tests	5
Water-quality sampling and analysis.....	6
Acknowledgments	7
Hydrogeology of the shallow aquifer system	7
Geology	7
Aquifers and confining units.....	8
Lithology and extent.....	8
Head distribution and direction of ground-water flow	17
Seasonal head fluctuations.....	17
Hydraulic properties	20
Water quality of the shallow aquifer system.....	22
Occurrence and distribution of selected chemical constituents.....	23
Columbia aquifer	24
Field properties.....	24
Major chemical constituents.....	26
Minor chemical constituents.....	26
Upper confined aquifer	26
Surface water.....	26
Probable sources of chemical constituents	27
Natural processes.....	27
Organic material	28
Carbonate minerals.....	29
Non-carbonate minerals.....	29
Exchangeable cations	29
Road salt	29
Well grout	30
Isotopes.....	30
Summary and conclusions.....	33
References cited.....	33

FIGURES

1, 2. Maps showing:	
1. Location of study area	2
2. Locations of observation wells, tide gage, surface-water sampling sites, and hydrogeologic sections	4
3. Diagram showing relation between geology and hydrogeology.....	9
4, 5. Hydrogeologic sections at the Mainside, Dahlgren, Virginia:	
4. Hydrogeologic section A-A'	10
5. Hydrogeologic section A-A".....	11

6-11. Maps showing:	
6. Altitude of the top and thickness of the upper confining unit.....	13
7. Altitude of the top, thickness of, and generalized ground-water-flow direction in, the upper confined aquifer	14
8. Altitude of the top and thickness of the Nanjemoy-Marlboro confining unit.....	15
9. Altitude of the top of, and generalized ground-water-flow direction in, the Aquia aquifer	16
10. Hydraulic heads in the Columbia aquifer, March 1993	18
11. Hydraulic heads in the Columbia aquifer, October 1993.....	19
12, 13. Hydrographs showing maximum daily water level in the Columbia aquifer in:	
12. Well 10, October 1992 through September 1993.....	20
13. Well 24 and total daily rainfall, October 1992 through September 1993	22
14. Hydrograph showing water levels in well M3 in the upper confined aquifer, well D2 in the Aquia aquifer, and tidal fluctuations in the Upper Machodoc Creek, May 7–9, 1993.....	23
15. Boxplots showing summaries of water-quality analyses for selected constituents in the Columbia aquifer.....	25
16, 17. Trilinear diagrams showing:	
16. Major-ion composition of water in wells in the Columbia aquifer.....	27
17. Major-ion composition of water in wells in the upper confined aquifer and surface water.....	28
18. Map showing locations of wells in the Columbia aquifer, including those where chloride constituent was greater than 40 percent of the total anion milliequivalents in a water-quality sample	31
19. Graph showing ratio variation in deuterium and oxygen-18 in ground water and surface water	32

TABLES

1. Saturated thickness of the Columbia aquifer on March 30, 1993, and fluctuation of the water-table between March and October 1993	8
2. Horizontal hydraulic conductivity values for the Columbia aquifer, determined from slug tests.....	21
3. Summary statistics for water-quality analyses from the Columbia aquifer.....	24

CONVERSION FACTORS, ABBREVIATED HYDROGEOLOGIC UNITS AND WATER-QUALITY UNITS, AND VERTICAL DATUM

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
acre	4,047	square meter
Volume		
gallon (gal)	3.785	liter
gallon (gal)	.003785	cubic meter
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day
Pressure		
pound per square inch (lb/in ²)	6.895	kilopascal

Hydrogeologic units: Hydraulic conductivity is reported in foot per day (ft/d), a mathematical reduction of the unit cubic foot per day per square foot [(ft³/d)/ft²].

For dimensions expressed in this report, L represents units of distance and T represent units of time.

Water-quality units: Water temperature in degree Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the following equation:

$$^{\circ}\text{F} = 1.8 \times (^{\circ}\text{C}) + 32.$$

Chemical concentration is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Specific electrical conductance of water is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Sea level: 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.

Hydrogeology and Water Quality of the Shallow Aquifer System at the Mainside, Naval Surface Warfare Center, Dahlgren Site, Dahlgren, Virginia

By George E. Harlow, Jr., and Clifton F. Bell

Abstract

Lithologic and geophysical logs of boreholes at 29 sites show that the hydrogeologic framework of the Mainside of the Naval Surface Warfare Center, Dahlgren Site at Dahlgren, Virginia, consists of unconsolidated sedimentary deposits of gravel, sand, silt, and clay. The upper 220 feet of these sediments are divided into five hydrogeologic units, including the (1) Columbia (water-table) aquifer, (2) upper confining unit, (3) upper confined aquifer, (4) Nanjemoy-Marlboro confining unit, and (5) Aquia aquifer.

The Columbia aquifer in the study area is a local system that is not affected by regional pumping. Ground-water recharge occurs at topographic highs in the northern part of the Mainside, and ground-water discharge occurs at topographic lows associated with adjacent surface-water bodies. Regionally, the direction of ground-water flow in the upper confined and Aquia aquifers is toward the southwest and southeast, respectively.

A downward hydraulic gradient exists between the aquifers in the shallow system, and stresses on the Aquia aquifer are indicated by heads that range between 2 and 12 feet below sea level. The ratio of median horizontal hydraulic conductivity of the Columbia aquifer to median vertical hydraulic conductivity of the upper confining unit, however, is approximately 2,600:1; therefore, under natural-flow conditions, most water in the Columbia aquifer probably discharges to adjacent surface-water bodies.

The composition and distribution of major ions vary in the Columbia aquifer. In general, water samples from wells located along the inland perimeter roads of the study area have chloride or a combination of chloride and sulfate as the dominant anions, and water samples from wells located in the interior of the

study area have bicarbonate or a combination of bicarbonate and sulfate as the dominant anions. Sodium and calcium were the dominant cations in most samples.

Dissolved solids and four inorganic constituents are present in water from the Columbia aquifer at concentrations that exceed the secondary maximum contaminant levels (SMCL's) for drinking water established by the U.S. Environmental Protection Agency. Concentration of dissolved solids exceed the SMCL of 500 milligrams per liter in 3 of 29 samples from the Columbia aquifer. An elevated concentration of sodium is present in one water sample, and elevated concentrations of chloride are present in two water samples. Concentrations of dissolved iron and manganese exceed the SMCL in 10 and 17 of 29 water samples, respectively, and are the most extensive water-quality problem with regard to inorganic constituents in the Columbia aquifer.

INTRODUCTION

The Navy is collecting hydrologic data and evaluating evidence of environmental contamination at the Naval Surface Warfare Center, Dahlgren Site (NSWCDL), Dahlgren, Va., (fig. 1) to assess the possible effects on public health and the environment. The NSWCDL is the principal Naval research, development, test, and evaluation facility for analysis of surface/ship weaponry, naval mines, strategic systems, and warfare. The installation, established in 1918, consists of two areas: (1) The Explosive Experimental Area (EEA), an isolated weapons testing range, encompassing 1,641 acres on Tetotum Flats; (2) the Mainside, which encompasses 2,678 acres north of, and separated from, the EEA by Upper Machodoc

Creek. The Mainside contains gun ranges and an airfield, as well as laboratories, computer facilities, and administration buildings. Nonordnance operations also are established on the Mainside, including metal plating, vehicle maintenance, carpentry, grounds maintenance, electrical work, and water treatment.

The Commonwealth of Virginia requires an Oil Discharge Contingency Plan for facilities having hydrocarbon storage tanks. Facilities having hydrocarbon storage tanks at a cumulative capacity of more than 1 Mgal must also conduct a Ground-Water Characterization Study to determine potential migration pathways in the event of a hydrocarbon release. The NSWCDL, in 1992, had hydrocarbon storage tanks with a cumulative capacity exceeding 1 Mgal.

In 1992, the U.S. Geological Survey (USGS), in cooperation with the Safety and Environmental Office, Naval Surface Warfare Center, began a study of the hydrogeology and water quality of the shallow aquifer system at the Mainside of the NSWCDL. The study was designed to provide the Navy with hydrogeologic data to meet the requirements for an Oil Discharge Contingency Plan.

Purpose and Scope

The hydrogeology and water quality of the shallow aquifer system at the Mainside of the NSWCDL is described in this report. Aquifers and confining units are delineated and the lithology of sedimentary deposits that comprise the units is described. The ground-water-flow system is discussed, including the head distribution, flow direction, and hydraulic properties of the aquifers and confining units. The distribution of inorganic constituents, organic carbon, and deuterium and oxygen-18 isotopes in ground water and surface water are described.

The shallow ground-water system is evaluated, particularly the first 220 ft of sediment below land surface. Historical water-level and water-quality data were lacking for the study area; therefore, a network of observation wells was constructed. Thirty-five wells were installed at 29 drill sites (fig. 2). Geophysical logs were recorded at 28 drill sites, and geologic logs were recorded at all sites. The geophysical logs were used to determine the extent and thickness of aquifers and confining units. Two hydrogeologic sections were drawn from the lithologic and geophysical data obtained during construction of the 35 wells and from the driller's record for 1 existing

well. Twenty-nine wells were completed in the Columbia aquifer, three wells were completed in an unnamed upper confined aquifer discovered during this study, and three wells were completed in the Aquia aquifer. Columbia aquifer wells were assigned numbers 1 through 30 (a well was not completed at proposed site 26); the three wells in the upper confined aquifer were assigned numbers M1, M2, and M3; and the three wells in the Aquia aquifer were assigned numbers D1, D2, and D3.

Analog-to-digital water-level recorders were installed on wells D1, D2, D3, M1, M2, M3, 4, 10, 11, 19, and 24, and a tide gage was installed on Upper Machodoc Creek. Continuous ground-water levels were recorded and plotted as hydrographs. Twelve synoptic water-level measurements were collected at each of the 35 observation wells. Two water-table contour maps were constructed representing the seasonal high-water and low-water periods in the Columbia aquifer. Slug tests were performed in all 35 wells.

Water-quality samples were collected once from the 35 wells and the 3 surface-water sites along Gambo Creek (fig. 2), and analyzed for major-inorganic and minor-inorganic constituents, organic carbon, and deuterium and oxygen-18 isotopes. Hydrogeologic data used in this report was collected from August 1992 through October 1993. Hydrogeologic data collected from August 1992 through September 1993 are documented in "Hydrogeologic and Water-Quality Data for the Main Site, Naval Surface Warfare Center, Dahlgren Laboratory, Dahlgren, Virginia," by Bell and others (1994).

Previous Investigations

Previous investigations of ground water at the NSWCDL were conducted primarily during confirmation studies, which focused on contaminated sites identified during an Initial Assessment Study (IAS) in May 1983. O'Brien & Gere Engineers, Inc. (1986), conducted a surface-water and ground-water investigation of several sites identified in the IAS. Twenty shallow wells were installed and sampled for inorganics, heavy metals, base-neutral organic compounds, and pesticide and polychlorinated biphenyl extractable compounds. Soil, leachate, and surface water also were sampled for the same constituents. Monitoring of ground-water quality indicated that elevated concentrations of phenols, sodium, sulfate,

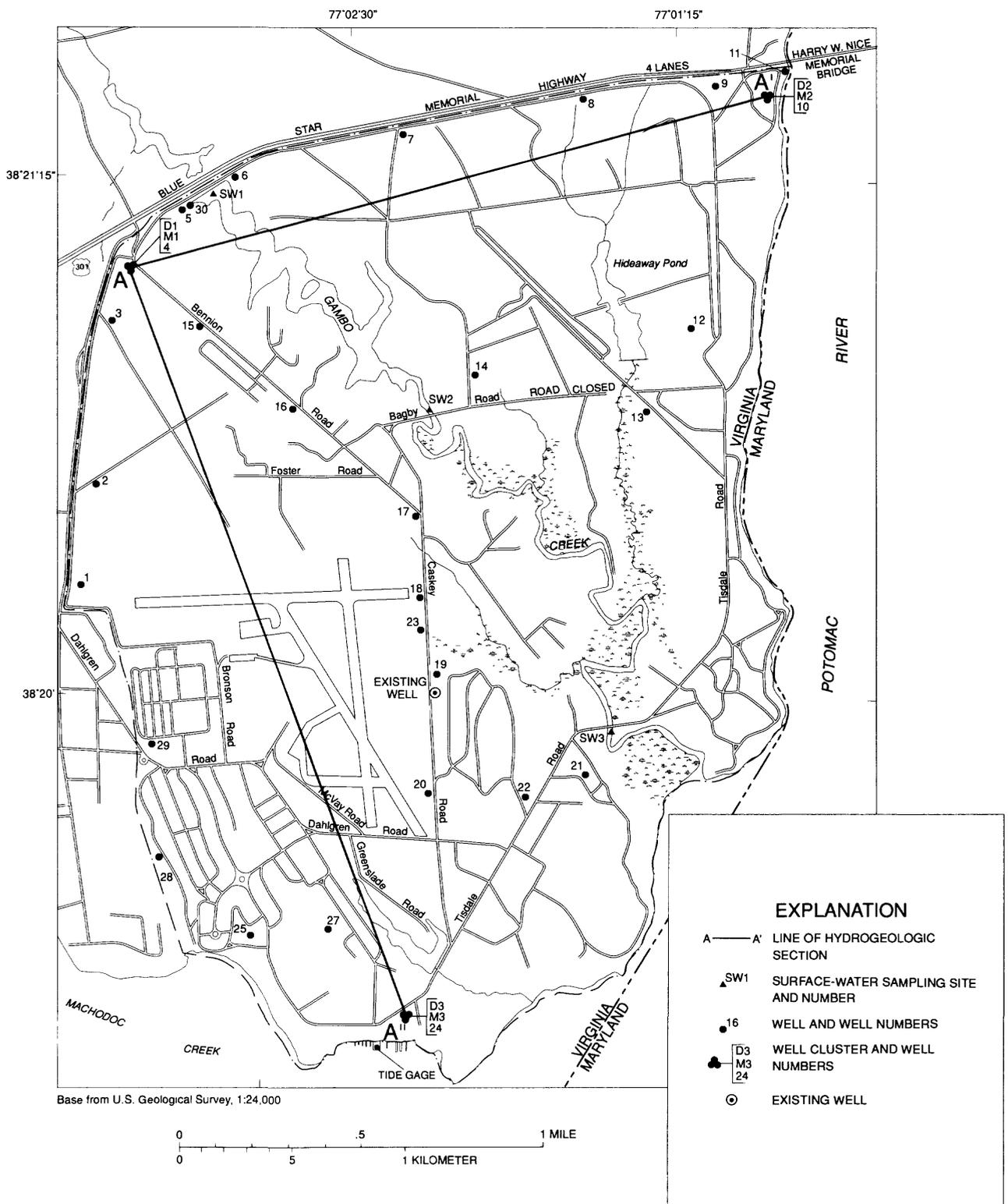


Figure 2. Locations of observation wells, tide gage, surface-water sampling sites, and hydrogeologic sections at the Mainside, Dahlgren, Virginia.

chloride, mercury, total organic carbon, and total organic halide were present at one or more of the sites.

Methods of Study

The hydrogeology and water quality of the shallow aquifer system at the Mainside were investigated by use of field and laboratory procedures that are described in the following sections. Procedures used include the following: (1) well installation and collection of lithologic data, (2) borehole geophysics, (3) water-level measurements, (4) single-well aquifer tests, and (5) water-quality sampling and analysis.

Well Installation and Collection of Lithologic Data

Between August and September 1992, 35 observation wells were drilled at 29 sites on the Mainside area of the NSWCDL. Well sites were chosen to provide for a wide areal distribution of data points that are representative of the lithology and hydrology of the NSWCDL. The wells range in depth from 12.4 to 219.2 ft below land surface and are screened in three aquifers.

Hydraulic-rotary drilling was used to construct all wells in the confined aquifers, and hollow-stem augering was used to construct the wells in the Columbia aquifer. Split-spoon and Shelby-tube samples were collected from each drill hole. Detailed lithologic descriptions of the split-spoon samples were made at the site by USGS personnel using a hand lens, Munsell color chart, and a grain-size comparison chart. The Shelby-tube samples were collected to analyze the vertical and areal variations in lithology and the vertical hydraulic properties. The Shelby-tube samples were labeled, capped on both ends, sealed with wax, and sent to the U.S. Army Corps of Engineers, Ohio River Division Laboratory, Cincinnati, Ohio, for mineralogic and hydraulic analyses.

Thirty-five Shelby-tube samples from 23 drill holes were analyzed. Mineralogy was determined by visual inspection, petrographic analysis, and x-ray diffraction analysis. Distribution of grain size was determined by sieve and hydrometer analysis. Vertical hydraulic conductivity values were determined by falling-head permeameter tests.

Borehole Geophysics

Borehole geophysical techniques were used to aid in the placement of observation-well screens in the

confined aquifers. Lithologic data collected during drilling supplemented the borehole geophysical data. Electric and natural-gamma logs were recorded from the hydraulic-rotary boreholes prior to well installation, and natural-gamma logs were recorded from the hollow-stem-auger holes subsequent to well installation.

Water-Level Measurements

Water levels were measured by use of chalked steel tape in each of the 35 observation wells, during a 1- or 2-day period, each month. Water-level measurements collected in March and October 1993 represent the seasonal high and low, respectively, water levels for the year. The water-level data were used to construct seasonal water-table contour maps and to establish vertical hydraulic gradients at the three well clusters.

Analog-to-Digital water-level recorders were installed on wells D1, D2, D3, M1, M2, M3, 4, 10, 11, 19, and 24 to record water levels at 1-hour intervals. A gage was installed on Upper Machodoc Creek to record tidal data at 5-minute intervals. The water-level recorders were used to monitor the tidal and seasonal head fluctuations in each aquifer.

Single-Well Aquifer Tests

Horizontal hydraulic conductivity was calculated for all 35 wells by analyzing slug tests using the Bouwer and Rice method (1976). The slug tests were conducted in March 1993 during seasonal high-water levels. Static water levels in all 35 wells were above the screen and in the casing, with the exception of well 10. The slug was induced by lowering a sand-filled polyvinyl chloride casing, with a displacement volume of about 1.2 gal, down the well. A 10-lb/in² pressure transducer and an In-Situ Hermit 1000B data logger were used to measure and record the water-level response. The pressure transducer was lowered into the well approximately 7-ft below the static water level. Water levels were monitored for 10 minutes prior to the slug. The slug was smoothly and rapidly introduced into the well and the falling-head response was recorded. Water levels were recorded at intervals ranging from 0.2 seconds at the beginning of the test to 120 seconds at the end. If the water level equilibrated within 15 minutes, then the slug was rapidly removed and the rising-head response also was recorded. Data from the falling-

head tests are used in this report, except for well 10 where the rising-head test was used because the static water level was in the screen at the start of the test.

Horizontal hydraulic conductivity (K) was determined from the slug-test data by the Bouwer and Rice method (1976). The method, applicable in unconfined, confined, and semiconfined aquifers (Bouwer, 1989, p. 308), is based on the Thiem equation of steady-state flow to a well. Horizontal hydraulic conductivity is determined from the following equation (Bouwer, 1989, p. 305, eq. 3):

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2L_e} \frac{1}{t} \ln \frac{y_0}{y_t}, \quad (1)$$

where

- K = the horizontal hydraulic conductivity (L/T),
- r_c = the inside radius of the casing (L),
- R_e = the effective radius over which head is dissipated in the flow system (L),
- r_w = the radial distance between the undisturbed aquifer and the well center (L),
- L_e = the length of screened or open section of well (L),
- t = time (T),
- y_0 = the initial instantaneous head (L),
- y_t = the head in the well at any time during recovery (L), and
- \ln = the natural logarithm, base e .

In this report, r_w is assumed to be the radius of the borehole in the screened interval of the well, and L_e is assumed to be the screen length, except for well 10 where L_e is the height of water in the screen.

The term " $(1/t)[\ln(y_0/y_t)]$ " is obtained from the best-fit straight line in a plot of $\ln(y)$ against t , and the term " $\ln(R_e/r_w)$ " is dependent on L_w , H , L_e , and r_w ; where L_w is the distance from the bottom of the screened or open section of the well and the top of the aquifer, and H is the saturated thickness of the aquifer (L).

If $H > L_w$, then

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln\left(\frac{L_w}{r_w}\right)} + \frac{A + B \ln\left[\frac{(H-L_w)}{r_w}\right]}{\frac{L_e}{r_w}} \right]^{-1}, \quad (2)$$

where A and B are dimensionless coefficients that are functions of L_e/r_w and are obtained from curves in Bouwer (1989, p. 305, fig. 2). When $H \gg L_w$, the effective upper limit of $\ln[(H-L_w)/r_w]$ is 6.

If $H = L_w$, which is the case of a fully penetrating well, then equation 2 should be modified to

$$\ln\left(\frac{R_e}{r_w}\right) = \left(\frac{1.1}{\ln\left(\frac{L_w}{r_w}\right)} + \frac{C}{\frac{L_e}{r_w}} \right)^{-1}, \quad (3)$$

where C is a dimensionless parameter that is a function of L_e/r_w and also is obtained from curves in Bouwer (1989, p. 305, fig. 2).

In this report horizontal and vertical hydraulic conductivity is reported in feet per day, a mathematical reduction of the unit cubic foot per day per square foot, which represents the volume rate of flow through a unit cross-sectional area.

Water-Quality Sampling and Analysis

Water-quality samples were collected once from the 35 wells and the 3 surface-water sites along Gambo Creek (fig. 2) from May 17–27, 1993. The surface-water sites were sampled first. The sampling was conducted during low tide beginning at the site nearest the mouth of Gambo Creek and ending at the most upstream site. Wells screened in the Columbia aquifer were sampled next, followed by wells in the upper confined aquifer, and the wells in the Aquia aquifer were sampled last.

Sampling methodology consisted of purging the wells, collecting, filtering, preserving (when necessary), and bottling samples to be sent to the USGS National Water Quality Laboratory in Arvada, Colo. Samples were analyzed for inorganic constituents, organic carbon, and deuterium and oxygen-18 isotopes; and field properties were collected for specific conductance, pH, temperature, dissolved oxygen, and alkalinity.

A minimum of three well volumes was purged from each well, except for a few wells that went dry during purging in which case the well was allowed to recover before samples were collected. A stainless-steel submersible pump with a Teflon discharge line was used to purge and collect samples from the wells.

Surface-water samples were obtained with a weighted-bottle sampler.

All equipment was decontaminated before sampling began by washing with a nonphosphatic detergent and rinsing with deionized carbon-free water. Equipment was rinsed with carbon-free water after samples had been collected at a site. The outside of the pump and the Teflon discharge line were rinsed with deionized carbon-free water between wells, and the entire system was flushed with deionized carbon-free water after each day of sampling.

Water-quality data were validated by use of laboratory quality-assurance procedures, quality-control samples, and examination of cation/anion balances. Laboratory quality-assurance procedures are described in Friedman and Erdmann (1982) and Jones (1987). Quality-control samples collected in the field include duplicate samples, equipment blanks, and deionized water blanks. At least 1 sample was duplicated for every 10 samples collected. Quality-assurance goals ensured that the relative percent difference of constituent concentration in duplicate samples was not to exceed 20 percent. Chemical constituents were not to be present in the equipment and deionized water blanks at concentrations above the reporting limits. Cation/anion imbalances were not to exceed 10 percent.

All duplicate analyses fell within 20 percent of the regular sample concentrations except those with concentrations near the reporting limits. Small concentrations of dissolved organic carbon (0.2 mg/L) and sulfate (0.2 mg/L) were measured in the deionized water blank. Similarly, dissolved organic carbon (0.2 mg/L), sulfate (0.5 mg/L), and dissolved solids (3 mg/L) were detected in the equipment blank. These concentrations are above the reporting limits but are small compared to concentrations observed in ground-water and surface-water samples.

The cation/anion imbalances of most water-quality samples (33 of 38) did not exceed 10 percent. The five samples with large cation/anion imbalances were SW1, SW2, 6, 23, and 29. All five of these analyses displayed greater milliequivalent cations than anions. High cation/anion imbalances suggest either an error in the laboratory measurement of major-ions, or a high concentration of unmeasured major-ions. High nitrate concentrations, for example, would explain the observed cation/anion imbalances. Another possibility is that the high dissolved iron concentrations reported in four of the five samples

(all except 23) are actually the result of micro-crystalline iron that passed through the 0.45 μm filter; thus, causing an overreporting of cations. In any case, these five water-quality analyses should be interpreted with caution.

Acknowledgments

The authors wish to thank Ann Swope and Billie Weedon of the Safety and Environmental Office, NSWCDL, who coordinated many aspects of the project. The U.S. Army Corps of Engineers installed the observation wells. Thanks also to personnel of the Fire Protection, Explosive Ordnance, and Public Works Divisions of the NSWCDL for providing support during well-drilling operations. Thanks are also extended to Daniel R. Conrad, former U.S. Geological Survey Hydrologic Technician, for helping to conduct the field work for this project.

HYDROGEOLOGY OF THE SHALLOW AQUIFER SYSTEM

The Mainside of the NSWCDL lies within the Atlantic Coastal Plain Physiographic Province. In Virginia, the Coastal Plain Physiographic Province consists of an eastward-thickening sedimentary wedge of unconsolidated gravel, sand, silt, and clay that unconformably overlies crystalline bedrock. In the study area, approximately 1,500 ft of unconsolidated sediments are present above the bedrock (Meng and Harsh, 1988, p. C16, fig. 8). These sediments range in age from Early Cretaceous to Holocene. The following sections describe the geology and aquifers and confining units at the Mainside of the NSWCDL.

Geology

The shallow aquifer system described in this report includes sediments in the Aquia Formation and the Marlboro Clay of Paleocene age; the Nanjemoy Formation of the Pamunkey Group, Eocene age; Pleistocene undifferentiated deposits; and Holocene deposits (fig. 3). Meng and Harsh (1988, p. C41) generally noted that the Pamunkey Group consists of glauconitic sand, silt, and clay, containing varying amounts of shell, with the exception of the Marlboro Clay, which solely consists of nonglauconitic, dense,

plastic clay. The Pleistocene sediments consist of riverine, estuarine, and terrace deposits composed of sequences of gravel, sand, silt, and clay deposited during interglacial high stands of the sea (Berquist, 1993, p. 60). The Pleistocene deposits often occur as paleochannel deposits incised into older sediments. The Holocene (most recent) sediments consist of alluvial deposits, disturbed ground, and artificial fill areas for waste disposal and construction.

Aquifers and Confining Units

The upper 220 ft of Coastal Plain Physiographic Province sediments at the Mainside have been divided into five hydrogeologic units that are called, from the land surface downward, (1) Columbia (water-table) aquifer, (2) upper confining unit, (3) upper confined aquifer, (4) Nanjemoy-Marlboro confining unit, and (5) Aquia aquifer (fig. 3). The hydrogeologic framework was interpreted through the use of geophysical logs supplemented with lithologic data (figs. 4 and 5). The Aquia aquifer and Nanjemoy-Marlboro confining unit were easily delineated on geophysical logs because of their areal continuity and relative uniformity at the Mainside. The remaining units were the most difficult to correlate because of the following: (1) The upper confined aquifer includes sediments associated with a paleochannel within the Nanjemoy-Marlboro confining unit and also may include sandy sediments in the upper Nanjemoy Formation; and (2) paleochannels also are present in the Columbia aquifer.

Lithology and Extent

In this report, the Columbia aquifer at the Mainside of the NSWCDL is defined as the unconfined aquifer in the sandy sediments that were mapped by Mixon and others (1989) as the Sedgfield Member; and undifferentiated Poquoson and Lynnhaven Members of the upper Pleistocene Tabb Formation. Unnamed sandy alluvial and fill deposits also are included in the aquifer.

The lithology of the Columbia aquifer consists of differing amounts of clay, silt, sand, and gravel (Bell and others, 1994, tables 1 and 3). The top of the Columbia aquifer is the water table; however, the altitude of the water table fluctuates seasonally and, thus, the saturated thickness of the aquifer also fluctuates seasonally (table 1). The Columbia aquifer generally is 5 ft, or more, in thickness and most of the

Mainside is underlain by the aquifer; however, the unit is missing in the stream valley of Gambo Creek in the northwestern part of the Mainside (fig. 4). The Columbia aquifer is thickest in the northeastern (wells 8 and 14), central (wells 18 and 23), and southeastern (well 21) parts of the Mainside (fig. 2). The Columbia aquifer generally is coarse grained in the central and northeastern parts of the Mainside. At wells 18 and 23 the Columbia aquifer consists of yellowish-brown to orange silty sand; clayey sand; silty clay; and clay underlain by yellow to orange, fine-grained to coarse-grained, sand that lacks clay. At wells 8 and 14 the Columbia aquifer consists of orange to brown sandy silt; clayey sand; silt; and clay underlain by gray to orange, medium-grained, poorly sorted conglomerate. The coarsest-grained sequences mark paleochannels within the Columbia aquifer.

In the northwestern (wells 2, 3, 4 and 5) and southwestern (wells 25, 27 and 28) parts of the Mainside, the Columbia aquifer generally is fine grained. At wells 2 and 3 the Columbia aquifer consists of

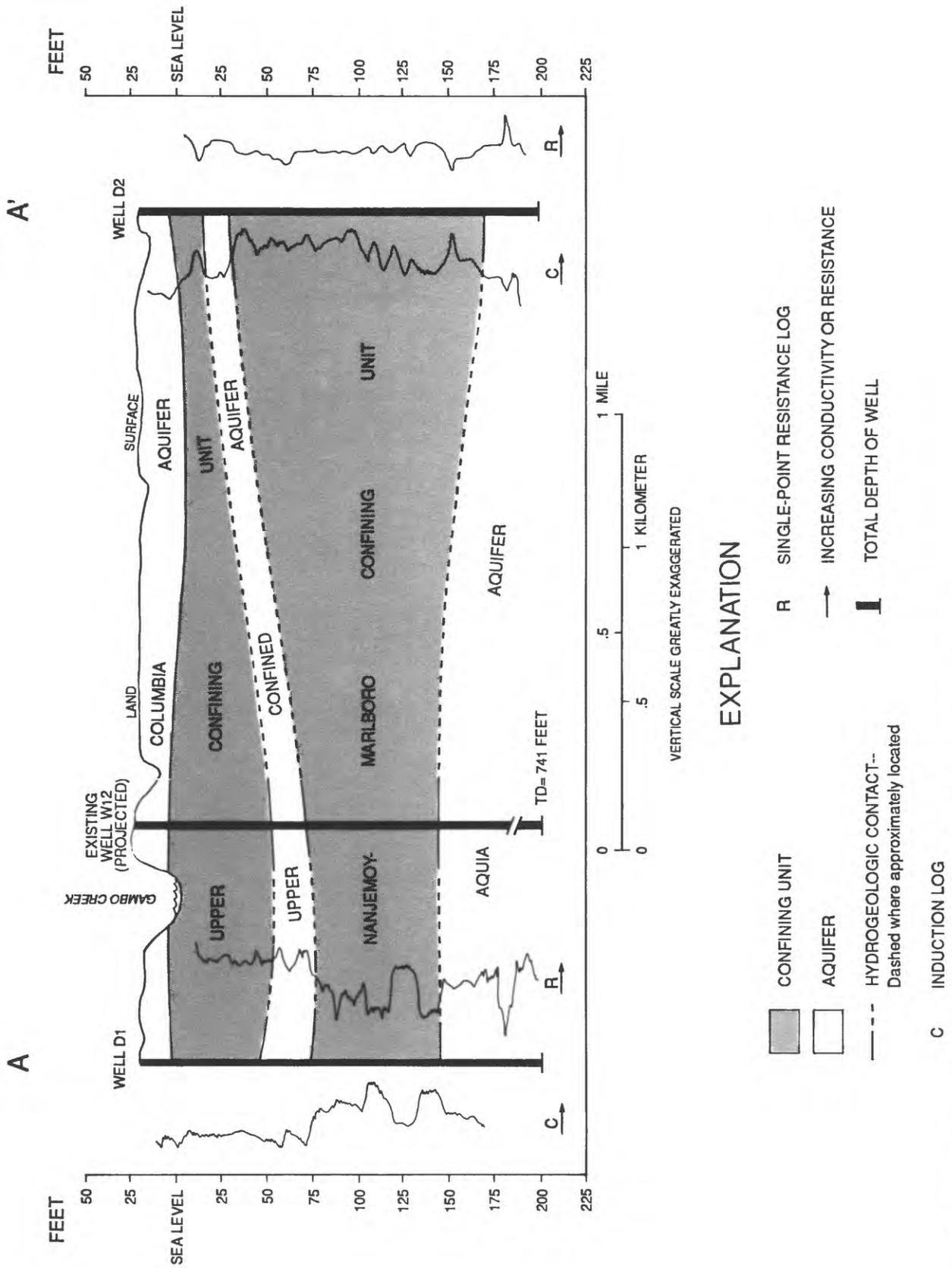
Table 1. Saturated thickness of the Columbia aquifer on March 30, 1993, and fluctuation of the water-table between March and October 1993 at the Mainside, Dahlgren, Virginia [--, no value; for location of observation wells, see figure 2]

Well number	Thickness (feet)	Fluctuation (feet)
1	13	9.9
2	20	9.3
3	21	7.6
4	18	9.0
5	18	7.7
6	10	10.0
7	16	5.8
8	27	4.5
9	23	8.8
10	18	4.0
11	--	3.0
12	18	8.4
13	21	7.8
14	28	4.9
15	18	7.5
16	14	7.6
17	14	8.8
18	23	1.7
19	14	9.3
20	23	5.4
21	24	2.7
22	14	7.0
23	22	2.1
24	14	7.7
25	21	4.3
¹ 27	18	8.0
28	15	6.5
29	12	5.6
30	18	1.8

¹A well was not completed at the site proposed for well 26.

SERIES	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT
HOLOCENE	ALLUVIAL AND FILL DEPOSITS	COLUMBIA AQUIFER
PLEISTOCENE	Poquoson and Lynnhaven Members	Upper confining unit
	Sedgefield Member and Pleistocene deposits Undivided	
PLIOCENE		Upper confined aquifer
MIOCENE		
OLIGOCENE		
EOCENE		
PALEOCENE		
PALEOCENE	PAMUNKEY GROUP	Upper confined aquifer--continued--
	Nanjemoy Formation	NANJEMOY-MARLBORO CONFINING UNIT
	Marlboro Clay	
	Aquia Formation	AQUIA AQUIFER

Figure 3. Relation between geology and hydrogeology at the Mainside, Dahlgren, Virginia.



EXPLANATION

- CONFINING UNIT
- AQUIFER
- HYDROGEOLOGIC CONTACT--
Dashed where approximately located
- C INDUCTION LOG
- R SINGLE-POINT RESISTANCE LOG
- INCREASING CONDUCTIVITY OR RESISTANCE
- ▬ TOTAL DEPTH OF WELL

Figure 4. Hydrogeologic section A-A' from figure 2 at the Mainside, Dahlgren, Virginia.

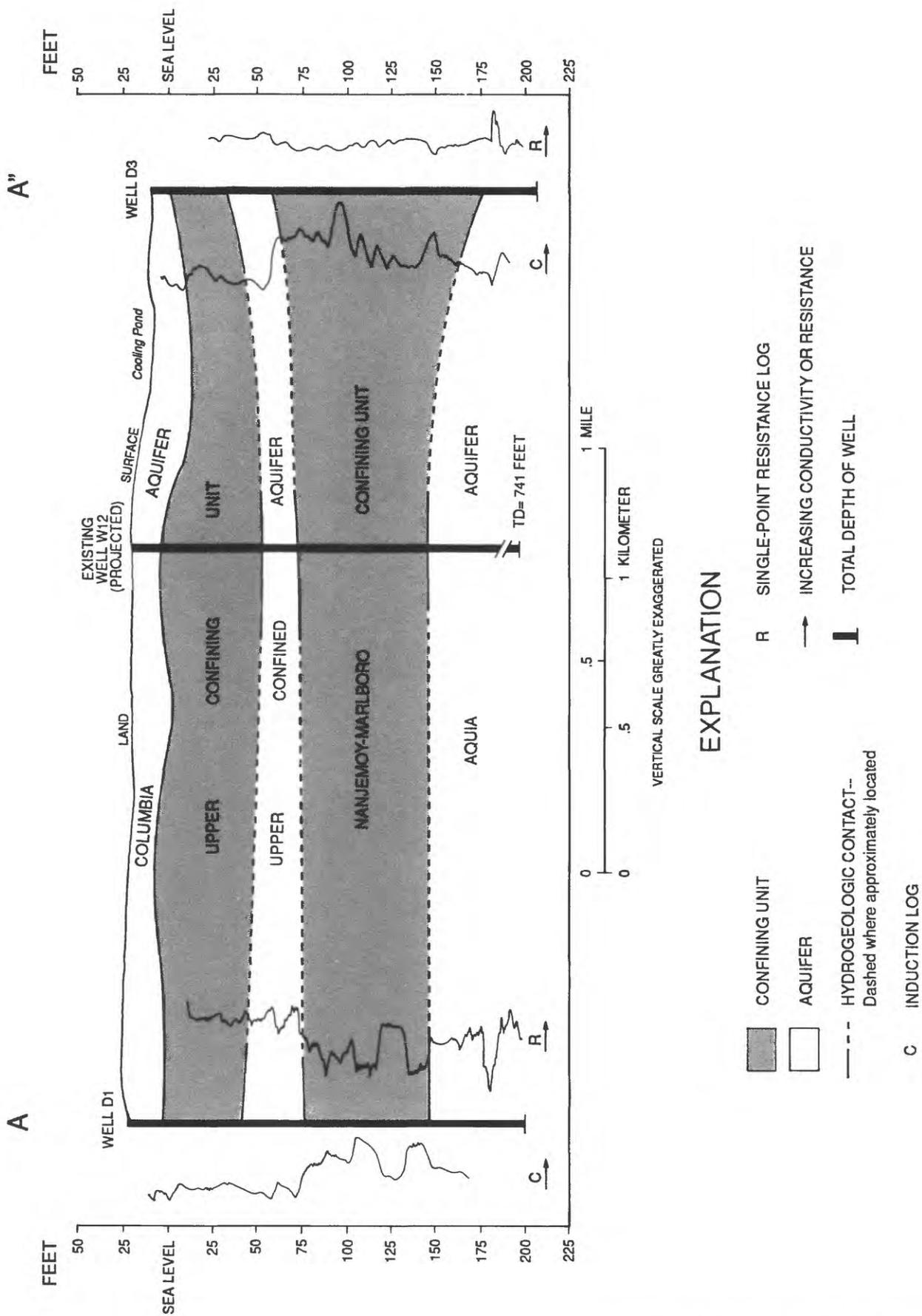


Figure 5. Hydrogeologic section A-A' from figure 2 at the Mainside, Dahlgren, Virginia.

yellowish-brown to light-brown sandy clay and clayey sand underlain by pale-blue to light-bluish-gray, very-fine to fine-grained, silty sand and clayey sand. At wells 27 and 28 the Columbia aquifer consists of pale-yellowish-brown to dark-yellowish-orange clayey sand; silty clay; and silty sand underlain by dark-yellowish-orange, very-fine to fine-grained, sand; sandy clay; and silty sand.

The upper confining unit underlies the Columbia aquifer and appears to be present throughout the Mainside. The unit crops out at the surface, along Gambo Creek, where the Columbia aquifer is absent. The upper confining unit impedes vertical ground-water flow between the Columbia aquifer and underlying aquifers in the study area. The unit was encountered at the base of all wells completed in the Columbia aquifer, but was only fully penetrated at the three sites where wells were completed in the upper confined and Aquia aquifers.

The top of the upper confining unit is highest in altitude at wells 1, 6, and 16—at 8 ft above sea level; and lowest at well 23—at 18 ft below sea level (fig. 6). Wells 11 and 30 were not used to contour the altitude of the top of the upper confining unit. A confining unit was not encountered during construction of well 11, and the depositional sequence has been affected probably by the present day Potomac estuary. A confining unit was encountered during the construction of well 30 but the deposits appear to have been disrupted, probably during construction of State route 301 and the inland perimeter roads at the Mainside. On the basis of the three sites where the confining unit was fully penetrated (M1, M2, and M3), the confining unit ranges from 20 to 44 ft thick and is thickest in the northwestern part of the study area (fig. 6). The unit is composed of olive-gray clay and silt and contains some fine-grained sand.

During deposition of the Columbia aquifer sediments, streams substantially eroded the confining unit and laid down the sand and gravel paleochannel deposits observed during the construction of wells 8, 14, 18, 21, and 23. Two channels (containing coarser-grained deposits) are present in the upper confining unit: A somewhat narrow channel, oriented approximately west-east, from well 1 toward well 23; and a broad channel, oriented northeast-southwest-southeast, from well 8 toward well 14 and then toward the present mouth of Gambo Creek.

The upper confined aquifer, which differs in lithology and thickness, underlies the upper confining

unit. The lithology and thickness of the upper confined aquifer is varied. The top of the upper confined aquifer is highest in altitude at the northeastern corner of the study area—at 18 ft below sea level; and lowest in the central part of the study area—at 52 ft below sea level (fig. 7). The upper confined aquifer ranges from 16 to 31 ft thick and is thickest in the northwestern part of the study area. The upper confined aquifer is composed of glauconitic, olive-gray to dark-greenish-gray sand; silt; and clay containing some gravel near its base. Gravel was present at the base of the upper confined aquifer at two of the three sites where data were collected (wells M1 and M3), and the upwards-fining sediment sequence could mark a paleochannel-fill sequence. At the third site (well M2) the aquifer lacked a basal gravel and was characterized by a fine-grained sequence of sediments. Presumably, either the paleochannel is not present at this site or the sediments were deposited at the distal edges of a paleochannel.

The Nanjemoy-Marlboro confining unit underlies the upper confined aquifer and is present throughout the study area. The Nanjemoy-Marlboro confining unit impedes vertical ground-water flow between the upper confined aquifer and underlying aquifers in the study area. The top of the Nanjemoy-Marlboro confining unit is highest in altitude at the northeastern corner of the study area—at 34 ft below sea level; and lowest in the northwestern corner of the study area—at 72 ft below sea level (fig. 8). The confining unit ranges from 73 to 143 ft thick and is thickest in the northwestern part of the study area (fig. 8). The confining unit is composed of glauconitic, dark-greenish-gray clay; silt; some fine sand of the Nanjemoy Formation; and light-brown Marlboro Clay near its base.

The Aquia aquifer is the deepest aquifer encountered in the shallow aquifer system of the study area and only the upper 22 to 51 ft were investigated. The top of the aquifer is highest in altitude in the central part of the study area—at 143 ft below sea level; and lowest in the southern limits of the study area—at 178 ft below sea level (fig. 9). The aquifer exceeds 22 ft in thickness and is composed of glauconitic, olive-black to olive-gray, very-fine-grained to medium-grained, sand; and silt containing some beds of calcium-carbonate-cemented shell.

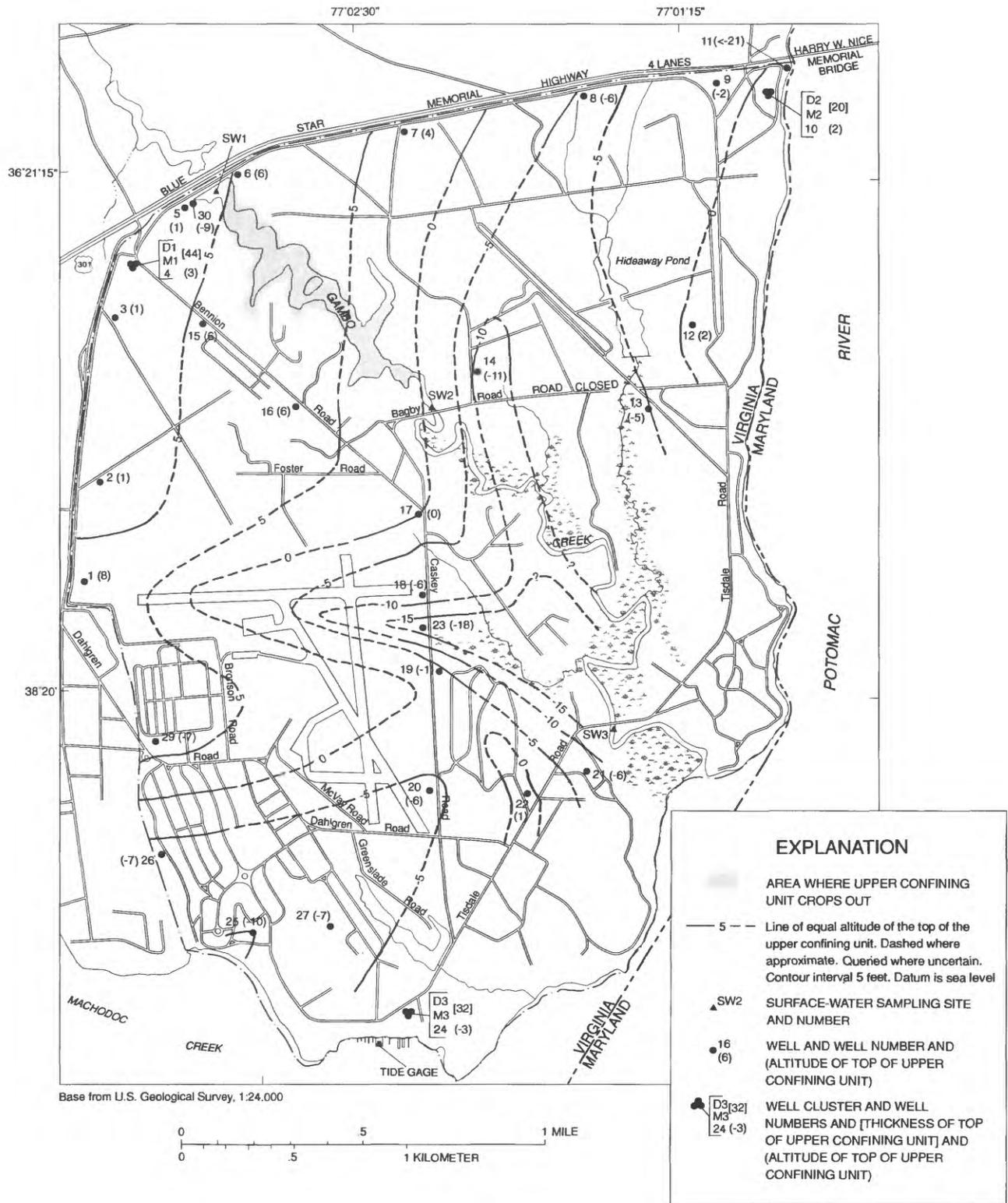


Figure 6. Altitude of the top and thickness of the upper confining unit at the Mainside, Dahlgren, Virginia.

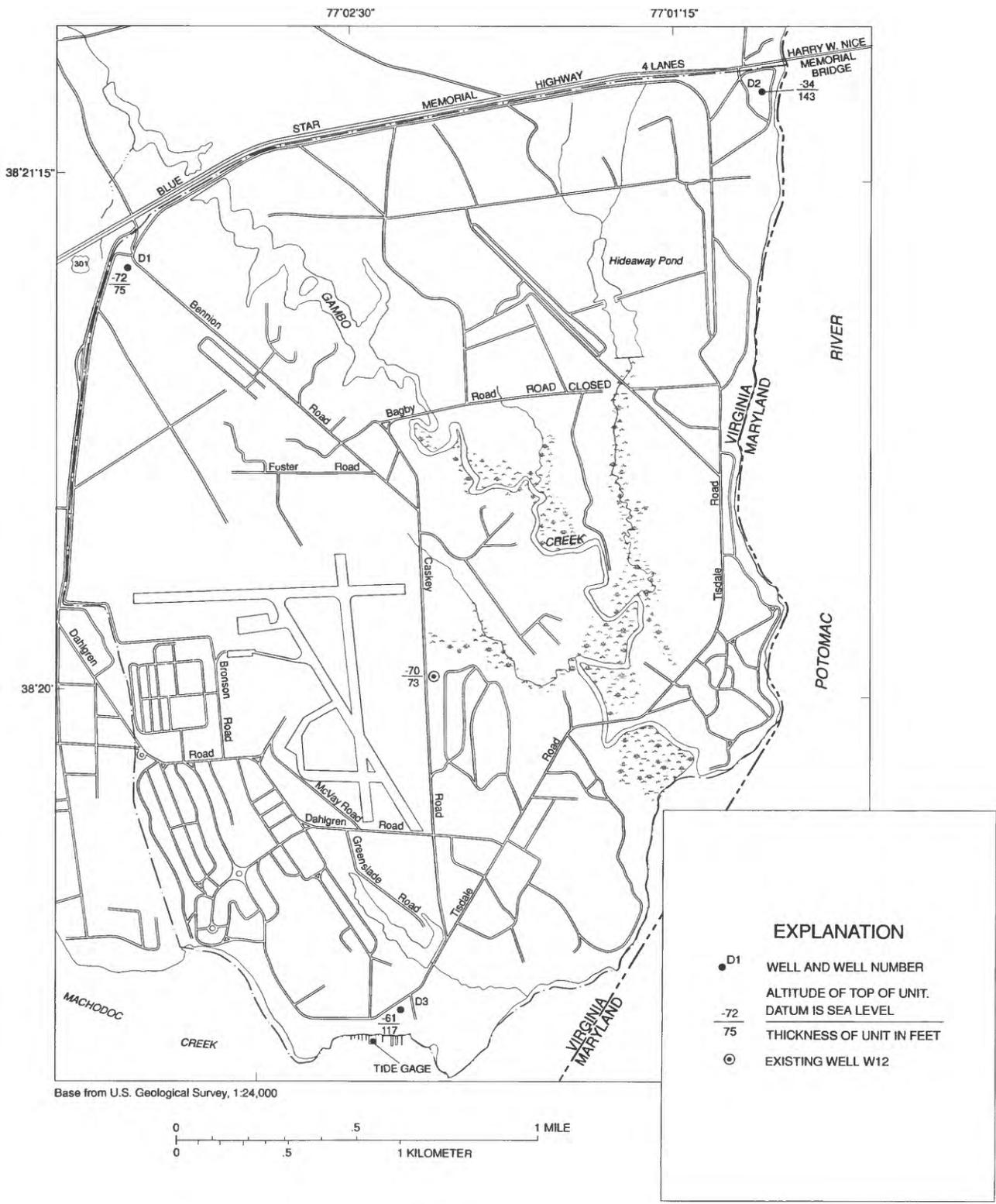


Figure 8. Altitude of the top and thickness of the Nanjemoy-Marlboro confining unit at the Mainside, Dahlgren, Virginia.



Figure 9. Altitude of the top of, and generalized ground-water-flow direction in, the Aquia aquifer at the Mainside, Dahlgren, Virginia.

Head Distribution and Direction of Ground-Water Flow

The head distribution in the Columbia aquifer is typical of an unconfined, unstressed flow system in an area of subdued topographic relief. Ground water generally flows from areas of high topographic relief and discharges to areas of low topographic relief (figs. 10 and 11). The Columbia aquifer at the study area is a local system that is not affected by any known pumping stress.

Gambo Creek, which flows from the northwest to the southeast across the study area, essentially dissects the Columbia aquifer into two local systems. Additionally, the aquifer is absent (figs. 10 and 11), and the upper confining unit crops out (fig. 6) at the base of the banks along Gambo Creek. Ground water flows from higher heads in the northeast and northwest toward the lower heads of the wetlands along Gambo Creek, Upper Machodoc Creek, or the Potomac River.

In the northwestern part of the Mainside, steep hydraulic gradients are present in the Columbia aquifer adjacent to Gambo Creek (fig. 10). These steep hydraulic gradients were documented by water-level measurements in wells 5, 30, 6, and the staff gage on Gambo Creek at SW1. High water levels in this area, during the spring of 1993, were a subdued reflection of topography and water-level contours were extrapolated along the bluffs, adjacent to the Creek, down to Bagby Road. The steepness of the hydraulic gradient in this area probably is the result of the topographic relief in the vicinity of the Creek and the fine-grained nature of the Columbia aquifer sediments in this area. Ground water flows to the Creek through the fine-grained sediments resulting in a steep change in head. Downstream of this area, Gambo Creek broadens and flows through wetlands.

In the central part of the Mainside, adjacent to Caskey Road at wells 18 and 23, a discharge area is evident in the Columbia aquifer. Ground-water levels in this area are not a direct reflection of topography. The elevation of land surface at wells 18 and 23 differs by approximately 10.5 ft but the heads differ by only 0.1 ft. The convergence of ground-water flow in this area probably is the result of the coarse-grained sediments that have filled a previously cut valley; consequently, these coarse-grained sediments allow water to be transmitted with minimal head loss. In addition, ground-water flow in this area could have been affected by airfield construction, and horizontal layering of the Columbia aquifer sediments could have

been disrupted by landfill excavation activities in some areas. The engineered drainage has resulted in interception and channelization of ground-water flow within the Columbia aquifer.

In the extreme northeastern corner of the Mainside, the area is a local topographic high (elevation of land surface is approximately 20.5 ft) and is underlain by fine-grained sediments. The hydrograph for well 10 shows relatively large seasonal fluctuations, but a relatively thick unsaturated zone year-round (fig. 12). This area appears to be hydrologically isolated from the Columbia aquifer to the west under natural-flow conditions (figs. 10 and 11).

Water-level measurements indicate a downward hydraulic gradient between the Columbia aquifer and the upper confined aquifer; however, the upper confining unit was encountered at the base of all wells completed in the Columbia aquifer.

Water levels in the upper confined aquifer indicate that ground-water flow within the aquifer is approximately northeast to southwest (fig. 7). The difference in head between the wells shows a gradient of 2.0 ft across the Mainside in October 1993 and 3.6 ft in March 1993; however, the general ground-water-flow direction does not change. Water-level measurements indicate a downward hydraulic gradient between the upper confined aquifer and the Aquia aquifer below; however, any movement of water between the aquifers would be impeded by the Nanjemoy-Marlboro confining unit, which was encountered at the base of all wells completed in the upper confined aquifer.

Ground-water flow within the Aquia aquifer is approximately northwest to southeast (fig. 9), and stresses on the Aquia aquifer are indicated by heads that range between 2 and 12 ft below sea level (Bell and others, 1994, figs. 7–9). Presently (1995) there are no known withdrawals from the Aquia aquifer within, or near, the study area. The heads are consistent with published maps of the potentiometric surface of the Aquia aquifer in southern Maryland, which indicate a regional decline in water levels caused by withdrawals in Maryland (Curtin and others, 1994).

Seasonal Head Fluctuations

Without pumping stress, precipitation and evapotranspiration are the primary contributing factors to seasonal head fluctuations, as indicated at well 24, where the heads rise with precipitation and drop slowly without precipitation, particularly during the

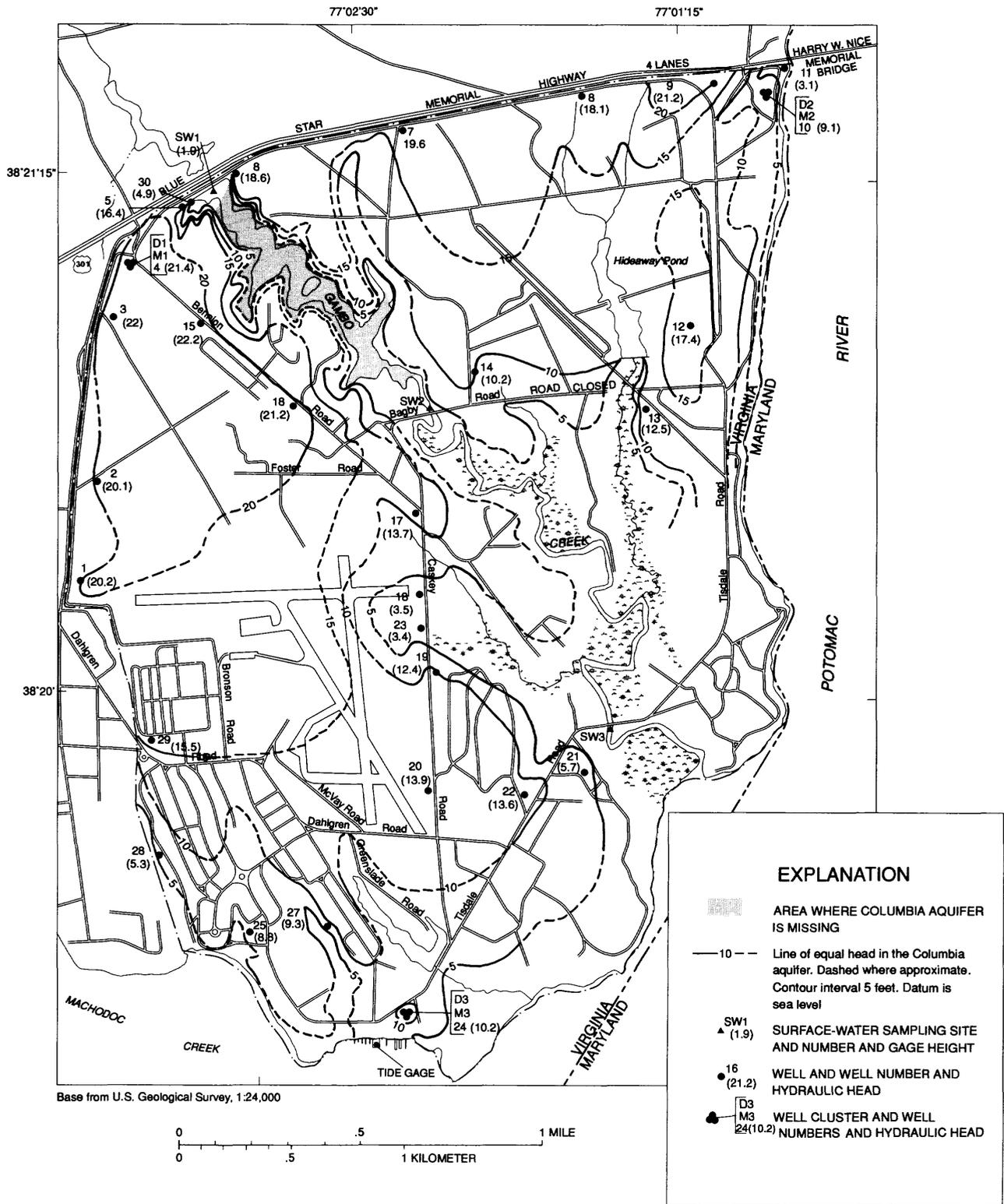


Figure 10. Hydraulic heads in the Columbia aquifer, March 1993, at the Mainside, Dahlgren, Virginia.

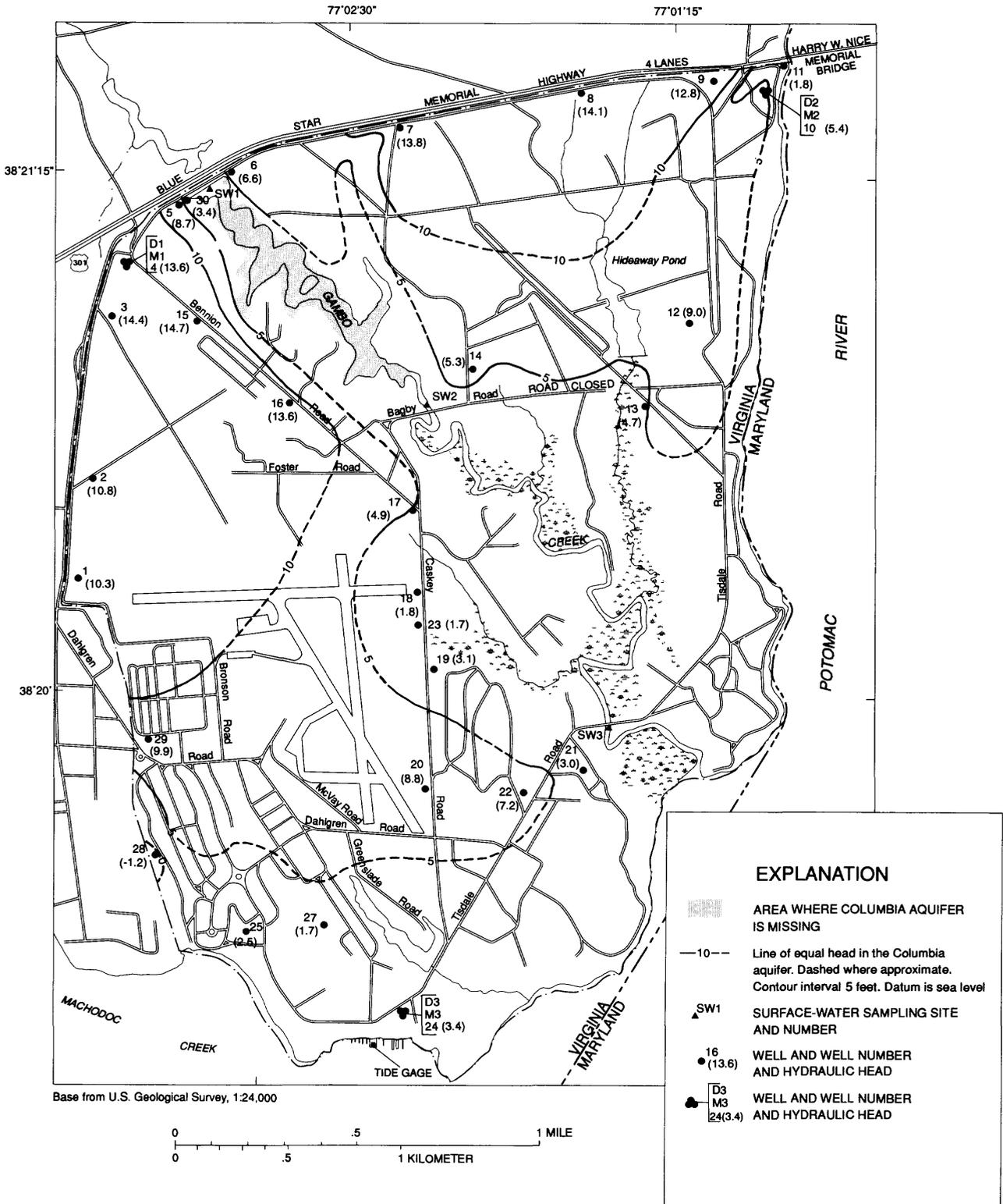


Figure 11. Hydraulic heads in the Columbia aquifer, October 1993, at the Mainside, Dahlgren, Virginia.

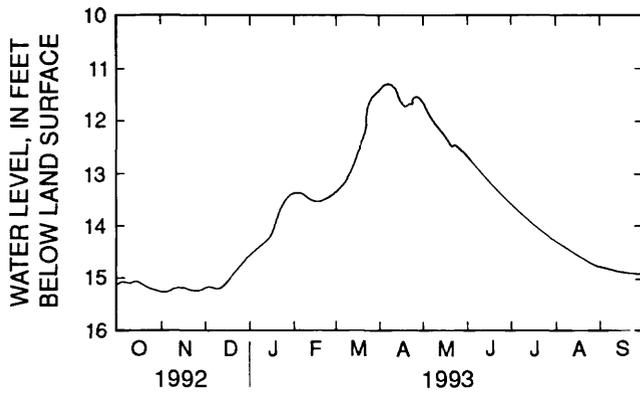


Figure 12. Maximum daily water level in the Columbia aquifer in well 10, October 1992 through September 1993, at the Mainside, Dahlgren, Virginia.

growing season (fig. 13). The amount of seasonal head fluctuation in the Columbia aquifer varies across the study area and is controlled by: (1) contributing area of recharge, (2) topographic relief, (3) position in the flow system, (4) permeability of the aquifer, and (5) amount of evapotranspiration. The saturated thickness of the Columbia aquifer on March 30, 1993, and maximum seasonal head fluctuation between March 30 and October 28, 1993, at the 29 well sites are listed on table 1. Fluctuations range from a high of 10.0 ft to a low of 1.7 ft.

Large fluctuations are observed in areas of high topographic relief underlain by fine-grained sediments (wells 1, 2, 3, 4, 9, and 19). Many of these wells also are located in heavily forested areas and high rates of evapotranspiration in season probably contribute to the large fluctuations that are observed. In contrast, small fluctuations are observed in discharge areas and areas underlain by coarse-grained sediments (wells 11, 18, 23, and 30).

The water level in well 28 (fig. 11) drops below sea level during the fall (Bell and others, 1994, table 5, p. 40); however, fluctuations are similar to the other observation wells. A possible explanation for the low water levels at well 28 may be the effect of transpiration by several large oak trees that are located near the well. These oak trees are among the largest trees at the Mainside, and well 28 is the only well that was constructed near trees of this size.

Fluctuations in head in the upper confined aquifer are probably pressure responses to seasonal changes in recharge and evapotranspiration in the

Columbia aquifer. The highest heads in the upper confined aquifer were generally observed during the early spring, and the lowest heads in the late summer (Bell and others, 1994, figs. 10–12); however, the general direction of ground-water flow did not change. Water levels in wells M2 and M3 (fig. 14) fluctuate slightly with the tide.

Fluctuations in head of approximately 2 ft were observed in the Aquia aquifer, seasonally. Generally, the highest heads were observed in the winter or early spring, and the lowest heads were observed in the late summer (Bell and others, 1994, figs. 7–9); however, the general direction of ground-water flow did not change. Water levels in wells D2 (fig. 14) and D3 fluctuate slightly with the tide.

Hydraulic Properties

Slug tests were done in 29 wells in the Columbia aquifer (table 2). The calculated horizontal hydraulic conductivity values range from a low of 1×10^{-2} ft/d (well 6) to a high of 2×10^1 ft/d (well 14). The median value for the 29 wells is 5×10^{-1} ft/d. These horizontal hydraulic conductivities correlate well to the lithology of sediments observed during well construction. Wells 8, 14, 18, 21, and 23, which penetrated coarse-grained sediments associated with paleochannels, had calculated horizontal hydraulic conductivities of 2, 20, 9, 1, and 9 ft/d, respectively. Wells 2, 3, 4, 5, and 25, which penetrated fine-grained sediments, had calculated horizontal hydraulic conductivities of 0.5, 0.2, 0.3, 0.3, and 0.09 ft/d, respectively.

The process by which dissolved substances are transported by the bulk movement of ground-water flow is referred to as advection. Nonreactive dissolved substances are transported at the rate of the average linear velocity of the water because of advection (Freeze and Cherry, 1979). The rate at which dissolved substances move through an aquifer, however, also is controlled by hydrodynamic dispersion, diffusion, and other factors that can inhibit or accelerate movement of dissolved substances with respect to average linear velocity of the water.

Knowledge of the effective porosity of an aquifer is needed to calculate average linear velocity \bar{v} , Lohman (1972) noted that

Table 2. Horizontal hydraulic conductivity values for the Columbia aquifer, determined from slug tests at the Main-side, Dahlgren, Virginia
[for location of observation wells, see figure 2]

Well number	Horizontal hydraulic conductivity (feet per day)
1	0.08
2	.5
3	.2
4	.3
5	.3
6	.01
7	2
8	2
9	1
10	3
11	2
12	10
13	.4
14	20
15	2
16	.5
17	.2
18	9
19	.1
20	.8
21	1
22	.6
23	9
24	.08
25	.09
¹ 27	.4
28	.3
29	3
30	.02

¹A well was not completed at the site proposed for well 26.

$$\bar{v} = \frac{-K \frac{dh}{dl}}{\theta}, \quad (4)$$

where

\bar{v} = average linear velocity (L/T),

K = horizontal (or vertical) hydraulic conductivity (L/T),

$\frac{dh}{dl}$ = hydraulic gradient, or unit change in head per unit length of flow, and

θ = effective porosity, as a decimal fraction.

Average linear velocity can range from less than to more than the actual velocity between two points in the aquifer (Lohman, 1972). In this report, average linear velocities are calculated for ground-water flow in the Columbia aquifer, and ground-water flow across the upper confining unit from the Columbia aquifer to the upper confined aquifer. For velocity calculations in the Columbia aquifer, the hydraulic gradient is

assumed to be 0.01 ft/ft (an observed gradient based on water-level measurements) and the effective porosity is assumed to be 0.30; and for velocity calculations across the upper confining unit, the hydraulic gradient is assumed to be 0.13 ft/ft (the average gradient at the three well clusters) and the effective porosity is assumed to be 0.30. Ground-water-flow rates in the Columbia aquifer, based on a gradient of 0.01, assumed porosity of 30 percent, and horizontal hydraulic conductivity values from slug tests, range from a low of 0.1 ft/yr to a high of 243 ft/yr, and a median value of 6 ft/yr. Spatial and seasonal differences in water levels will cause changes in velocity and direction of flow. Seasonal changes generally will be small because velocities are generally low. Spatial differences could, however, be significant. The reader is reminded that the rate of ground-water flow is controlled by hydraulic conductivity, hydraulic gradient, and effective porosity, and differences in these inputs will result in changes in the average linear velocity.

Falling-head permeameter tests were done on 13 samples of the Columbia aquifer to provide measurements of vertical hydraulic conductivity (Bell and others, 1994, p. 34). The calculated vertical hydraulic conductivity values range from a low of 3.63×10^{-5} ft/d (well 21) for a sample of clay to a high of 5.10×10^0 ft/d (well 18) for a sample of sand. The median value for the 13 samples is 5.95×10^{-3} ft/d.

Falling-head permeameter tests were done on 18 samples of the upper confining unit. The calculated vertical hydraulic conductivity values range from a low of 2.65×10^{-6} ft/d (well 19) for a sample of clay to a high of 2.23×10^{-1} ft/d (well 18) for a sample of silty sand. The median value for the 18 samples is 1.88×10^{-4} ft/d. The ratio of median horizontal hydraulic conductivity of the Columbia aquifer to median vertical hydraulic conductivity of the upper confining unit is approximately 2,600:1. Ground-water-flow rates across the upper confining unit, based on an average measured gradient of 0.13, assumed porosity of 0.30, and vertical hydraulic conductivity values from permeameter tests, range from a low of 0.0004 ft/yr to a high of 35 ft/yr, and a median value of 0.03 ft/yr.

Slug tests were done in the three wells in the upper confined aquifer. The calculated horizontal hydraulic conductivity values are 2×10^0 ft/d (well M1), 8×10^{-2} ft/d (well M2), and 8×10^0 ft/d (well M3). Falling-head permeameter tests were done on two samples of the upper confined aquifer. The calculated

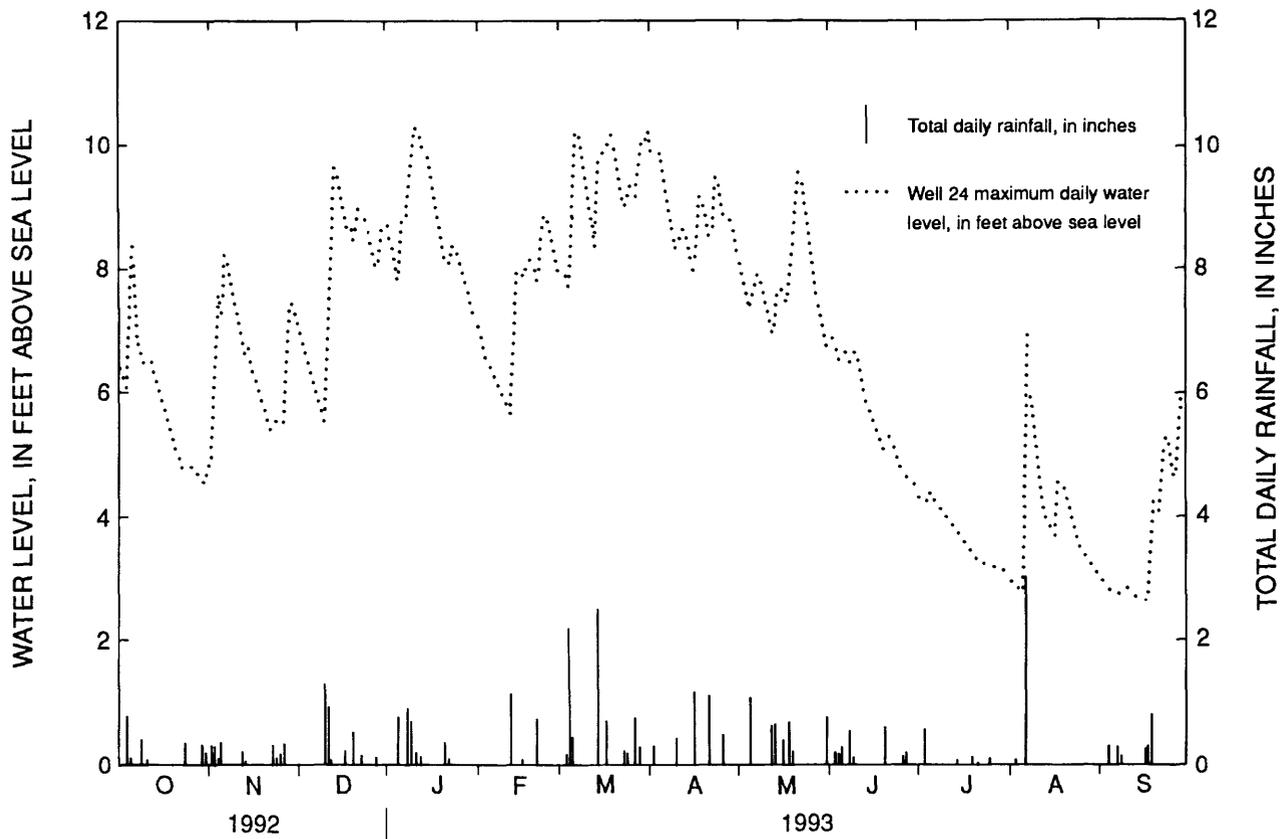


Figure 13. Maximum daily water level in the Columbia aquifer in well 24 and total daily rainfall, October 1992 through September 1993, at the Mainside, Dahlgren, Virginia.

vertical hydraulic conductivity values were 7.80×10^{-5} ft/d and 5.67×10^{-3} ft/d.

Falling-head permeameter tests were done on two samples of Nanjemoy sediments from the Nanjemoy-Marlboro confining unit. The calculated vertical hydraulic conductivity values were 6.72×10^{-4} ft/d and 1.59×10^{-3} ft/d.

Slug tests were done in the three wells in the Aquia aquifer. The calculated horizontal hydraulic conductivity values were 4×10^{-3} ft/d (well D1), 3×10^{-1} ft/d (well D2), and 4×10^{-2} ft/d (well D3).

WATER QUALITY OF THE SHALLOW AQUIFER SYSTEM

The purpose of sampling ground water and surface water at the Mainside, NSWCDL, was to determine background water quality of the three aquifers under investigation, to describe the possible exchange of water between aquifers, and to gain

insight into the interactions between ground water and surface water. Sampling locations, collection techniques, and results of chemical analyses are documented in Bell and others (1994). Laboratory analytical techniques are described in Fishman and Friedman (1989) and Wershaw and others (1987).

Water from all 35 wells and 3 surface-water sites located on Gambo Creek was sampled in May 1993 for several selected chemical constituents and indicators. Field properties measured include specific conductance, pH, temperature, dissolved oxygen, and alkalinity. Major dissolved constituents measured at the USGS National Water Quality Laboratory include calcium, magnesium, sodium, potassium, sulfate, chloride, fluoride, and silica. Minor dissolved constituents, which are defined in this report as those constituents that generally occur in concentrations of less than 5 mg/L include iron, aluminum, and manganese. Also measured were total dissolved solids, dissolved organic carbon, suspended organic carbon, and the isotopic ratios oxygen-18 and deuterium.

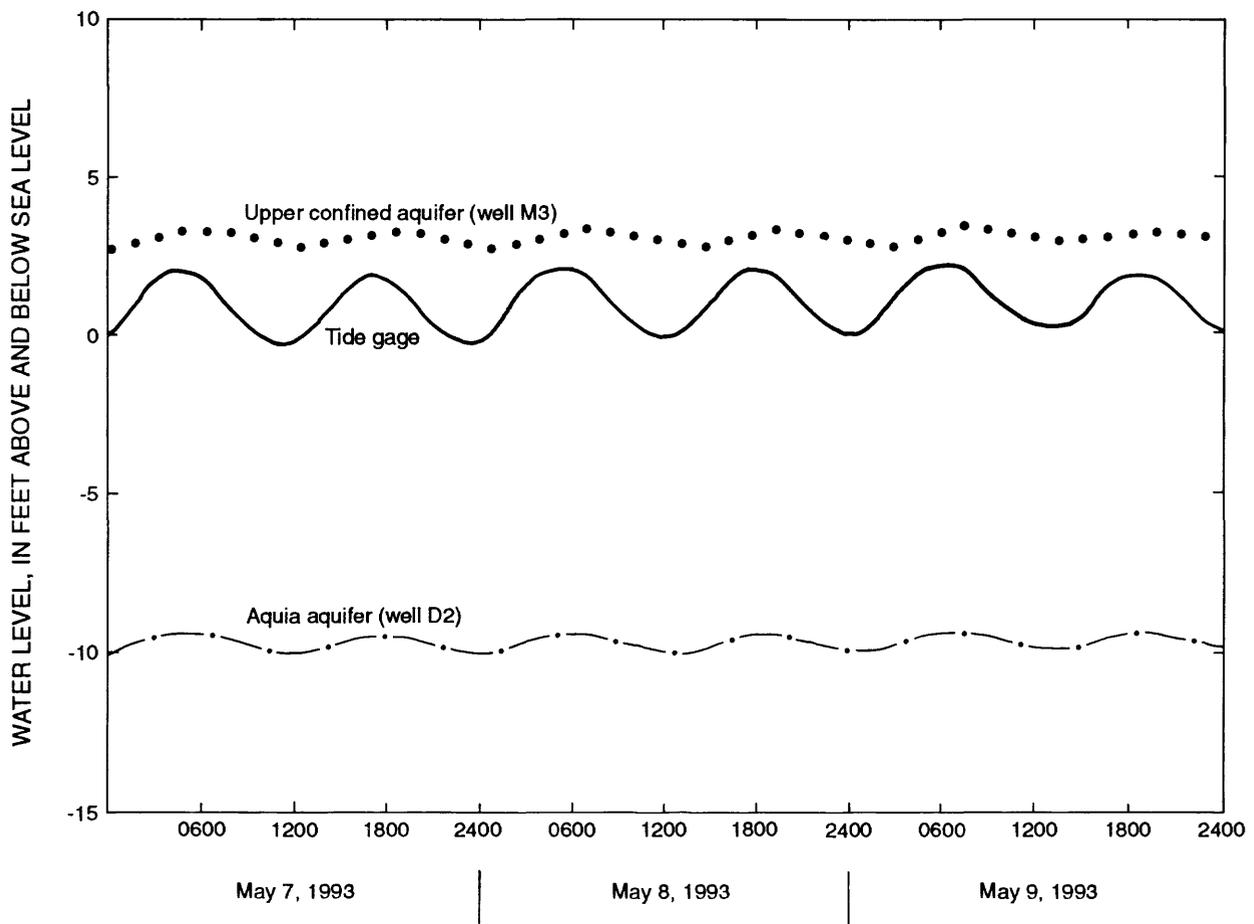


Figure 14. Water levels in well M3 in the upper confined aquifer, well D2 in the Aquia aquifer, and tidal fluctuations in the Upper Machodoc Creek, May 7–9, 1993, at the Mainside, Dahlgren, Virginia.

Water samples were collected from 29 wells screened in the Columbia aquifer. Of the three aquifers under investigation, the Columbia aquifer is most likely to be chemically affected by surface sources, such as waste-disposal sites or tidal creeks; thus, most of the discussion of water-quality at the Mainside relates to the Columbia aquifer. Water samples also were obtained from three wells in the upper confined aquifer (M1, M2, M3) and three wells in the Aquia aquifer (D1, D2, and D3).

Anomalously high pH values were measured in water samples from all three wells in the Aquia aquifer, which probably were due to reaction of the ground water with cement grout during well construction. Chemical analyses from these wells, therefore, are not representative of formation water and are not discussed in this report. The effects of cement grout on ground-water samples is discussed at greater length in the section, “Well Grout.”

Occurrence and Distribution of Selected Chemical Constituents

This section presents a summary of the results of chemical analyses of water from the Columbia aquifer, upper confined aquifer, and Gambo Creek at the Mainside, including graphical and statistical summaries of water-quality data. The range in concentration of selected chemical constituents in water from the Columbia aquifer, upper confined aquifer, and Gambo Creek is discussed with regard to spatial distribution of these chemical constituents and the U.S. Environmental Protection Agency’s (USEPA) secondary maximum contaminant level (SMCL), or the Virginia Ground-Water Standard (VGWS). The SMCL and VGWS are nonenforceable standards established for constituents that can adversely affect the odor, appearance, taste, or usability of drinking water (U.S. Environmental Protection Agency, 1995). Though neither the Columbia aquifer nor the upper confined aquifer at the Mainside are currently (1994)

Table 3. Summary statistics for water-quality analyses from the Columbia aquifer at the Mainside, Dahlgren, Virginia

[all analyses are for the dissolved constituent unless otherwise noted; results from 29 analyses were used to calculate all statistics; °C, degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; <, less than; C, carbon; CaCO₃, calcium carbonate; SMCL, secondary maximum contaminant level; VGWS, Virginia Ground-Water Standard; --, no data]

Water-quality constituent	Maximum concentration	Minimum concentration	Median concentration	SMCL ¹ or VGWS	Number of samples exceeding SMCL
Specific conductance, µS/cm	2,190	50	137	--	--
pH, standard units	6.9	4.7	5.3	6.5–8.5	26
Dissolved oxygen, mg/L	9.4	.5	2.2	--	--
Calcium, mg/L	94	.18	4.8	--	--
Magnesium, mg/L	39	<.1	1.6	--	--
Sodium, mg/L	320	4.0	11	270	1
Potassium, mg/L	17	.30	.80	--	--
Alkalinity, mg/L, as CaCO ₃	291	<1	11	--	--
Sulfate, mg/L	85	<.10	14	250	0
Chloride, mg/L	480	2.2	9.2	250	2
Fluoride, mg/L	.20	<.10	<.10	--	--
Silica, mg/L	76	8.4	22	--	--
Dissolved solids, residue at 180°C, mg/L	1,190	49	110	500	3
Aluminum, µg/L	630	10	60	--	--
Iron, µg/L	30,000	<10	160	300	10
Manganese, µg/L	7,000	<10	95	50	17
Dissolved organic carbon, mg/L, as C	18	<.1	1.1	1	10

¹U.S. Environmental Protection Agency (1995).

being used as a source of drinking water, comparison of water-quality data by use of SMCL or VGWS is a convenient way of evaluating water quality in these aquifers.

Columbia Aquifer

The range and median of measured values for water-quality analyses from the Columbia aquifer are presented in table 3, and the distribution of selected chemical constituents is graphically presented in boxplots in figure 15.

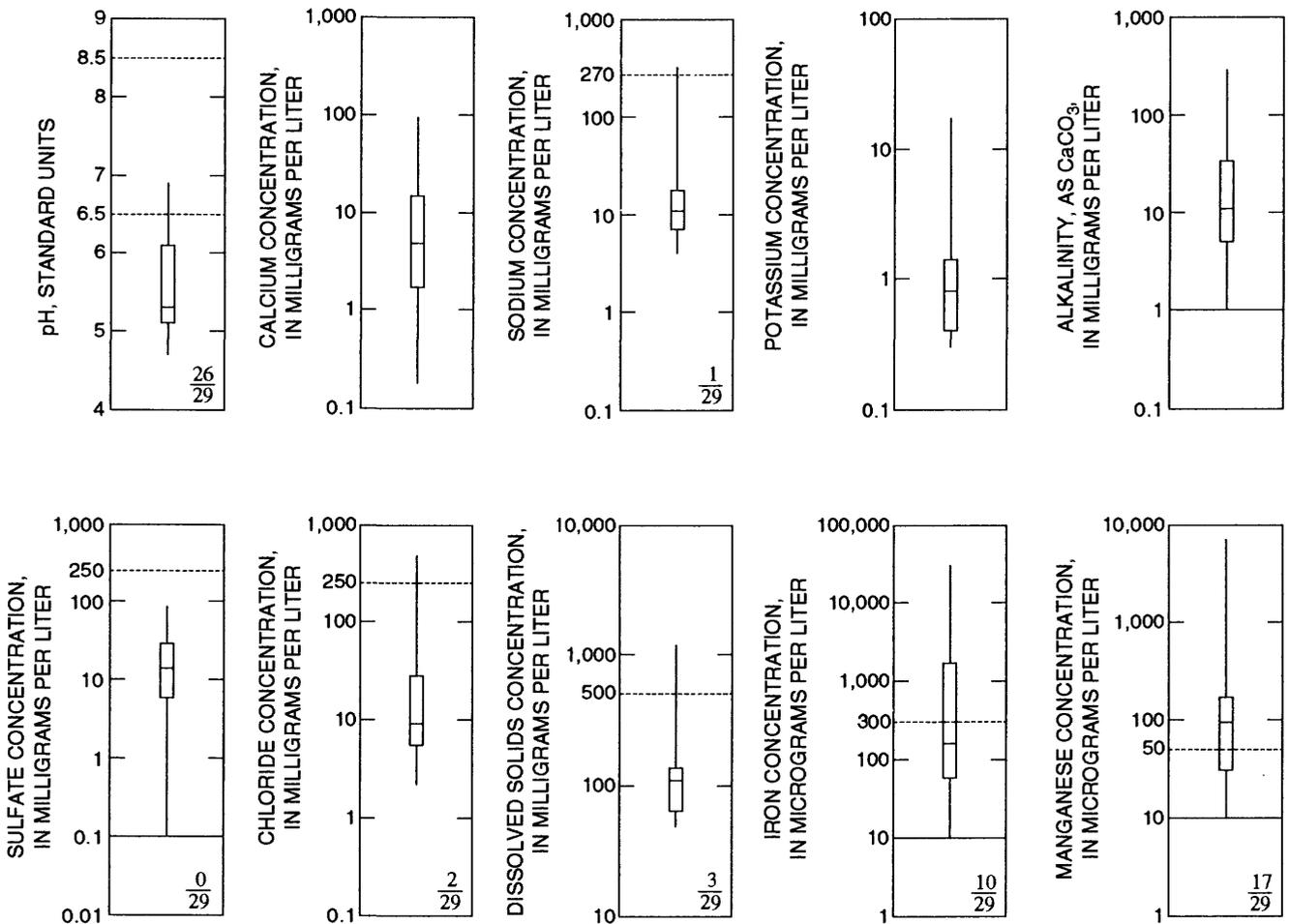
Field Properties

Water from the Columbia aquifer is characterized by low pH. Only 3 of the 29 water samples collected from the Columbia aquifer had pH's that were within the SMCL range of 6.5 to 8.5; the pH of all other samples were below this range. Most pH values of water from wells along the inland perimeter roads of the Mainside were below 5.5, whereas most pH values of water from wells on the interior of the Mainside were above 5.5. Alkalinity, composed primarily of the bicarbonate ion (HCO₃⁻) in the Columbia aquifer, generally was low, having a median concentration of only 11 mg/L. However, alkalinity

was highly varied across the Mainside, having concentrations ranging from less than 1 to 291 mg/L.

Specific conductance and total dissolved solids in water from the Columbia aquifer are also highly varied. The highest concentrations of specific conductances and dissolved solids were observed in water from wells situated along the inland perimeter roads. For example, water from the three wells (3, 9, and 30) located on the inland perimeter roads had specific conductances greater than 500 µS/cm and concentrations of total dissolved solids greater than the SMCL of 500 mg/L.

Dissolved oxygen was detected in water from all the Columbia aquifer wells, but it should be noted that dissolved oxygen measurements in well water are not always representative of the concentration of dissolved oxygen in the aquifer because of aeration of well water by contact with the atmosphere or by the sampling pump. Typically, dissolved oxygen in water from a surficial aquifer are affected by local conditions such as the amount of organic material in aquifer sediments, and concentrations can range from 0 to more than 9 mg/L. High concentrations of dissolved iron and manganese, as observed in many ground-water samples, indicate anoxic conditions in parts of the Columbia aquifer.



EXPLANATION

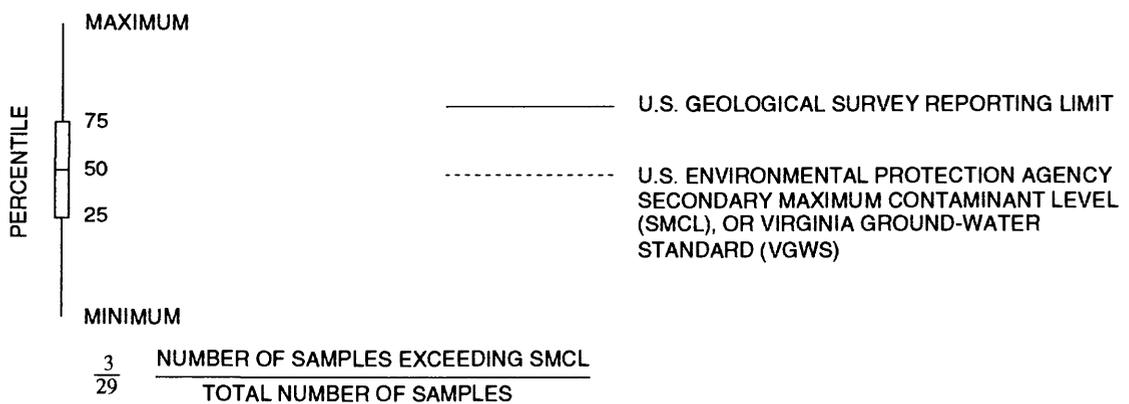


Figure 15. Summaries of water-quality analyses for selected constituents in the Columbia aquifer at the Mainside, Dahlgren, Virginia.

Major Chemical Constituents

A plot of water-quality data from the Columbia aquifer on a trilinear diagram (fig. 16) shows the highly varied composition of water from this aquifer. Rather than falling into water-type categories characterized by a single dominant anion and cation, most water samples from the Columbia aquifer (20 of 29) are of mixed-ionic character. In general, water samples from the Columbia aquifer can be grouped into two categories, as follows: (1) Those having chloride or a combination of chloride and sulfate as the dominant anions; and (2) those having bicarbonate or a combination of bicarbonate and sulfate as the dominant anions. Sodium and calcium were the dominant cations, and a small percentage of magnesium, in most of the Columbia aquifer samples.

Water from most wells situated along the inland perimeter roads of the Mainside fell into category 1, whereas water from most wells situated within the interior fell into category 2 (fig. 16). Similarly, water from wells along the inland perimeter roads generally had higher concentrations of chloride, and to a lesser extent, sodium and magnesium, than interior wells. Chloride concentrations exceeded the SMCL in water from wells 9 and 30. Calcium concentration had a wide range and showed no well-defined spatial distribution. Concentrations of potassium, silica, and sulfate were less varied in magnitude than concentration of calcium but also showed no well-defined spatial distribution. Very little fluoride concentration was detected in water samples from the Columbia aquifer.

Minor Chemical Constituents

Dissolved iron concentration in water from the Columbia aquifer was highly varied, from below the USGS reporting limit of 10 to 30,000 $\mu\text{g/L}$ (fig. 15). Concentrations of manganese and aluminum also showed a wide range in magnitude. Ten of 29 ground-water samples exceeded the SMCL for iron and 17 exceeded the SMCL for manganese. In general, iron and manganese correlated positively with each other in water from the Columbia aquifer, and correlated negatively with dissolved oxygen concentration. Aluminum concentration showed a slight negative correlation with pH. No obvious pattern of spatial distribution was observed for any of these metals.

Dissolved organic carbon concentration was detected in all but one sample from the Columbia aquifer (well 19) and suspended organic carbon

concentration was detected in water from all the Columbia aquifer wells. Water from most wells on the inland perimeter roads of the Mainside had dissolved organic carbon concentration above the median value of 1.1 mg/L, for the Columbia aquifer, whereas water from most wells in the interior of the Mainside had dissolved organic carbon concentration below the median.

Upper Confined Aquifer

The geochemistry of the upper confined aquifer is markedly different than that of the Columbia aquifer. The pH of water in the upper confined aquifer is higher (6.5, 7.1, and 7.6) than water in the Columbia aquifer; water from all three wells in the upper confined aquifer have pH's above the median pH value in water from the Columbia aquifer. Concentrations of specific conductance (180, 430, and 515 $\mu\text{S/cm}$), alkalinity (85, 197, and 252 mg/L as CaCO_3), and total dissolved solids (131, 272, and 311 mg/L) were also above the median concentration for water from the Columbia aquifer. The higher concentration of these field properties are the result of higher concentrations of calcium, magnesium, sodium, potassium, and bicarbonate in water from the upper confined aquifer. Conversely, concentrations of sulfate, chloride, and dissolved oxygen in water from the upper confined aquifer were lower than the median concentrations in water from the Columbia aquifer. All three water samples from the upper confined aquifer are classified as sodium-calcium-bicarbonate waters (fig. 17).

Water from two of the three wells in the upper confined aquifer had iron concentration exceeding the SMCL, and water from all three wells exceeded the SMCL for manganese. All other constituents measured, however, were below the SMCL. Dissolved organic carbon and suspended organic carbon were detected in water from all three wells.

Surface Water

The three surface-water samples collected from Gambo Creek showed a trend in which most major chemical constituents and field properties, including pH, increase downstream. The only exceptions are silica, which decreased downstream, and dissolved oxygen, which did not change. Concentrations of minor chemical constituents, such as iron, manganese, aluminum, dissolved organic carbon, and suspended organic carbon decreased downstream. The most

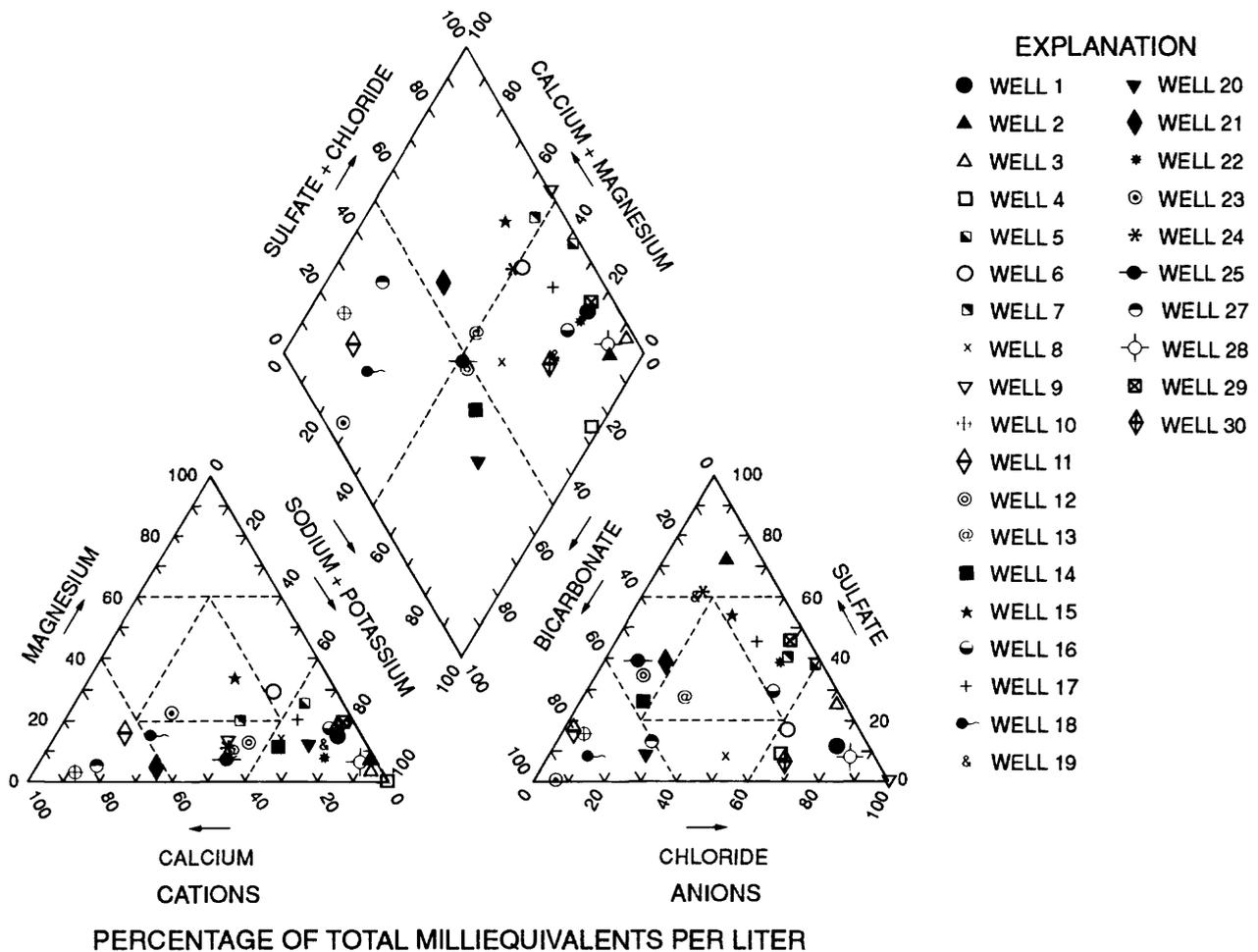


Figure 16. Major-ion composition of water in wells in the Columbia aquifer at the Mainside, Dahlgren, Virginia.

upstream surface-water sample is classified as a sodium-calcium-magnesium-bicarbonate-chloride water, whereas the other two samples are sodium-chloride waters (fig. 17).

Probable Sources of Chemical Constituents

The chemical composition of ground water is affected by the composition of the precipitation that recharges an aquifer. Chemical reactions occur as water enters and flows through an aquifer, resulting in mixing of water between aquifers, and the contribution of surface water to the aquifer. The geochemistry of ground water at the Mainside reflects both natural and anthropogenic sources of chemical constituents.

Natural Processes

Precipitation in the Coastal Plain Physiographic Province of Virginia typically contains 1 to 3 mg/L sodium, chloride, sulfate, and nitrate (Richardson and Brockman, 1992), and a pH between 4.2 and 4.7 (Drever, 1988). Sodium, chloride, and sulfate are derived from fine droplets of sea water in the atmosphere. Nitrate and additional sulfate is derived from atmospheric gases that have their origin in biological activity, including burning of fossil fuels and forest fires. Precipitation is usually close to saturation with respect to dissolved oxygen (about 9 mg/L). Despite the presence of these chemical constituents, most precipitation has very low dissolved solids concentration; however, as precipitation reaches the earth's surface and infiltrates the ground, it begins to react with the materials encountered on the surface and the

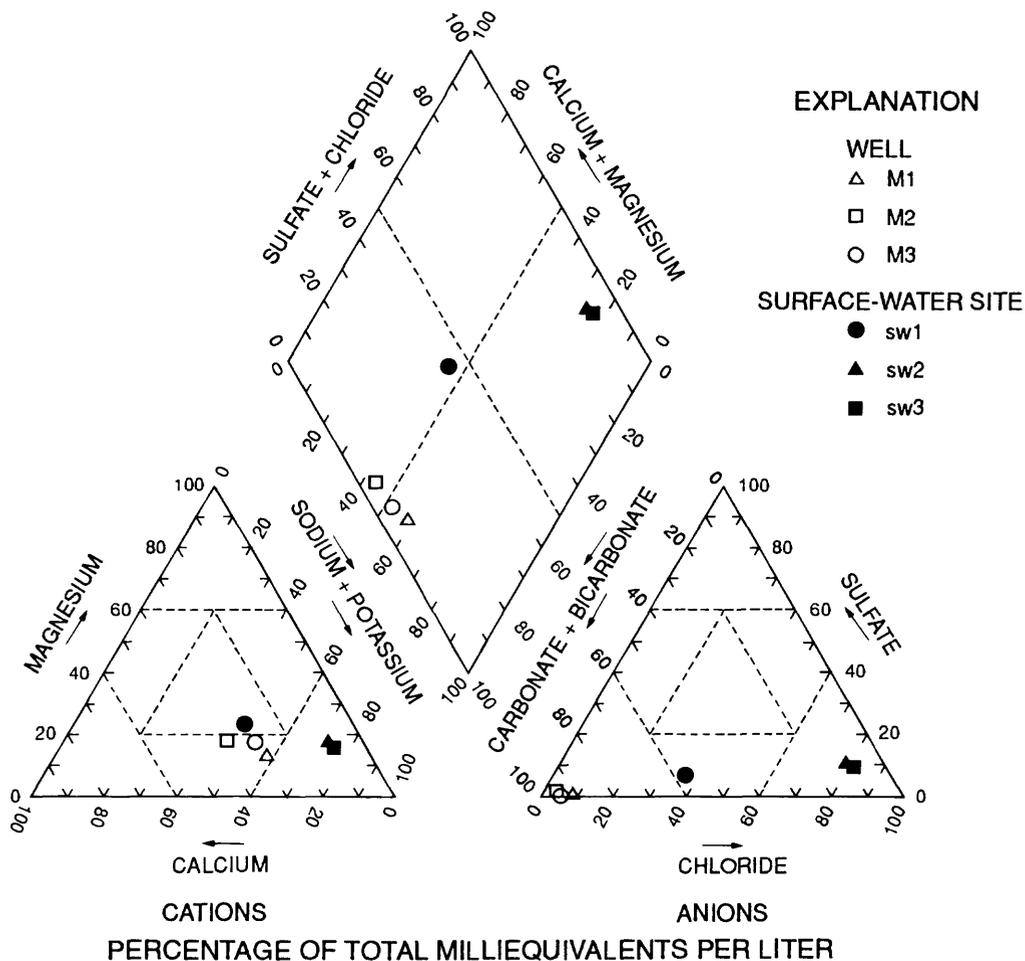


Figure 17. Major-ion composition of water in wells in the upper confined aquifer and surface water at the Mainside, Dahlgren, Virginia.

subsurface and dissolved solids concentration increases.

Organic Material

In the soil zone and aquifer sediments, microorganisms are able to use dissolved oxygen to biochemically oxidize organic material. This reaction depletes dissolved oxygen and increases the concentration of dissolved carbon dioxide, which reacts with water to form carbonic acid (H_2CO_3). Carbonic acid decreases the pH of ground water and increases the rate of mineral dissolution. The low pH of precipitation in the Coastal Plain Physiographic Province of Virginia, and the production of carbonic acid in the subsurface probably is responsible for the low pH observed in water from the Columbia aquifer. Similarly, microbial oxidation of organic material

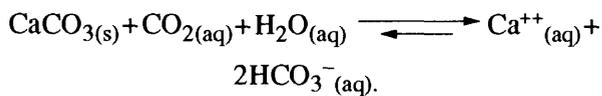
causes low dissolved oxygen concentration in water from the upper confined aquifer and from parts of the Columbia aquifer, which in turn causes high concentrations of dissolved iron and manganese as described in the section on “Non-Carbonate Minerals” below.

Concentrations of dissolved organic carbon and suspended organic carbon in uncontaminated ground water is derived from precipitation, the soil zone, and aquifer sediments; most dissolved organic carbon and suspended organic carbon have their origin in decaying plant material and microbial waste products. Although naturally occurring concentrations of dissolved organic carbon and suspended organic carbon in ground water are low compared to those of most surface waters, they can be significant compared to organic carbon concentrations derived from contaminants. In the Columbia and upper confined aquifers, both dissolved organic carbon and suspended

organic carbon are minor but widespread naturally occurring chemical constituents; therefore, the presence of dissolved organic carbon and suspended organic carbon does not constitute evidence of contamination, and should be compared with background concentrations.

Carbonate Minerals

As water flows through soil and aquifer materials, many important reactions occur that tend to increase dissolved solids and alkalinity. Carbonate minerals, such as calcite and aragonite in fossil shells, react with carbon dioxide and water to dissolve according to the following reaction (Drever, 1988):



The production of bicarbonate increases alkalinity and pH. The Columbia aquifer contains little shell material and, thus, alkalinity and pH in water remain low. The upper confined aquifer, however, contains moderate amounts of fossil shell material (Bell and others, 1994), which causes high pH values and increased concentrations of alkalinity, total dissolved solids, and calcium in water.

Non-Carbonate Minerals

Silicate minerals, such as feldspars, micas, and some clays also react and dissolve, producing sodium, potassium, calcium, magnesium, silica, and bicarbonate. These processes are especially important in the carbonate-poor Columbia aquifer, where silicate reactions and dissolution probably are responsible for a large percentage of the total dissolved solids.

Sulfate in water from the shallow aquifer system is derived from the oxidation of sulfide minerals and hydrogen sulfide (H₂S) released from decaying organic material. Under moderately to strongly reducing conditions, sulfate will be reduced back to H₂S or metallic sulfide minerals. The high sulfate concentration in water from the Columbia aquifer, relative to that from the upper confined aquifer, is a result of the presence of dissolved oxygen in parts of the Columbia aquifer.

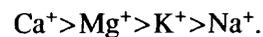
The solubilities of iron and manganese in ground water also are related to dissolved oxygen concentration. In aquifer sediments, iron exists in the relatively insoluble ferric (Fe(III)) or Fe(IV) forms, mostly as iron oxides, oxyhydroxides, and

polysulfides (Hem 1989); however, if dissolved oxygen is depleted by the microbial oxidation of organic matter, then ferric iron is reduced to a much more soluble ferrous (Fe(II)) form. Similarly, manganese solubility is increased by the reduction of Mn(IV) in manganese oxyhydroxides to Mn(III) and Mn(II) (Hem, 1989). High concentrations of iron and manganese at the Mainside probably are the result of anoxic water conditions in the upper confined aquifer and parts of the Columbia aquifer.

Aluminum solubility is affected primarily by pH rather than redox conditions. Extremely insoluble at a pH of about 6.0, aluminum becomes more soluble with both increasing and decreasing pH (Hem, 1989). This explains the slight negative correlation between aluminum and pH in water from the Columbia aquifer.

Exchangeable Cations

The relative concentration of dissolved ions produced by the reactions described above will be further modified by cation exchange. Cation exchange is the interchange between a cation in solution and a cation on a surface-active material, such as clay minerals, iron and manganese oxides, organic materials, and glauconite. Because of difference in size and charge, some cations are more easily held to surfaces than others. The selectivity order of major cations in aquifers of the Coastal Plain Physiographic Province is (Chapelle and Knobel, 1983)



This selectivity order suggests that, along a flow path, dissolved calcium in ground water will decrease and sodium will increase. Calcium can be exchanged for sodium in solution, however, if the sodium concentration is very high (Howard and others, 1993).

In the upper confined aquifer, calcium derived from dissolution of carbonate material is exchanged probably for sodium on the surfaces of glauconite and other minerals, resulting in a sodium-calcium-bicarbonate water rather than a calcium-bicarbonate water. Cation-exchange probably is less important in the Columbia aquifer because of shorter flow paths.

Road Salt

The natural processes described above should result in ground water in which the dominant cations are sodium and calcium, and the dominant anions are bicarbonate and sulfate. This composition is observed in water from the upper confined aquifer and in many

water samples from the Columbia aquifer. Many water samples from Columbia aquifer wells situated near the inland perimeter roads of the Mainside, however, also contain high percentages of chloride (fig. 18). Many of these same wells have water containing high absolute concentrations of chloride, specific conductance, and total dissolved solids. Background chloride concentration in water from the Columbia aquifer are 2 to 12 mg/L, but most water samples collected along the inland perimeter roads contain concentrations of chloride greater than 20 mg/L, and as high as 480 mg/L (well 30).

In shallow aquifers of the Coastal Plain Physiographic Province of Virginia, two major sources of chloride occur: The intrusion of saline surface water into aquifers, and the contamination of infiltrating ground water by chloride salts used to de-ice roads. Head data suggest that it is unlikely that brackish river or creek water is flowing into the Columbia aquifer except in a narrow zone adjacent to the surface-water bodies. On the other hand, the proximity of affected wells to major roads strongly suggests road-salt contamination of the Columbia aquifer.

Road salt is applied in two major forms: rock salt, which is predominantly sodium chloride (NaCl), and calcium chloride (CaCl₂). The King George headquarters of the Virginia Department of Transportation reports applying between 1,700 and 1,800 tons of rock salt to the county's roads between December 1991 and March 1994, including 1,200 to 1,300 tons during the winter of 1993-94. Calcium chloride is used only during extremely cold weather; about 25 tons were applied to the county's roads during 1991-94 (Martin, oral commun., 1994). The stretch of State route 301 that borders the NSWCDL on the north receives an undetermined part of this treatment. Similarly, the Transportation Division of the NSWCDL applied about 15 tons of rock salt to roads on the installation during the winter of 1993-94.

Road salt mainly enters the ground-water system during the early spring, as melting snow and heavy rains flush salts off roads. The expected water type in road-salt-affected wells would be sodium-chloride, as is observed in wells 1, 3, 4, 5, 28, and 30. Concentrations of high calcium and (or) sulfate, however, are also observed in wells containing high chloride. These chemical constituents are derived probably from the natural processes described above, including exchange of sodium in solution for calcium

in waters of very high sodium concentration (Howard and others, 1993).

Well Grout

Ground-water samples from wells D1, D2, and D3 displayed pH values of 12.5, 10.0, and 11.6, respectively. These pH values are too high for natural ground water in the Aquia aquifer and, thereby, indicate some kind of contamination. Cement grout, commonly used to create a seal above the screen in monitoring wells, has been observed to cause anomalously high pH values in ground-water samples (Lorah and Vroblesky, 1989). Although a bentonite seal was placed between the screened and filter-packed interval and the interval of cement grout, this seal may have been breached during emplacement of the grout.

In addition to high pH, grout-contaminated water has been observed to have high concentrations of alkalinity and potassium (Lorah and Vroblesky, 1989). Water from wells D1, D2, and D3 have alkalinities of 1,360, 176, and 327 mg/L as CaCO₃, respectively, all significantly above the Columbia aquifer median of 11 mg/L as CaCO₃. Similarly, potassium concentrations of 230, 28, and 120 mg/L are all above the Columbia aquifer median of 0.80 mg/L. This evidence indicates that water from these wells is grout-contaminated and water-quality analyses are not representative of formation water.

It should be noted that water from wells M1, M2, M3, and 14 also contain concentrations of alkalinity and potassium significantly above the Columbia aquifer median. The pH's of samples from these wells, however, were within a normal range, so that water from these wells has been interpreted as being representative of formation water.

Isotopes

Isotopic ratio variations are expressed as the relative per mil difference in abundance of an isotope with respect to that of a standard reference sample (standard mean ocean water) and are denoted δD for deuterium and $\delta^{18}O$ for oxygen-18. Values of δD and $\delta^{18}O$ in water from the Columbia aquifer and the upper confined aquifer are similar in composition but are markedly different than the values of δD and $\delta^{18}O$ in surface water (fig. 19).

δD and $\delta^{18}O$ of the Columbia aquifer are probably representative of local precipitation that

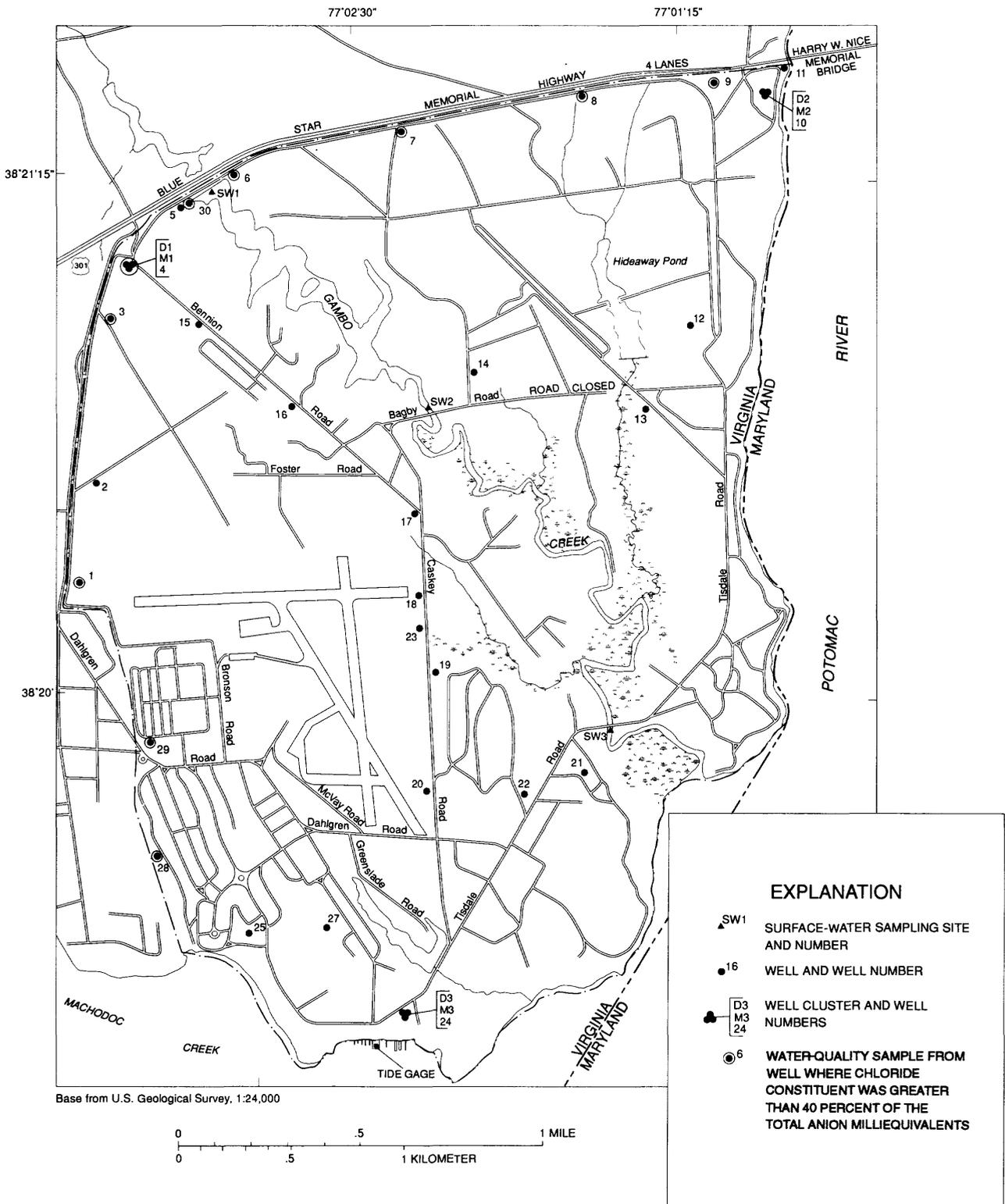


Figure 18. Locations of wells in the Columbia aquifer, including those where chloride constituent was greater than 40 percent of the total anion milliequivalents in a water-quality sample.

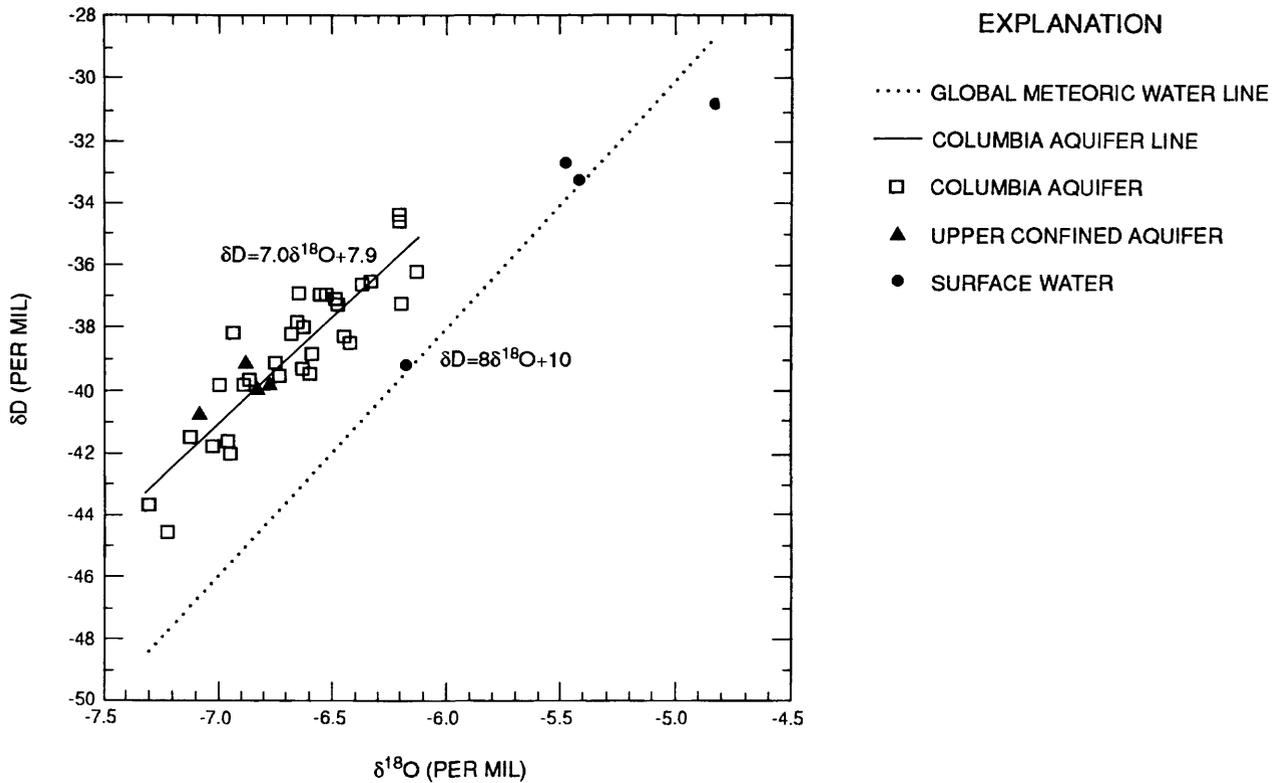


Figure 19. Ratio variation in deuterium (δD) and oxygen-18 ($\delta^{18}O$) in ground water and surface water at the Mainside, Dahlgren, Virginia. Also shown are the global meteoric-water line and least-squares regression line of data for the Columbia aquifer.

recharges the aquifer. Least-squares linear regression of isotope data indicates a δD excess of about 7.9 per mil. This value represents a local variation from the mean global meteoric excess deuterium (about 10 per mil) and causes data from the Columbia aquifer to plot off the global meteoric water line. δD and $\delta^{18}O$ values of the upper confined aquifer are close to those of the Columbia aquifer; thus, these isotopic ratios cannot be used to distinguish the source of recharge to an aquifer or to identify mixing between aquifers.

The similarity in δD and $\delta^{18}O$ of the Columbia aquifer and upper confined aquifer has three likely explanations. First, both aquifers may be recharged by meteoric waters of similar isotopic composition, which would be expected if the upper confined aquifer cropped out nearby, or equivalently, if the upper confining unit was missing nearby. Alternatively or additionally, the Columbia aquifer may recharge the upper confined aquifer through the upper confining unit. Finally, the upper confined aquifer may receive water of similar isotopic composition from the

adjacent and underlying Nanjemoy-Marlboro confining unit.

Surface-water samples from Gambo Creek plot close to the global meteoric water line and were enriched in both δD and $\delta^{18}O$ relative to ground water. The difference in isotopic composition of surface water and ground water is due to three effects. First, much of the recharge of the Columbia aquifer occurs during the winter months, December through March, when colder temperatures cause precipitation to be isotopically lighter than other periods of the year. Conversely, surface-water sampling was conducted in May, when Gambo Creek contained runoff from warm spring rains. Second, surface water is subject to evaporation more than ground water, which causes enrichment of heavy isotopes (Gat, 1981). Third, Gambo Creek is subject to mixing with the Potomac River, which contains water from a very large area and, thereby, will be more similar to global meteoric water than local precipitation.

SUMMARY AND CONCLUSIONS

The Mainside of the NSWCDL lies within the Atlantic Coastal Plain Physiographic Province. In Virginia, the Coastal Plain is comprised of an eastward-thickening sedimentary wedge of unconsolidated gravel, sand, silt, and clay that unconformably overlies crystalline bedrock. The upper 220 ft of these sedimentary deposits are divided into five hydrogeologic units, including the (1) Columbia aquifer, (2) upper confining unit, (3) upper confined aquifer, (4) Nanjemoy-Marlboro confining unit, and (5) Aquia aquifer.

The head distribution in the Columbia aquifer is typical of an unconfined, unstressed flow system in an area of subdued topographic relief. Ground-water recharge occurs at topographic highs in the northern part of the Mainside, and ground-water discharge occurs at topographic lows associated with adjacent surface-water bodies. The Columbia aquifer at the study area is a local system that is not affected by any known pumping stress.

In general, water samples from the Columbia aquifer can be grouped into two categories, as follows: (1) Those having chloride or a combination of chloride and sulfate as the dominant anions; and (2) those having bicarbonate or a combination of bicarbonate and sulfate as the dominant anions. Sodium and calcium were the dominant cations, and a small percentage of magnesium, in most of the Columbia aquifer samples. Many water samples from Columbia aquifer wells, situated near the inland perimeter roads of the Mainside, contain high percentages of chloride. Many of these same wells have water containing high concentrations of chloride, specific conductance, and total dissolved solids. Background chloride concentration in water from the Columbia aquifer are 2 to 12 mg/L, but most water samples collected along the inland perimeter roads contain concentrations of chloride greater than 20 mg/L, and as high as 480 mg/L (well 30). The application of road salt along State route 301 and the inland perimeter roads of the Mainside is probably affecting the water in the Columbia aquifer near these areas.

Dissolved solids and four inorganic constituents are present in water from the Columbia aquifer at concentrations that exceed the SMCL for drinking water established by the USEPA. Concentration of dissolved solids exceed the SMCL of 500 mg/L in 3 of 29 water samples. An elevated concentration of sodium is present in one sample and elevated concen-

trations of chloride are present in two samples. Concentrations of dissolved iron and manganese exceed the SMCL in 10 and 17 of 29 water samples, respectively, and are the most extensive water-quality problem with regard to inorganic constituents in the Columbia aquifer. High concentrations of iron and manganese at the Mainside probably are the result of anoxic water conditions in parts of the Columbia aquifer.

A downward hydraulic gradient is observed between the Columbia aquifer and the upper confined aquifer; however, the upper confining unit was encountered at the base of all wells completed in the Columbia aquifer. The ratio of median horizontal hydraulic conductivity of the Columbia aquifer to median vertical hydraulic conductivity of the upper confining unit is approximately 2,600:1; therefore, under natural-flow conditions, most water in the Columbia aquifer probably discharges to adjacent surface-water bodies.

The head distribution in the upper confined aquifer indicates that ground-water flow within the aquifer is approximately northeast to southwest across the Mainside, and water samples from the upper confined aquifer are classified as sodium-calcium-bicarbonate waters. A downward hydraulic gradient is observed between the upper confined aquifer and the Aquia aquifer; however, the Nanjemoy-Marlboro confining unit was encountered at the base of all wells completed in the upper confined aquifer.

The head distribution in the Aquia aquifer indicates that ground-water flow within the aquifer is approximately northwest to southeast across the Mainside. Stresses on the Aquia aquifer are indicated by hydraulic heads that range between 2 and 12 ft below sea level. Water samples from wells in the Aquia aquifer were contaminated by cement grout during well construction.

REFERENCES CITED

- Bell, C.F., Bolles, T.P., and Harlow, G.E., Jr., 1994, Hydrogeologic and water-quality data for the Main Site, Naval Surface Warfare Center, Dahlgren Laboratory, Dahlgren, Virginia: U.S. Geological Survey Open-File Report 94-301, 81 p.
- Berquist, C.R., Jr., 1993, Mapped units of the Coastal Plain, in Rader, E.K., and Evans, N.H., eds., 1993, Geologic map of Virginia—expanded explanation: Virginia Division of Mineral Resources, 80 p.

- Bouwer, Herman, 1989, The Bouwer and Rice slug test— an update: *Ground Water*, vol. 27, no. 3, p. 304–309.
- Bouwer, Herman, and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: *Water Resources Research*, vol. 12, no. 3, p. 423–428.
- Chapelle, F.H. and Knobel, L.K., 1983, Aqueous geochemistry and the exchangeable cation composition of glauconite in the Aquia aquifer, Maryland: *Ground Water*, v. 21, no. 3, p. 343–352.
- Curtin, S.E., Mack, F.K., and Andreasen, D.C., 1994, Potentiometric surface of the Aquia aquifer in southern Maryland, September 1993: U.S. Geological Survey Open-File Report 94–390, 1 p.
- Drever, J.I., 1988, *The geochemistry of natural waters: Englewood Cliffs, N.J., Prentice-Hall*, 437 p.
- Fishman, M.J., and Friedman, L.C., 1989, Methods for the determination of inorganic substances in water and fluvial sediments (3d ed.): U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.
- Freeze, R.A., and Cherry J.A., 1979, *Groundwater: New Jersey, Prentice-Hall*, 604 p.
- Friedman, L.C., and Erdmann, D.E., 1982, Quality assurance practices for the chemical and biological analyses of water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A6, 181 p.
- Gat, J.R., 1981, Isotopic fractionation, in Gat, J.R., and Gonfiantini, R., eds., *Stable isotope hydrology, deuterium and oxygen-18 in the water cycle: International Atomic Energy Agency Technical Report Series*, no. 210, p. 21–34.
- Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.
- Howard, K.W.F., Boyce, J.I., Livingstone, S.J., and Salvatore, S.L., 1993, Road salt impacts on ground-water quality—the worst of it is still to come: *GSA Today*, vol. 3, no. 12, p. 301, 319, 321.
- Jones, B.E., 1987, Quality control manual of the U.S. Geological Survey's National Water Quality Laboratory: U.S. Geological Survey Open-File Report 87–451, 7 p.
- Lohman, S.W., 1972, *Ground Water Hydraulics: U.S. Geological Survey Professional Paper 708*, 70 p.
- Lorah, M.M., and Vroblesky, D.A., 1989, Inorganic and organic ground-water chemistry in the Canal Creek area of Aberdeen Proving Ground, Maryland: U.S. Geological Survey Water Resources Investigations Report 89–4022, 97 p.
- Meng, A., III, and Harsh, J.F., 1988, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1404–C, 82 p.
- Mixon, R.B., Berquist, C.R., Jr., Newell, W.L., Johnson, G.H., Powars, D.S., Schindler, J.S., and Rader, E.K., 1989, Geologic Map and generalized cross sections of the Coastal Plain and adjacent parts of the Piedmont, Virginia: U. S. Geological Survey Miscellaneous Investigations Series Map I–2033, 2 sheets, scale 1:250,000.
- O'Brien and Gere Engineers, Inc., 1986, Confirmation Studies at Naval Surface Weapons Center, Dahlgren, Virginia: Chesapeake Division Naval Facilities Engineering Command, contract no. P11 N62477–83–C–0113, 141 p.
- Richardson, D.L., and Brockman, A.R., 1992, Hydrogeology and water quality of the shallow ground-water system in eastern York county, Virginia: U.S. Geological Survey Water-Resources Investigations Report 92–4090, 41 p.
- U.S. Environmental Protection Agency, 1995, *Drinking water regulations and health advisories: Washington, D.C., Office of Water*, 11 p.
- Wershaw, R.L., Fishman, M.J., Grabbe, R.R., and Lowe, L.E., eds., 1987, Methods for the determination of organic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A3, 80 p.