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

Ground-Water Flow and Saline Water in the Shallow Aquifer System of the Southern Watersheds of Virginia Beach, Virginia

Water-Resources Investigations Report 03-4258

Prepared in cooperation with:

The City of Virginia Beach Department of Public Utilities

science for a changing world

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By Barry S. Smith

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Richmond, Virginia
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U.S. DEPARTMENT OF THE INTERIOR
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Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in)
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square centimeters (cm^2)	0.155	square inch (in)
square kilometer (km^2)	0.3861	square mile (mi^2)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
kilogram (kg)	2.205	pounds (lbs)
grams per cubic centimeter (g/cm^3)	62.43	pounds per cubic foot (lbs/ft^3)
liter per second (L/s)	15.85	gallon per minute (gal/min)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
meter per day (m/d)*	3.281	foot per day (ft/d)
square meter per day (m^2/d)*	10.76	square foot per day (ft^2/d)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 x °C + 32

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). In this report, that vertical reference also is called sea level.

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

***Hydraulic conductivity:** The standard unit for hydraulic conductivity is cubic meter per day per square meter of aquifer cross-sectional area (m^3/d)/m^2. In this report, the mathematically reduced form, meter per day (m/d), is used for convenience.

Abbreviated water-quality units: 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 mass (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 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 conductance of water is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Ground-Water Flow and Saline Water in the Shallow Aquifer System of the Southern Watersheds of Virginia Beach, Virginia

By Barry S. Smith

ABSTRACT

Population and tourism continues to grow in Virginia Beach, Virginia, but the supply of freshwater is limited. A pipeline from Lake Gaston supplies water for northern Virginia Beach, but ground water is widely used to water lawns in the north, and most southern areas of the city rely solely on ground water. Water from depths greater than 60 meters generally is too saline to drink. Concentrations of chloride, iron, and manganese exceed drinking-water standards in some areas. The U.S. Geological Survey, in cooperation with the city of Virginia Beach, Department of Public Utilities, investigated the shallow aquifer system of the southern watersheds to determine the distribution of fresh ground water, its potential uses, and its susceptibility to contamination.

Aquifers and confining units of the southern watersheds were delineated and chloride concentrations in the aquifers and confining units were contoured. A ground-water-flow and solute-transport model of the shallow aquifer system reached steady state with regard to measured chloride concentrations after 31,550 years of freshwater recharge. Model simulations indicate that if freshwater is found in permeable sediments of the Yorktown-Eastover aquifer, such a well field could supply freshwater, possibly for decades, but eventually the water would become more saline. The rate of saline-water intrusion toward the well field would depend on the rate of pumping, aquifer properties, and on the proximity of the well field to saline water sources. The steady-state, ground-water-flow model also was used to simulate drawdowns around two hypothetical well fields and drawdowns around two hypothetical open-pit mines. The chloride concentrations simulated in the model did not approximate the measured concentrations for some wells, indicating sites where local hydrogeologic units or unit properties do not conform to the simple hydrogeology of the model.

The Columbia aquifer, the Yorktown confining unit, and the Yorktown-Eastover aquifer compose the hydrogeologic units of the shallow aquifer system of Virginia Beach. The Columbia and Yorktown-Eastover aquifers are poorly confined throughout most of the southern watersheds of Virginia Beach. The freshwater-to-saline-water distribution probably is in a dynamic equilibrium throughout most of the shallow aquifer system. Freshwater flows continually down and away from the center of the higher altitudes to mix with saline water from the tidal rivers, bays, salt marshes, and the Atlantic Ocean. Fresh ground water from the Columbia aquifer also leaks down through the Yorktown confining unit into the upper half of the Yorktown-Eastover aquifer and flows within the Yorktown-Eastover above saline water in the lower half of the aquifer. Ground-water recharge is minimal in much of the southern watersheds because the land surface generally is low and flat.

INTRODUCTION

The city of Virginia Beach encompasses 803 km^2 of coastal lowlands and wetlands in southeastern Virginia. Land area of the city is 670 km^2 and water 133 km^2 (City of Virginia Beach Department of Economic Development, 2002, p.1). It is the most populous city in Virginia (425,257 citizens in the 2000 census) and attracted nearly 3 million tourists in the year 2000. Population and tourism continue to grow in Virginia Beach, but the supply of freshwater is limited. A pipeline from Lake Gaston supplies water for northern Virginia Beach, but ground water is widely used to water lawns in the north and most southern areas of the city rely solely on ground water (fig. 1).

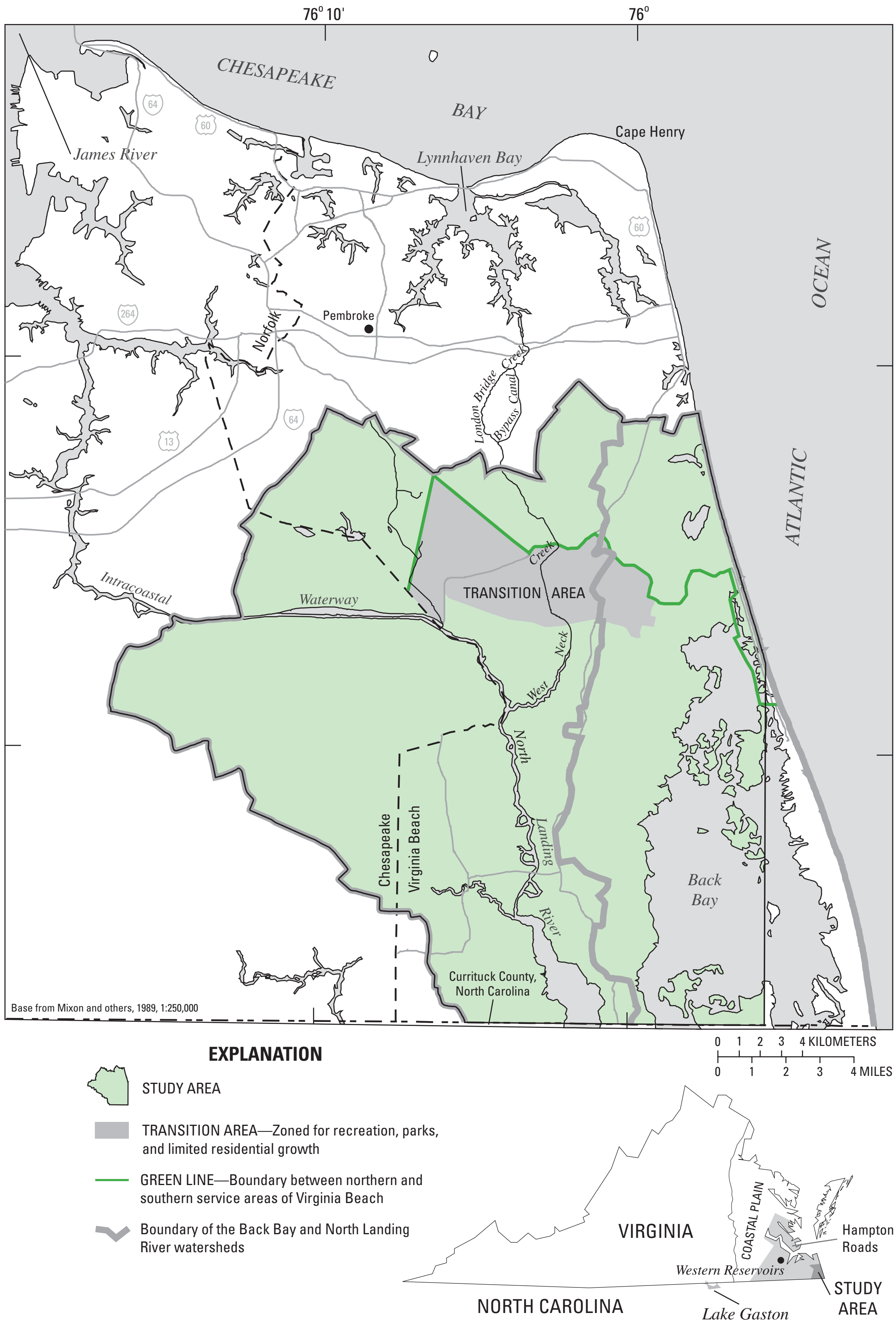


Figure 1. Location of the southern watersheds of Virginia Beach, Virginia, and the study area.

Wells in Virginia Beach provide water from depths generally less than 60 m. The shallow aquifers supply water for drinking, lawn watering, irrigation, and heat pumps. The water-table aquifer also is partially dewatered, in places, by open-pit sand-and-gravel mines that can lower the water levels in nearby wells.

Supplies of fresh ground water are limited in many areas of Virginia Beach. Concentrations of chloride, iron, and manganese exceed drinking-water standards in some areas and water from depths greater than 60 m generally is too saline to drink. "Water that generally is considered unsuitable for human consumption or for irrigation because of high content of dissolved solids" is called saline (U.S. Geological Survey, 1985, p. 461). Most high production wells in and around Virginia Beach have had a history of increasing chloride concentrations with higher pumping rates.

Background

The city of Virginia Beach has a keen interest in preserving the limited supply of usable water in the shallow aquifers beneath the city. The U.S. Geological Survey (USGS), in cooperation with the Virginia Beach Department of Public Utilities, has revised the conceptual hydrogeologic framework of the shallow aquifer system beneath the city and has established a network of wells to measure water levels and water quality in the city (Smith and Harlow, 2002, p. 23). The purpose of this continuing cooperative project is to better understand the distribution of fresh ground water, its potential uses, and its susceptibility to contamination (Johnson, 1999, p. 2).

Specific objectives of this phase of the investigation were to (1) map chloride concentrations in the southern watersheds of Virginia Beach within the context of the revised framework of the shallow aquifer system, (2) determine the patterns of ground-water flow in the southern watersheds, and (3) evaluate potential changes in drawdowns and chloride concentrations, representing saline-water intrusion, resulting from hypothetical withdrawals of ground water in the southern watersheds of Virginia Beach.

Purpose and Scope

Ground-water flow and the distribution of saline water in the southern watersheds of Virginia Beach are described in this report. A ground-water-flow and solute-transport model also is documented.

Chloride concentrations in the shallow aquifer system were mapped in the context of the revised hydrogeologic framework. The chloride data and average water levels were used to calibrate a ground-water-flow and solute-transport model. The calibrated model then was used to simulate drawdowns and potential changes in chloride concentrations (saline-water intrusion) resulting from hypothetical withdrawals of ground water. In this investigation, saline water was inferred from measured concentrations of naturally occurring chloride.

This phase of the investigation focused on the southern watersheds of Virginia Beach. Ground water is the sole source of freshwater in the southern watershed and the distribution of land to water in the southern watersheds is more aggregated than that of the north, where many bays, lakes, rivers, and reservoirs separate the shallow aquifers into numerous local ground-water-flow regimes. More extensive well-data networks and a more detailed hydrogeologic framework would be needed for a similar analysis of the northern watersheds. Also, the rural nature of the southern watersheds renders a simpler conception of ground-water recharge with fewer hydrologic variables and assumptions to consider than that of the urban north.

Description of the Study Area

The southern watersheds of Virginia Beach encompass the coastal lowlands and wetlands draining into the North Landing River and the Back Bay (fig. 1). The watersheds and the study area, which constitutes most of the watersheds, are in the Coastal Plain Physiographic Province of southeastern Virginia. The average altitude of Virginia Beach is 4 m above sea level. From 1895 to 2001, the average annual air temperature was 15º C (59º F) and average annual precipitation was 120 cm at Norfolk, Va., which is adjacent to Virginia Beach (National Climatic Data Center, 2002). About 18 cm of snow falls each year.

The North Landing River and the Back Bay are tidal. The North Landing River is connected to the Intracoastal Waterway to the west through the city of Chesapeake, Va., by the Intracoastal Waterway (Albemarle and Chesapeake Canal) and to the north, just beyond the southern watersheds, through northern

Virginia Beach by West Neck Creek, London Bridge Creek, and the Bypass Canal. The North Landing River and the Back Bay are connected to Currituck Sound south of the study area in Currituck County, N.C.

The Back Bay watershed includes wetlands, barrier beaches, and dune sands adjacent to the Atlantic Ocean, but the narrow strip of land adjacent to the ocean east of the bay probably is isolated from the rest of the watershed with respect to ground-water flow, and was not included as a part of the study area. The watershed of the North Landing River also includes the part of the city of Chesapeake, Va., that is immediately west of Virginia Beach. Currituck County, N.C. is immediately south of the study area.

The northern and western perimeters of the watersheds are within the commercial, residential, and transportation sectors of Virginia Beach and Chesapeake, Va., which generally were built on or raised to slightly higher altitudes than the surrounding areas (fig. 2). The watershed boundaries generally follow the higher altitudes, but also can follow subtle changes in altitude along and across roads or drainage ditches adjacent to roads and air-strip runways.

A "Green Line" and Transition Area mark a planned separation between the populated, urban northern service area of Virginia Beach and the relatively unpopulated, rural southern service area (fig. 1). Pungo and Blackwater boroughs, which together form most of the southern service area, had an estimated 5,200 residents combined in 1996 (City of Virginia Beach Department of Planning, 1996, p. 10).

Agriculture and wetlands dominate land use in the southern watersheds. Pasture, hay, and row crops are common on higher ground whereas woody and herbaceous wetlands remain at the lower altitudes.

Surficial Geology

Holocene (recent) and Pleistocene (glacial and interglacial) sediments form the present landscape of Virginia Beach. The Holocene sediments have been deposited in the estuaries, swamps, marshes, rivers, and on the banks of streams, dunes, and shorelines since the end of the last major glacial advance about 11,500 years ago. Before then, Pleistocene sediments were deposited in similar coastal settings. The Pleistocene deposits of the Tabb Formation form most of the landscape of the southern watersheds of Virginia Beach (fig. 3). The Tabb has been divided from oldest to youngest into the Sedgefield, Lynnhaven, and Poquoson Members (Johnson and Berquist, 1989, p. 16).

The Sedgefield Member of the Tabb Formation rises to about 6 to 8 m above sea level in the southern watersheds. It forms Oceana Ridge in Virginia Beach, the southernmost tip of which marks the northeastern juncture of the southern watersheds. The Sedgefield also forms much of the higher ground west of Hickory Scarp in Chesapeake, Va., marking the northwestern boundary of the southern watersheds north of the Albemarle and Chesapeake Canal and the high ground near the western boundary south of the Canal. The Sedgefield Member was deposited in a shallow sea about 70,000 years ago (Mixon and others, 1989, sheet 1, description of map units).

The Sedgefield Member is a pebbly to bouldery, clayey sand and fine to medium shelly sand grading upward to sandy and clayey silt. Paleochannel fill up to 15 m thick composes the bottom of the Sedgefield Member found beneath some of the major tidal rivers of southeastern Virginia. This fill is a fine to coarse, cross-bedded sand and clayey silty peat, interbedded with tree stumps and wood fragments of ancient forests. The fill has been identified at the base of the lower member of the Great Bridge Formation of Oaks and Coch (1973, p. 67), which correlates to the base of the Sedgefield Member (Peebles and others, 1984, p. 14). One such paleochannel lies beneath the North Landing River in the southern watersheds. The bottom of the broad paleochannel is 18 to 21 m below sea level (Oaks and Coch, 1973, fig. 13, p. 50). Broad tidal wetlands along the North Landing River identified as soft mud on the map of surficial geology probably are a geomorphic expression of the ancient paleochannel.

The Lynnhaven Member of the Tabb Formation forms much of the low, flat, poorly drained ground of Virginia Beach and the southern watersheds. The Lynnhaven forms the surficial deposits of the North Landing River watershed generally less than 6 m above sea level. It stretches from the west side of Pungo Ridge to Hickory Scarp and from Lynnhaven Bay beyond the northern boundary of the southern watersheds to the southern city limits along the North Carolina border. It is a gray, pebbly and cobbly, fine to coarse sand, grading upward into clayey and silty fine sand and sandy silt. Channel fill and abundant plant material are found at the base of the unit in some places.

The Poquoson Member of the Tabb Formation forms the east side of Pungo Ridge just west of the Back Bay of Virginia Beach from sea level to about

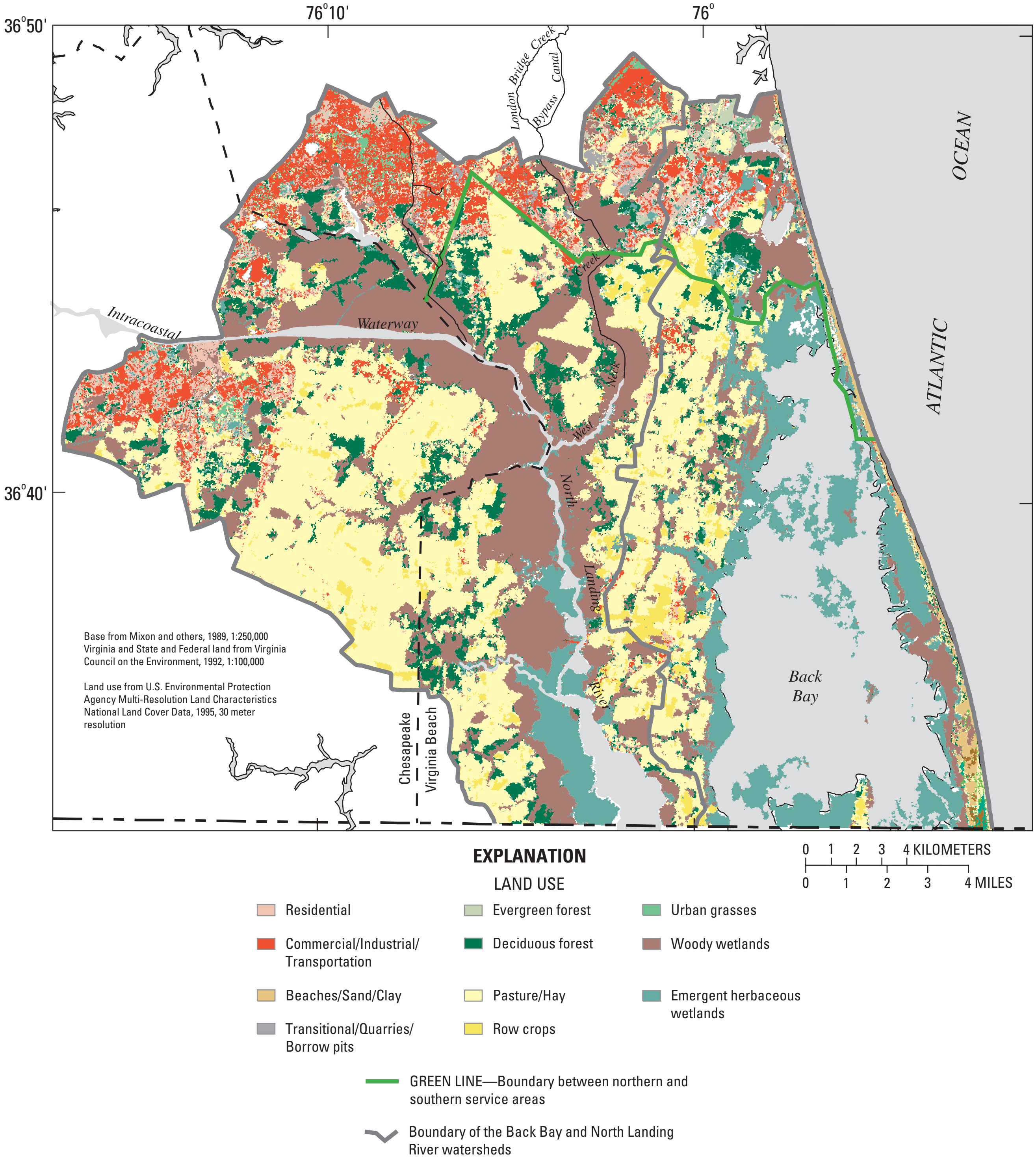


Figure 2. Land use in the southern watersheds of Virginia Beach, Virginia.3.3 m above sea level (Mixon and others, 1989, sheet 1).

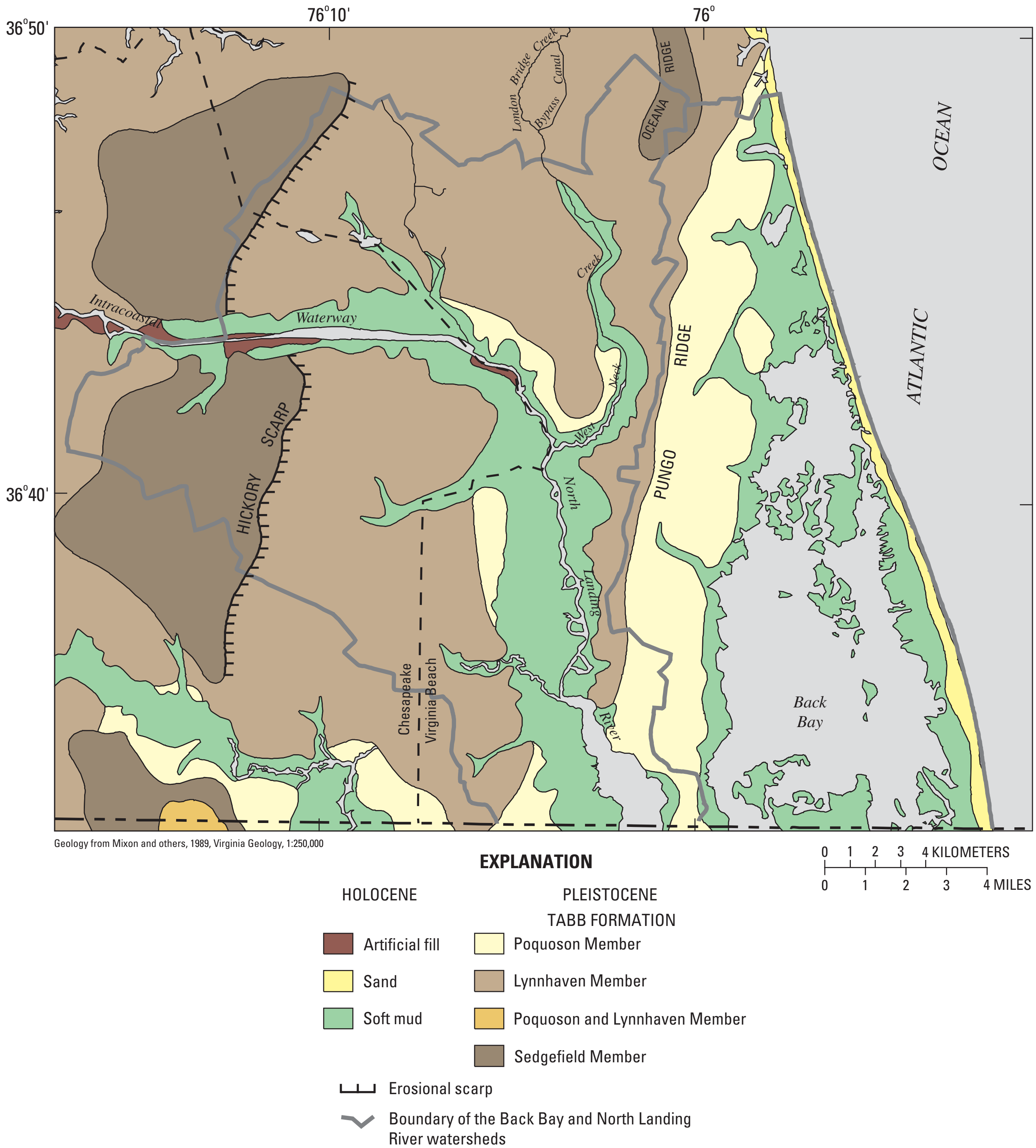


Figure 3. Surficial geology of the southern watersheds of Virginia Beach, Virginia.

It is a gray, medium to coarse, pebbly sand grading upward into a clayey, fine sand and silt. Some of the sand deposits of Pungo Ridge were formed as a coastal barrier and are a part of the Poquoson Member.

Approach

The revised conceptual hydrogeologic framework of the shallow aquifer system was based primarily on continuous cores and downhole geophysical logs from 7 sites, each approximately 60 m deep (Smith and Harlow, 2002, p. 8 and 9). That framework was extended in this study to other sites in and around the southern watersheds using lithologic descriptions and geophysical logs collected by previous investigators and filed in local, State, and Federal databases.

The basic geometry of the shallow aquifer system was contoured by linear variogram Kriging using Surfer®7 from Golden Software, Inc. Concentrations of chloride collected during this investigation and from previous studies also were contoured by linear Kriging using Surfer7 to map the general distribution of chloride concentrations and to infer freshwater to saline water gradients in the hydrogeologic units of the shallow aquifer system.

The land-surface altitudes of the southern watersheds of Virginia Beach likewise were contoured using data from USGS digital elevation models; the contoured surfaces then were imported into Visual MODFLOW®, Waterloo Hydrogeologic, Inc., to represent the basic framework of the shallow aquifer system and the geometry of the ground-water-flow and solute-transport model. A regionally continuous marine deposit of generally low permeability was contoured to mark the bottom of the shallow aquifer system and of the model. Three conceptual hydrogeologic units that constitute the shallow aquifer system were divided further into seven layers to represent the most common local configuration of the aquifers and confining units of the southern watersheds.

Average water levels from 38 wells and the chloride measurements from 123 wells were imported into Visual MODFLOW to provide calibration points. The parameter estimator WinPEST® as incorporated into Visual MODFLOW was used with the water-level data to adjust the hydraulic conductivities of the units. (Windows is a trademark of Microsoft Corporation. PEST is a trademark of Watermark Numerical Computing.)

Limits to the horizontal and vertical hydraulic conductivities for WinPEST were determined from the data reported in previous studies in and around Virginia Beach. For the calibration, the ground-water-flow model was assumed to be in steady state with average annual water levels.

Initially, saline water was assigned throughout the solute-transport model. Freshwater recharge was applied steadily to the simulated land surface of the model for about 35,000 years, until a new steady state with measured concentrations of chlorides was approximated. The calibrated ground-water-flow and solute-transport model then was used to simulate drawdowns around hypothetical well fields and open-pit mines and the movement of chloride concentrations toward a hypothetical well field.

Previous Studies

Geraghty and Miller (1978, p. 11) defined a leaky aquifer system beneath Virginia Beach composed of the “Water-Table Aquifer (mostly Columbia Group)” and the confined “Yorktown Aquifer (upper part of the Yorktown Formation),” as well as units below the shallow aquifer system that were presumed to contain “brackish to salty water.” Based on geology and a controlled test of the “Yorktown Aquifer” at the Pembroke well field in Virginia Beach, Geraghty and Miller (1979, p. 5 and 35) reported the potential for upconing of “brackish water known to be present at depths of 100 to 200 ft below land surface” (fig. 1).

Betz-Converse-Murdoch, Inc. (1981, p. II-1), conducted an investigation for fresh ground water in Virginia Beach, particularly in the southern watersheds of the city. Dewatering of large sand pits indicated possible supplies of freshwater from the water-table aquifer (p. IV-6). However, large productive well fields from the “upper Yorktown aquifer” were precluded over much of the city by the limited extent of permeable sediments (p. IV-7). Some southern areas of the city possibly could supply ground-water supplies, if treated to remove iron and manganese (p. II-1 and II-2), but problems with finding enough ground water to support the city’s needs were limited primarily because of the potential for upconing or intrusion of “salt water” (p. IV-7).

Geotrans Inc. (1981, p. 12 and 13) analyzed aquifer tests at four sites in the southern watersheds using solute-transport simulations. Fair to poor potential for water supplies were reported based on water-level declines. All of the sites were at risk of "brackish water" upconing (p. ii and p. 12). Increases in chloride concentrations observed in some "deeper" wells during the aquifer tests were not caused, however, by upconing, but were possibly contributed by clay deposits within the aquifer.

Siudyla and others (1981, p. 18-27) defined a "water-table aquifer" and three generally continuous sand units in the "Yorktown aquifer" of southeastern Virginia, including Virginia Beach, on the basis of geophysical and geologic logs, including some research wells. The thickness, permeability, and coarseness of the units, however, varied considerably from one point to another. They also noted that well fields in the Yorktown aquifer could cause "lateral salt water encroachment, and upconing of brackish water from underlying strata" (p. 84 and 85).

Leahy (1986, p. 44) summarized the potential for desalinating brackish water and seawater for southeastern Virginia and Virginia Beach. He compared the long-term price of finished water from desalination to that of building a pipeline to Lake Gaston (p. 43).

Meng and Harsh (1988, p. C52) defined the regional aquifer system of the Coastal Plain of Virginia including Virginia Beach. They recognized the unconfined Columbia aquifer, the Yorktown confining unit, and the confined Yorktown-Eastover aquifer, as well as deeper units in the Coastal Plain.

Hamilton and Larson (1988, p. 4) analyzed the aquifer systems of southeastern Virginia by use of a three-dimensional, digital ground-water-flow model. They reported vertical recharge to the Yorktown-Eastover aquifer beneath the higher ground of Virginia Beach, but upward discharge from the aquifer beneath the low areas, back bays, and off shore (fig. 74, p. 108). They also showed some areas in and near Virginia Beach where ground-water discharge to the water-table aquifer was reduced because of local pumping (fig. 66, p. 100) and noted that saline water probably began infiltrating the shallow confined aquifers offshore beneath the Atlantic Ocean, Chesapeake Bay, and the James River estuary in the 1950's (p. 169).

Harsh and Laczniak (1990, p. F4) described the hydrogeologic units of the Coastal Plain of Virginia and analyzed ground-water flow in the region and adjacent parts of North Carolina by use of a three-dimensional, digital ground-water-flow model. They showed downward flow of ground water into the Yorktown-Eastover aquifer in the northern parts of Virginia Beach and upward flow from the Yorktown-Eastover in most of the southern parts prior to pumping (fig. 41, p. F50). Pumping simulated for 1980 indicated downward flow into the Yorktown Eastover aquifer that had been upward prior to pumping in a small area of the southwestern part of Virginia Beach (fig. 63, p. F71).

As part of the USGS National Water-Quality Assessment (NAWQA) Program, Spruill and others (1998, p. 24) analyzed the ground-water chemistry of the shallow aquifers in the southern watersheds of Virginia Beach. They indicated that concentrations of dissolved solids under the urban area of the southern watersheds of Virginia Beach were ranked between the median and the 75th percentile of the national average of the 20 aquifer systems sampled (p. 24-25).

After the discovery of the Chesapeake Bay impact crater at the mouth of the Chesapeake Bay, Powars (2000, p. 4) refined the geologic framework of southeastern Virginia. He indicated that the Yorktown, Eastover, and St. Marys Formations are continuous across the region, but that the Chowan River Formation is not extensive in Virginia (p. 37). Powars also correlated the geologic units to the hydrogeology south of the James River in three core holes, which showed the need for further refinements of the hydrogeologic framework. He indicated that the Columbia aquifer of previous investigators is in the Tabb and Yorktown Formations in the core holes near Virginia Beach, and that the Calvert confining unit of Hamilton and Larson (1988) predominantly is within the St. Marys Formation (Powars, 2000, p. 42).

Smith and Harlow (2002, p. 23) refined the conceptual framework of the shallow aquifer system primarily on the basis of seven continuous cores and geophysical logs. They confirmed that the unconfined Columbia aquifer, the Yorktown confining unit, and the confined Yorktown-Eastover aquifer compose the shallow aquifer system at Virginia Beach and that the shallow system is separated from deeper units by the St. Marys confining unit. They also noted that some sand deposits in the Yorktown confining unit supply "small to moderate amounts of freshwater in some areas" but that on a regional scale the confining unit is leaky (Smith and Harlow, 2002, p. 26). They reported deposits of biofragmental sand in the Yorktown-Eastover aquifer at some sites and noted that the extent and hydraulic properties of the biofragmental sand needed further study (Smith and Harlow, 2002, p. 30).

Acknowledgments

The author thanks the citizens of Virginia Beach and the Virginia Beach Department of Public Utilities, Water Resources Division, for their cooperation and support of the shallow ground-water study. Thomas M. Leahy, III, and Rebecca L. Mitchel of the Department of Public Works particularly were helpful.

Various USGS employees contributed to this study and report. Former project chiefs Alan R. Brockman and Henry M. Johnson, IV, organized much of the background information, previous data, and resources for the initial phases of the project. Previous project chief George E. Harlow, Jr., organized and managed the coring, well installation, and water sampling and was the principal hydrologist of the revised hydrogeologic framework. USGS employees Roger M. Moberg and Karl M. Dydak collected water-level and water-quality data and maintained the network wells. R. Brent Banks, III, coded and entered information into USGS databases and prepared the illustrations of this report. Ted B. Samsel of the USGS also is acknowledged for preparing base maps, illustrations, and for his assistance with geographic information systems. Martha L. Erwin of the USGS edited this report. Colleagues Mark D. Kozar and William Fleck of the USGS provided technical review comments.

SHALLOW AQUIFER SYSTEM OF THE SOUTHERN WATERSHEDS

The revised conceptual hydrogeologic framework of the shallow aquifer system from Smith and Harlow (2002, p. 23) was extended in this study to other sites in and around the southern watersheds on the basis of lithologic descriptions and geophysical logs collected by previous investigators and filed in local, State, and Federal databases.

Hydrogeologic Framework

The shallow aquifer system is composed of the Columbia aquifer, the Yorktown confining unit, and the Yorktown-Eastover aquifer (table 1). The St. Marys confining unit separates the shallow aquifer system from deeper units.

Columbia Aquifer

The Columbia aquifer of the Virginia Coastal Plain is defined as the predominantly sandy surficial deposits above the Yorktown confining unit (Meng and Harsh, 1988, p. C52). The Columbia sediments are, for the most part, of the Holocene and Pleistocene ages but also can include sandy sediments of Pliocene age above the Yorktown confining unit.

The Holocene sediments have been deposited in the estuaries, swamps, marshes, rivers, and on the riverbanks, stream banks, dunes, and shorelines since the end of the last major glacial advance about 11,500 years ago. Before then, Pleistocene sediments were deposited in similar coastal settings, primarily during marine transgressions as the continental ice sheets melted and during high stands of the ancient seas of the Late Pleistocene (Peebles and others, 1984, p. 20). Pleistocene deposits of the Tabb Formation form much of the Columbia aquifer, as well as much of the landscape of the southern watersheds of Virginia Beach.

The Columbia aquifer is unconfined generally, and the top of the aquifer is the water table. In a humid climate, the water table closely follows the contours of the land surface; therefore, altitudes of the land surface can be used to approximate the top of the aquifer. For the top of the study area, digital elevation models of 7.5-minute quadrangles were merged from the National Elevation Database of the USGS in 2002 (fig. 4). The merged data were contoured by linear Kriging using Surfer7 and imported as the top of the ground-water-flow model of the southern watersheds.

Although the Columbia aquifer is unconfined generally, deposits of silt, clay, and peat within the aquifer can cause confined or semi-confined conditions, locally inhibiting infiltration of freshwater. In other areas, the clayey fine sand and silt that form semi-confining beds in the Columbia are absent, and the aquifer is composed of dune sand nearly 24 m thick (Smith and Harlow, 2002, p. 26). The Columbia aquifer reaches a maximum thickness where the sand dunes are large, along the shores of the Atlantic Ocean, and in the older sand banks such as Pungo Ridge.

The Columbia aquifer is recharged by local precipitation. Dunes and sand ridges allow precipitation to infiltrate readily and ground water percolates downward to the water table. The water table tends to mound beneath the dunes and the mound forces freshwater to

Table 1. Geologic age, geologic units, and hydrogeologic units of the shallow aquifer system at Virginia Beach, Virginia

<table>
<tr><th>Series</th><th>Geologic unit[1]</th><th colspan="2">Hydrogeologic unit</th></tr>
<tr><td>Holocene</td><td>Post-glacial deposits</td><td rowspan="2">Columbia aquifer</td><td rowspan="5">Shallow Aquifer System</td></tr>
<tr><td>Pleistocene</td><td>Tabb Formation</td></tr>
<tr><td rowspan="2">Pliocene</td><td>Chowan River Formation</td><td>Yorktown confining unit</td></tr>
<tr><td>Yorktown Formation</td><td rowspan="2">Yorktown-Eastover aquifer</td></tr>
<tr><td rowspan="2">Miocene</td><td>Eastover Formation</td></tr>
<tr><td>St. Marys Formation</td><td colspan="2">St. Marys confining unit</td></tr>
</table>

[1]After Powars (2000, p. 45-52).

flow downward and outward toward the nearest tidal stream or shore, where the freshwater flows into and mixes with saline water. Betz-Converse-Murdoch, Inc. (1981, p. IV-6 and IV-7), noted that "large quantities of water have been and are being pumped from many of the sand pits of Virginia Beach, which indicates that the 'water-table' aquifer potentially could yield significant quantities of water . . .". However, the water-table aquifer is vulnerable to contamination from various land uses and generally is used for irrigation, lawn watering, or for heat pumps. The Columbia is used for domestic drinking water where no other sources of freshwater are available. Concentrations of dissolved chloride, iron, and manganese greater than the Secondary Drinking Water Regulations of the U.S. Environmental Protection Agency (USEPA) (2002, p. 10) have been reported in some areas of Virginia Beach in previous reports.

Yorktown Confining Unit

The Yorktown confining unit is defined as a series of coalescing clay layers at or near the top of the Yorktown Formation (Meng and Harsh, 1988, p. C51). The Yorktown confining unit is not a single continuous layer but a series of very fine, sandy to silty clay units of various colors at the top of the Yorktown Formation (p. C51). The Yorktown Formation was deposited during a succession of marine advances in the Early and Late Pliocene Epoch (Johnson and Berquist, 1989, p. 11). The top of the Yorktown Formation in southeastern Virginia was mapped by Oaks and Coch (1973,

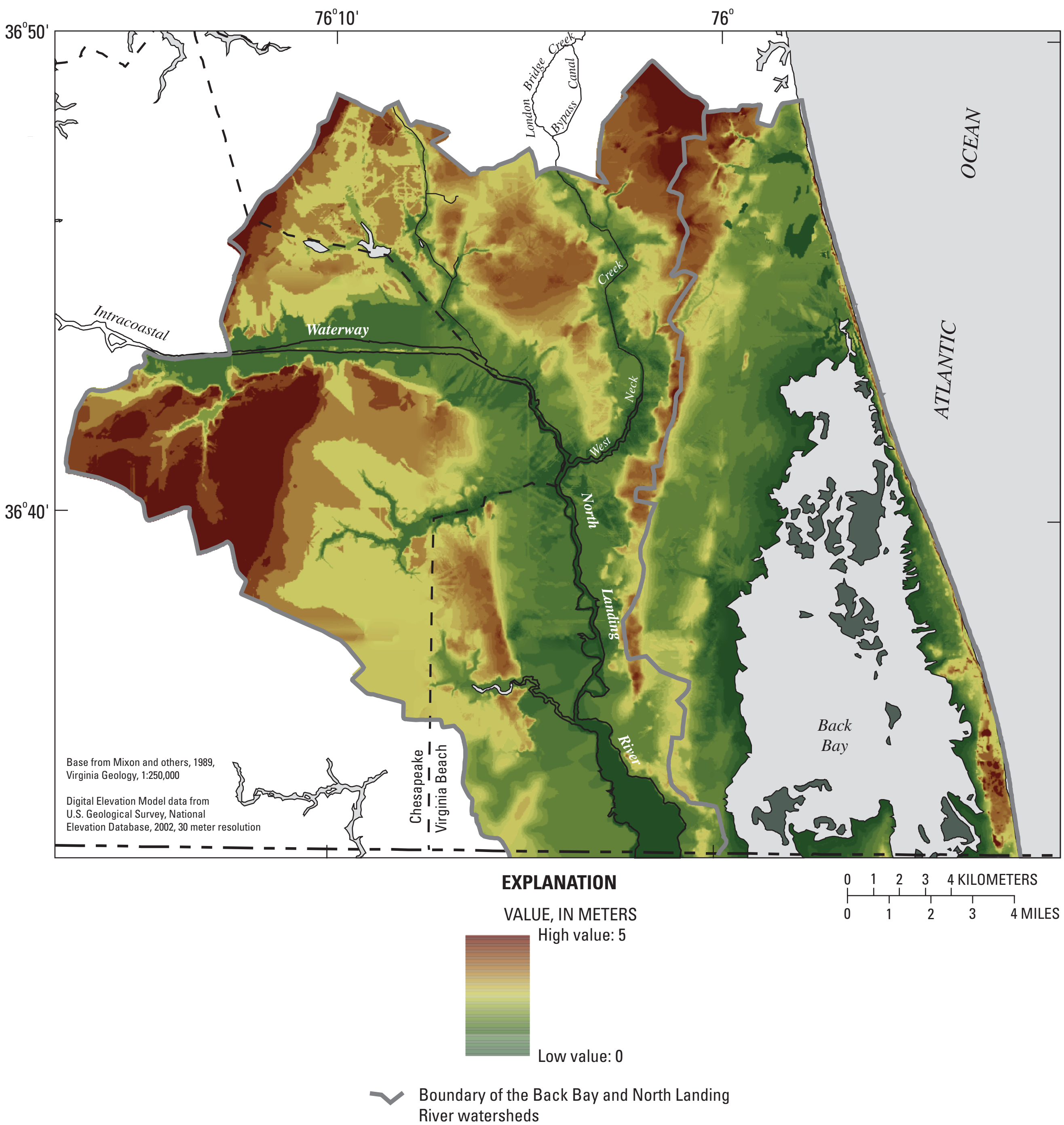


Figure 4. Land-surface altitudes of the southern watersheds of Virginia Beach, Virginia.

fig. 13, p. 50), who described a fossiliferous clay facies with minor amounts of sand and coquina at the top of the Yorktown Formation south and east of Portsmouth and Norfolk, Va. Ancient streams and estuaries cut valleys into the top of the Yorktown Formation and subsequently filled the channels with sediments, forming paleochannels upon the surface, one of which was mapped below the North Landing River.

The uppermost competent clays that form the Yorktown confining unit were deposited on a shallow marine shelf in broad lagoons and bays (Meng and Harsh, 1988, p. C52). Locally, the fine-grained sediments of the Pleistocene Tabb Formation and possibly the Pliocene Chowan River Formation (Powars, 2000, fig. 13, p. 42) may lie upon and in effect be a part of the Yorktown confining unit (table 3). The Chowan River Formation is difficult to distinguish from the Yorktown; the Chowan River Formation is an interbedded, silty fine sand, clayey silt, and bioclastic sand of limited extent in southeastern Virginia (Powars, 2000, p. 37).

The Yorktown confining unit varies in thickness and in composition (Smith and Harlow, 2002, p. 26). The top of the Yorktown confining unit ranges from about 7 to 18 m below sea level in and near the southern watersheds of Virginia Beach (fig. 5). Some of the lower altitudes of the top of the Yorktown confining unit could indicate paleochannels carved into the surface. The altitudes were plotted and contoured by linear variogram Kriging.

On a regional scale, the Yorktown confining unit is leaky. Some sand layers within the confining unit that had been mapped previously as the upper and middle Yorktown-Eastover aquifers are considered, in this report, to be local discontinuous sand units within the more regional confining unit. These discontinuous sand deposits are capable of producing small to moderate amounts of freshwater in some areas. The supply of freshwater in the discontinuous sands of the Yorktown confining unit is limited, however, by concentrations of dissolved iron, manganese, and chloride that are greater than the Secondary Drinking Water Regulations of the USEPA (2002, p. 10). The potential for upconing or intrusion of brackish or saline water into the sand units of the Yorktown also is a concern in some areas.

Yorktown-Eastover Aquifer

The Yorktown-Eastover aquifer is defined as the predominantly sandy deposits of the Yorktown Formation and the upper part of the Eastover Formation above the confining clays of the St. Marys Formation (Meng and Harsh, 1988, p. C50). The Yorktown-Eastover aquifer previously was called the Yorktown aquifer by some investigators in Virginia (Geraghty & Miller, Inc., 1978, p. 12) and in North Carolina (Meng and Harsh, 1988, pl. 1). The Yorktown-Eastover aquifer as defined in this report is equivalent generally to the lower Yorktown aquifer of some previous investigators (Siudyla and others, 1981, p. 27).

The Yorktown Formation is a bluish-gray, greenish- and dark greenish-gray, very fine to coarse sand, in part glauconitic and phosphatic, commonly very shelly and interbedded with sandy and silty clay (Powars, 2000, p. 37). The Yorktown also includes abundant microfauna and cross-bedded, biofragmental lenticular sand bodies, which locally may be overlain by and difficult to distinguish from the Chowan River Formation. The Yorktown Formation was deposited in the Pliocene.

The Eastover Formation is dark gray, bluish-to greenish-gray, muddy fine sand interbedded with finer and coarser grained sand (Powars, 2000, p. 37). It can include shells, shell hash, and indurated beds. Locally, it may be glauconitic and micaceous. The Eastover was deposited in restricted to open shallow seas of the Miocene (Powars, 2000, p. 37).

In the southern watersheds of Virginia Beach, the top of the Yorktown-Eastover aquifer varies from about 23 to about 37 m below sea level (fig. 6). The top surface undulates and generally is higher to the west and along Pungo Ridge than elsewhere.

On a regional scale, the Yorktown-Eastover aquifer generally thickens towards the east. At Virginia Beach, it generally ranges from about 30 to 60 m thick, but attains a maximum known thickness at the shoreline of Virginia Beach of about 73 m, according to Meng and Harsh (1988, p. C50), to 85 m, according to Hamilton and Larson (1988, p. 33).

The Yorktown-Eastover aquifer generally is confined. Freshwater is limited to the upper part of the Yorktown-Eastover aquifer, and "upconing [of saline water] as a result of excessive withdrawal rates from wells has occurred at several locations in the city" (Betz-Converse-Murdoch, Inc., 1981, p. IV-7).

St. Marys Confining Unit

The top of the St. Marys confining unit, a regionally continuous deposit of generally low permeability, marks the bottom of the shallow aquifer system (Powars, 2000, p. 37). The St. Marys Formation is

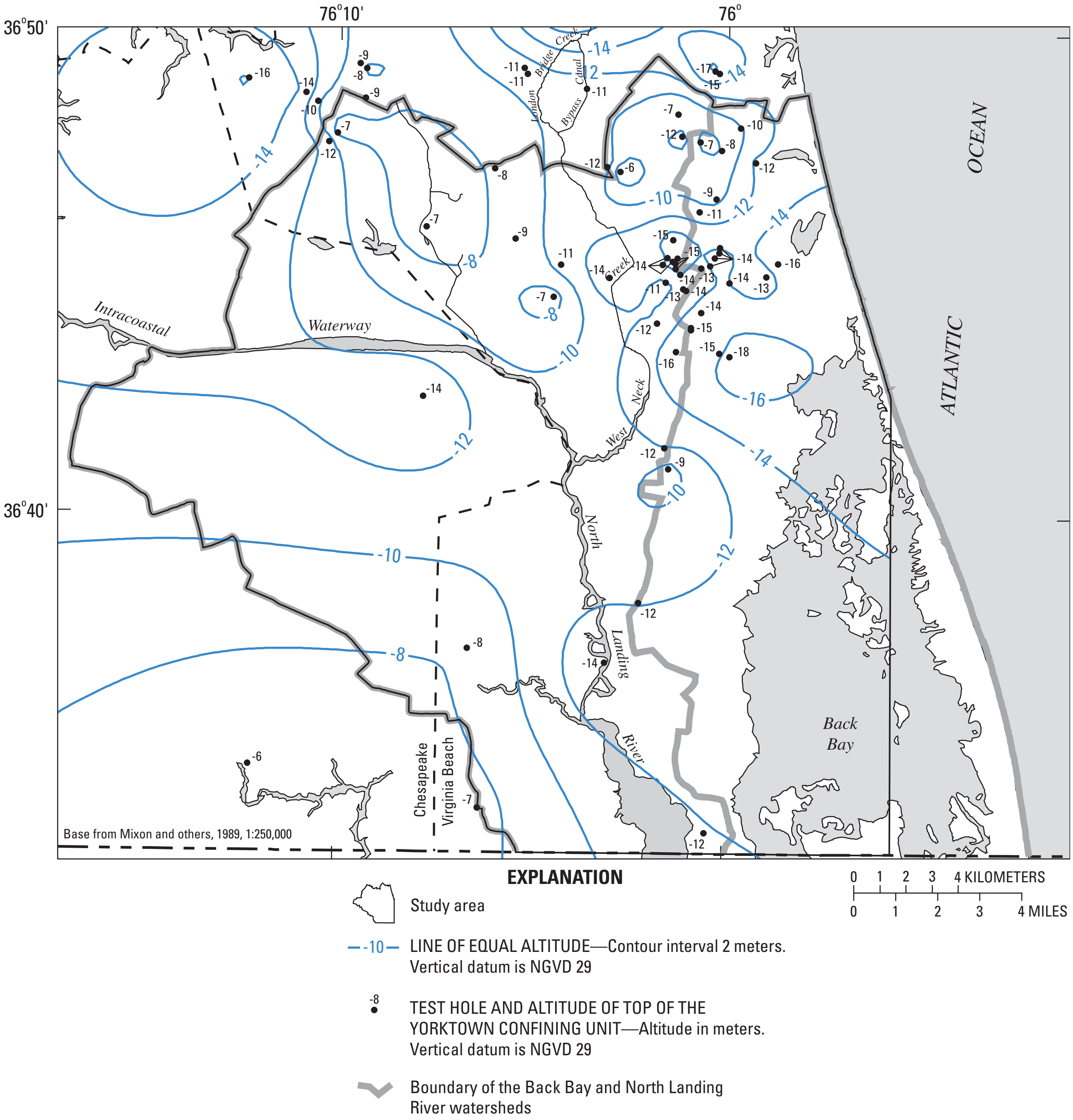


Figure 5. Altitudes of the top of the Yorktown confining unit of the southern watersheds of Virginia Beach, Virginia.

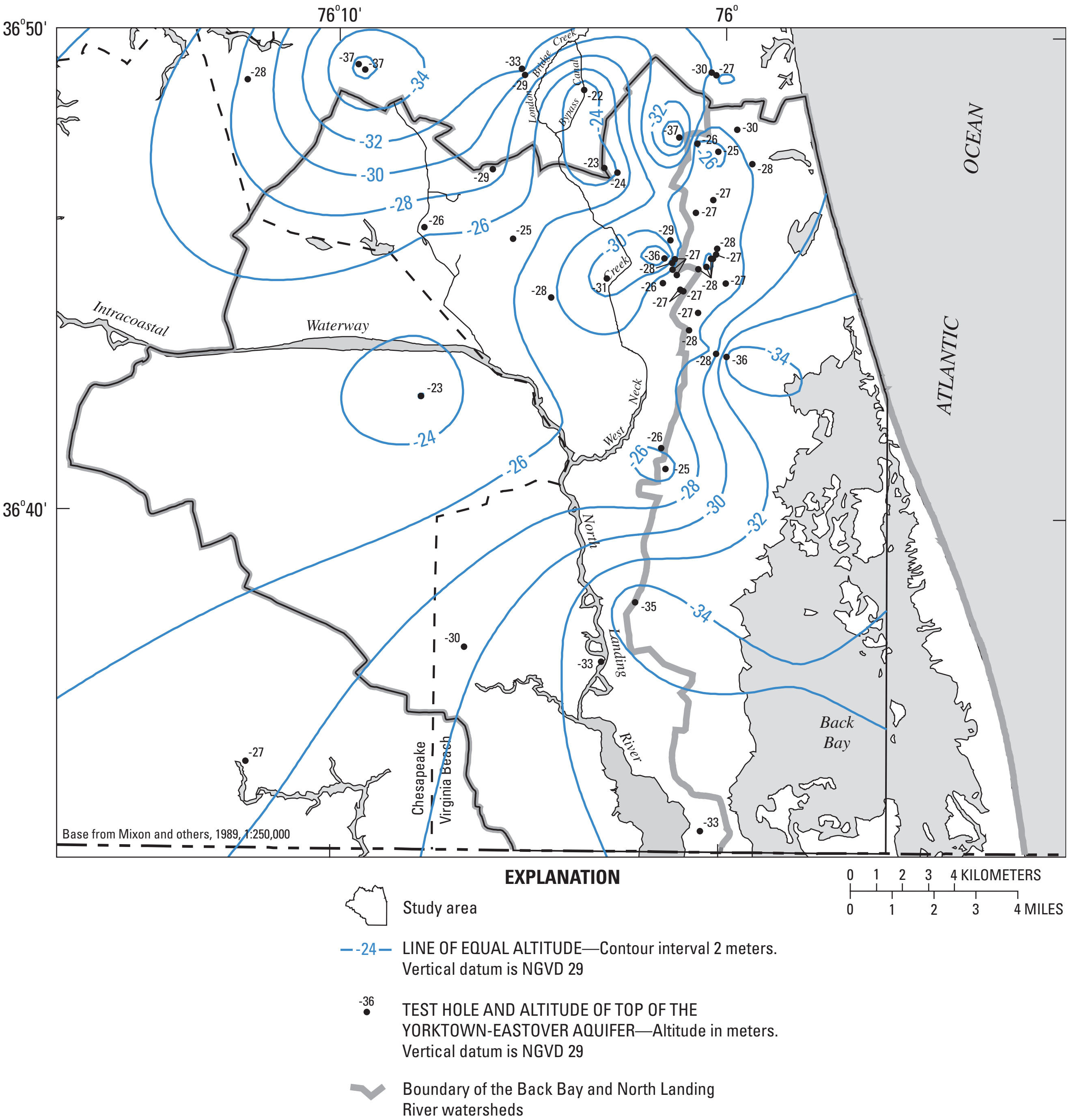


Figure 6. Altitudes of the top of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

composed of mostly muddy, very fine sand and sandy clay and silt deposits of marine origin (Powars, 2000, p. 37). The St. Marys confining unit, in places, also includes clays of the overlying Eastover Formation (Meng and Harsh, 1988, p. C50). Within the southern watersheds of Virginia Beach, the top of the St. Marys confining unit, which is the bottom of the shallow aquifer system, varies from about 80 to 110 m below sea level.

Hydraulic Properties

The sediments that compose the shallow aquifer system were deposited in shifting currents of an ever-changing coastal environment. The extent of and the hydraulic properties of such poorly sorted (heterogeneous) units can vary considerably over relatively short distances. Previous investigators have estimated the hydraulic properties of the aquifers and confining units of the shallow aquifer system in southeastern Virginia by various methods. However, the sampled volume of the aquifer or confining unit tested depends on the method. Sample volumes can range from cubic centimeters analyzed by sieves and permeameters, to cubic meters of single-well (slug) tests or specific-capacity tests, to the field scales of aquifer tests with multiple wells, to ground-water-flow models that usually represent hydraulic properties from the field scale to the watershed or even regional scales. For this study, the hydraulic conductivities estimated by previous investigators were used to set minimum, initial, and maximum limits for a parameter estimator (WinPEST) that was used to calibrate the ground-water-flow model.

Horizontal Hydraulic Conductivities

Horizontal hydraulic conductivities of the Columbia aquifer from previous studies in southeastern Virginia ranged from 1 to 23 m/d (table 2). The average hydraulic conductivity probably was in the range from 6 to 9 m/d.

Horizontal hydraulic conductivities of the Yorktown confining unit varied, depending on the material tested. In the previous studies, clay and silt units ranged from 0.0003 to 6 m/d. Sand units in the Yorktown ranged from 0.4 to 16 m/d with an average probably from 6 to 9 m/d.

Horizontal hydraulic conductivities of the Yorktown-Eastover aquifer ranged from 0.4 to 7.7 m/d in previous studies. The average hydraulic conductivity probably was about 4 m/d.

Vertical Hydraulic Conductivities

Vertical hydraulic conductivities of the Columbia aquifer in southeastern Virginia ranged from 0.000052 to 0.052 m/d (table 3) and averaged about 0.02 m/d. The maximum and minimum of the range came from five permeameter tests of sediment cores with a median of 0.02 m/d. A vertical conductivity of 0.02 m/d also was used to calibrate a ground-water-flow model of the same area where the cores were taken (Smith, 2001, p. 9).

An aquifer test encompassing confining beds in the Columbia aquifer, 62B 9 (fig. 8), within the southern watersheds of Virginia Beach had a narrower range from 0.0030 m/d in the lower confining bed to 0.015 m/d in the upper confining bed (Geotrans, Inc., 1981, p. 16) and would have an average of 0.0090 m/d if combined.

Vertical hydraulic conductivities of the Yorktown confining unit ranged from 0.000004 m/d to 0.002 m/d in previous studies and averaged 0.00058 m/d. The lowest value was from a laboratory analysis of a sediment core (Richardson, 1994a, p. 19) and the highest value was from a calibrated ground-water-flow model (Smith, 2001, p. 9). Results from calibrated flow models of southeastern Virginia, however, indicated lower vertical hydraulic conductivities of 0.00026 m/d (Hamilton and Larson 1988, p. 60; Harsh and Laczniak, 1990, p. F94). Values from two aquifer tests of the Yorktown confining beds in the southern watersheds of Virginia Beach, 63C 25 and 62C 25 (fig. 8), were in and near the middle range (Geotrans, Inc.,1981, p.16).

Vertical hydraulic conductivities of the Yorktown-Eastover aquifer ranged from 0.0000052 m/d to 0.15 m/d in previous studies and averaged 0.0014 m/d. The maximum and minimum of the range came from 23 permeameter tests of sediment cores. The median of the sediment cores was 0.0021 m/d (Smith, 2001, p. 9). A vertical conductivity of 0.002 m/d also was used to calibrate a ground-water-flow model of the area where the cores were taken (Smith, 2001, p. 9). The aquifer test encompassing confining beds in the Yorktown-Eastover aquifer, 62C 63 (fig. 8), in the southern watersheds of Virginia Beach had the same vertical hydraulic

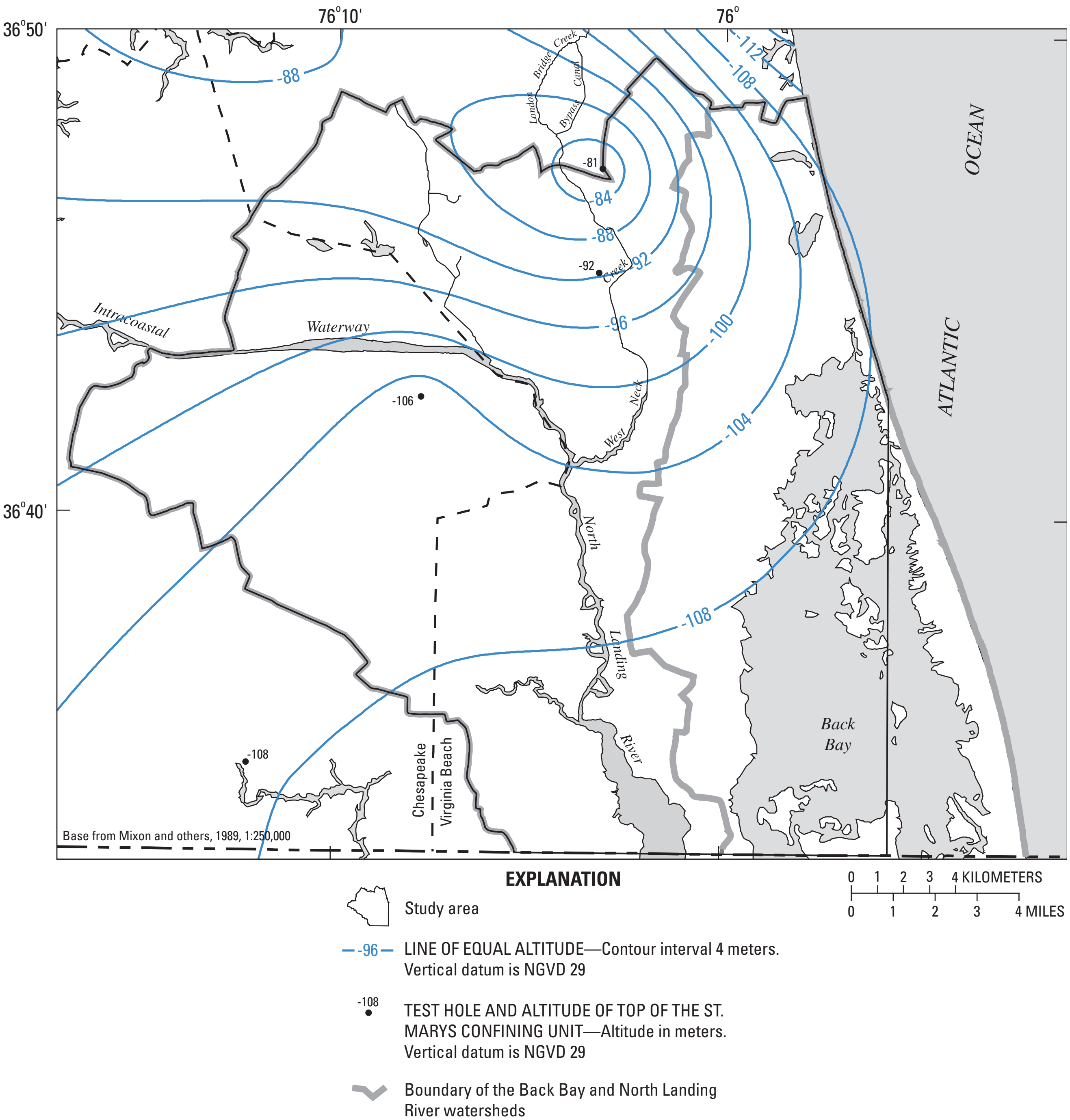


Figure 7. Altitudes of the top of the St. Marys confining unit of the southern watersheds of Virginia Beach, Virginia.

Table 2. Horizontal hydraulic conductivities of the shallow aquifer system in and near Virginia Beach, Virginia

[–, no data; U, Upper; P, Paleochannel; M, Middle; L, Lower]

Unit	Method											
	Median of specific-capacity test (meters per day)		Aquifer-test analyses (meters per day)				Calibrated ground-water-flow model (meters per day)					
Columbia aquifer	–	7.3	2 to 9	4.6	5.5 to 6.4	23	1	–	5.5	6	9	11
Yorktown confining unit	3.2 (U) 5.2 (M)	–	2.1 (U) 16 (M)	–	7.0 to 7.3 (M)	12 9 (Sand) 6 (Silt)	0.0003 (silt, clay)	0.4 and 16 (U) 1.3 (P) (M) 0.4 and 13 (M)	–	16 (M)	9 (U)	–
Yorktown-Eastover aquifer	2.7 (L)	7.7	–	6.1	–	5.5	1	0.4 and 2.6 (L)	4.5	–	–	–
Source citation	1	2	3	4	5	6	7	1	4, 8	3	5	9

1. Richardson (1994a, p. 19 and 50).
2. Laczniak and Meng (1988, p. 57).
3. Malcolm Pirnie (1997a, p. 1-4, 1-6,1-8, 2-4, and 2-5).
4. Harsh and Laczniak (1990, p. F17 and F94).
5. Malcolm Pirnie (1997b, p. 1-4, 1-6, 2-4, and 2-6).
6. Geotrans, Inc. (1981, p. 15 and 16).
7. Smith (2001, p. 8 and 9).
8. Hamilton and Larson (1988, p. 49).
9. Robinson and Reay (2002, p. 126).

Table 3. Vertical hydraulic conductivities of shallow aquifer system in and near Virginia Beach, Virginia.

[max., maximum; med., median; min., minimum; U, upper; L, lower; –, no data; A, average; figures in parentheses are the number of samples or tests; ?, number of samples unknown.]

Unit	Method							
	Aquifer tests of confining beds (meter per day)	Laboratory analyses of sediment cores (meter per day)				Calibrated ground-water flow model (meter per day)		
Columbia aquifer	William Oliver 62B 9 max. 0.150 (U) med. 0.0090 (2) min. 0.0030 (L)	–	–	–	max. 0.052 med. 0.021 (5) min. 0.000052	0.02	–	–
Yorktown confining unit	Redwing Park 63C 25 max. 0.00046 (U) med. 0.00046 (2) min. 0.00046 (L) Cameron Munden 62C 25 max. 0.0015 (U) med. 0.00083 (2) min. 0.00015 (L)	0.00000424 (1)	max. 0.0012 med. 0.00069 (2) min. 0.00018	0.000263(A?)	max. 0.0023 med. 0.000037 (6) min. 0.0000040	0.002	0.000263	0.000263
Yorktown-Eastover aquifer	Oceana II 62C 63 max. 0.000055 (U)\ med. 0.000055 (2) min. 0.000055 (L)	–	–	–	max. 0.15 med. 0.0021 (23) min. 0.0000052	0.002	–	–
St. Marys confining unit	–	max. 0.00000497 med. 0.00000442 (2) min. 0.00000387	max. 0.0000061 med. 0.0000035 (2) min. 0.00000085	0.000126(A?)	–	–	0.000126	0.000126
Source citation	1	2	3	4	5	5	6	7

[1] Geotrans, Inc. (1981a, p. 16). See figure 8 for site locations.
[2] Richardson (1994a, p. 19).
[3] Harsh and Laczniak (1990, F92).
[4] Laczniak and Meng (1988, p. 68 and 70).
[5] Smith (2001, p. 9).
[6] Hamilton and Larson (1985, p. 60).
[7] Harsh and Laczniak (1990, p. F94).

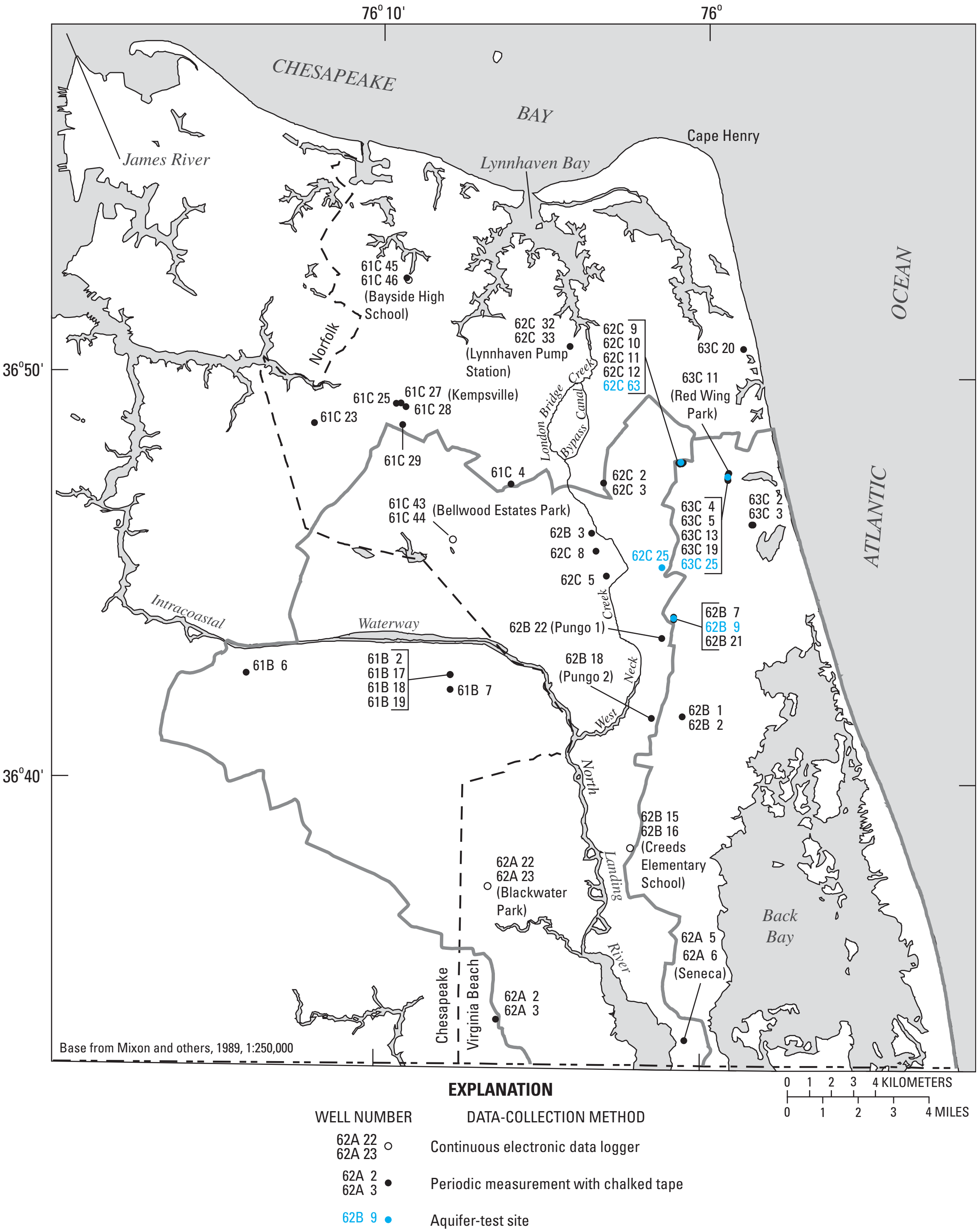


Figure 8. Location of monitoring wells and selected aquifer-test wells in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia.

conductivities above and below the aquifer, 0.000055 m/d (Geotrans, Inc., 1981, p. 16).

Vertical hydraulic conductivities of the St. Marys confining unit in southeastern Virginia generally were much less than those of the shallow aquifer system (table 3). The vertical hydraulic conductivities of the St. Marys ranged from 0.00000085 m/d to 0.00013 m/d.

Ground-Water Recharge

Ground-water recharge is that part of precipitation that reaches the water table. Recharge rates from previous studies of the shallow aquifer system in southeastern Virginia were used to set reasonable limits for calibrating the ground-water-flow model of this study.

Previous studies have estimated ground-water-recharge rates of the shallow aquifer system by hydrologic budget analyses, streamflow-separation techniques, hydrogeologic unit area regression, and by calibration of ground-water-flow models. Those recharge rates ranged from 10 to 30 cm/yr (table 4). The average and median of the previous studies is about 20 cm/yr.

The lowest values of 10 to 13 cm/yr were estimated by hydrologic budget analyses for a site in the southern watersheds of Virginia Beach (Malcolm Pirnie, 1997a, p. 2-7). An average recharge rate of 19.1 cm/yr was estimated from 1970 to 1990 at the stream gage nearest the study area using streamflow-separation techniques (Richardson, 1994b, p. 5, fig. 3 and p. 6, table 1). The stream gages in the Coastal Plain of Virginia, however, are above the tidal zone and probably estimate ground-water-recharge rates higher than those of Virginia Beach. Extensive wetlands and clayey soils in much of Virginia Beach inhibit freshwater recharge. A recharge rate of 20 cm/yr was estimated for an area that included the southern watersheds of Virginia Beach by hydrogeologic-area regression, assuming that ground-water discharge equals ground-water recharge (Richardson, 1994b, p. 12, fig. 5). This rate, however, was based on the same long-term hydrographs as that used for the streamflow-separation method and also could have over-estimated the ground-water recharge for Virginia Beach. Recharge rates of 15 to 30 cm/yr were used to calibrate previous ground-water-flow models of southeastern Virginia (table 4). The recharge rates ranged from local site applications of flow models within the southern watersheds of Virginia Beach (Malcolm Pirnie, 1977a, p. 2-7; Malcolm Pirnie 1977b, p. 2-6) to regional analyses of the Coastal Plain of southeastern Virginia (Hamilton and Larson, 1988, p. 61).

Evapotranspiration rates generally reach a maximum at the land surface (McDonald and Harbaugh, 1988, p. 10-5). For simulation of ground-water flow in this study, it was assumed that recharge would be zero where the water table was at land surface. Where the water table was below the land surface, the evapotranspiration rate would decrease from the land surface to a specified extinction depth, as depicted by McDonald and Harbaugh (1988, p. 10-3). Ground-water recharge, therefore, would increase when the water table was below land surface to an extinction depth below which recharge again would drop to zero.

A maximum recharge rate of 20 cm/yr was assumed initially for the ground-water-flow model of this study, equal to the average annual ground-water discharge estimated for southeastern Virginia and for

Table 4. Ground-water-recharge rates in and near the southern watersheds of Virginia Beach, Virginia.

Method	Recharge Estimate (centimeters per year)	Source
Hydrologic budget analysis	10 to 13	Malcolm Pirnie (1997a, Permit Part 14, p. 2-7).
Streamflow separation at gage nearest to study area (02043500)	19.1	After Richardson (1994, p. 5, fig. 3 and p. 6, table 1) assuming ground-water recharge equals discharge.
Hydrogeologic-unit area regression	20	After Richardson (1994, p. 12, fig. 5), assuming ground-water recharge equals discharge.
Calibrated ground-water-flow models	15	Malcolm Pirnie (1997b, Permit Part 14, p. 2-6).
	23	Smith (2001, p. 15).
	30	Hamilton and Larson (1988, p. 61).
	30	Malcolm Pirnie (1997a, Permit Part 14, p. 2-7).

the southern watersheds of Virginia Beach. This initial maximum recharge rate, however, produced simulated water levels much higher than measured. Model calibration and subsequent sensitivity tests indicated a better approximation of measured water levels if a maximum recharge rate of 10 to 15 cm/yr was assumed.

Ground-Water Levels

Average water levels from 38 wells were used to calibrate the ground-water-flow model for this study (table 5). Long-term records of selected wells show trends in water levels from 1984 to 2002 in the southern watersheds of Virginia Beach (fig. 9).

Most hydrographs of wells at Virginia Beach indicate periodic and seasonal fluctuations in water levels, but unchanging or steady states when viewed over several years. A steady state indicates that ground-water recharge is in balance with ground-water discharge. Such a steady state also is called a dynamic equilibrium. Wells 61C 27 in the Yorktown-Eastover and 62A 2 in the Yorktown confining unit indicate typical long-term, steady states (fig. 9). However, hydrographs of two other wells in the Yorktown-Eastover–62C 10 and 63C 4–show generally lower or declining water levels over the period of record. Such long-term declines typically are the result of ground-water withdrawals.

Continuous recorders installed in seven wells in April 2001 show seasonal changes in water levels at Virginia Beach (fig. 10). The continuous records indicate generally higher water levels in the spring, followed generally by months of decline through the summer. Such declines typically are caused by the emergence of leaves and high rates of evapotranspiration. Precipitation and pumping wells, mostly for irrigation, cause short-term fluctuations in the water levels that are superimposed on the longer cycles and contribute to or detract from the seasonal patterns, in kind.

Water levels in wells 61C 43 and 61C 44 at Bellwood Estates Park and 61C 46 at Bayside High School declined until the summer of 2001, reaching seasonal lows in July and early August. The declines generally were followed by gradual water-level recoveries that increased after the leaves fell in October. In 2002, similar seasonal patterns were repeated in those wells, but the fall recoveries began in late August and early September. The water levels at Bellwood Estates Park fluctuate through greater amplitudes than the other wells and the water levels have declined below sea level, indicating the possible effects of a pumping well.

Water levels in wells 62A 22 and 62A 23 at Blackwater Park and 62B 15 and 62B 16 at Creeds Elementary School declined through the summer of 2001, but continued to decline through the fall and winter of 2001 until January 2002. Water levels in those wells recovered until April and May 2002 when the normal seasonal declines began again.

Table 5. Construction and water-level data for selected wells in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; na, not applicable; See figure 8 for location of wells.]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Top of screen (meters below land surface)	Bottom of screen (meters below land surface)	Average water level (meters above or below NGVD 1929)	Hydrogeologic unit
61B 19	na	364227076074713	234-00198	36 42 27	76 07 47	4.57	6.10	3.05	6.10	3.51	Columbia aquifer
61B 7	SOW 091D	364227076074704	234-00067	36 42 27	76 0 747	4.57	6.71	5.18	6.71	3.51	Columbia aquifer
62A 3	SOW 097B	363537076061002	228-00171	36 33 55	76 06 17	3.05	7.32	6.10	7.32	2.13	Columbia aquifer
62B 1	SOW 098A	364126076003501	228-00167	36 41 27	76 00 35	3.05	7.32	6.10	7.32	1.86	Columbia aquifer
63C 19	na	364721075591701	228-00248	36 47 21	75 59 17	2.74	9.14	7.62	9.14	.59	Columbia aquifer
62C 11	SOW 172C	364745076004303	228-00253	36 47 46	76 00 43	6.09	10.67	6.10	9.14	3.96	Columbia aquifer
63C 3	SOW 100C	364613075583202	228-00207	36 46 14	75 58 29	2.44	10.67	9.14	10.67	.30	Columbia aquifer
63C 2	SOW 100B	364613075583201	228-00206	36 46 14	75 58 29	2.44	16.46	14.94	16.46	.55	Columbia aquifer
62C 8	SOW 127	364529076031501	228-00078	36 45 33	76 03 20	4.57	18.29	15.24	16.76	1.83	Columbia aquifer
62B 7	na	364354076005401	228-00265	36 43 54	76 00 55	2.59	19.81	15.24	18.29	.54	Columbia aquifer
62B 21	na	364353076005401	228-00264	36 43 53	76 00 54	3.11	19.81	15.24	18.29	.69	Columbia aquifer
62C 3	SOW 092B	364715076030801	228-00133	36 47 14	76 03 07	4.27	17.68	16.15	17.68	1.91	Yorktown confining unit
62B 3	SOW 128	364455076032801	228-00079	36 44 55	76 03 28	3.05	19.81	16.76	19.81	.30	Yorktown confining unit
62C 5	SOW 093	364504076031301	228-00135	36 44 56	76 03 01	4.27	19.81	18.29	19.81	.15	Yorktown confining unit
61B 18	na	364227076074712	234-00197	36 42 27	76 07 47	4.57	20.42	17.37	20.42	2.29	Yorktown confining unit
62B 9	na	364352076005401	228-00263	36 43 52	76 00 54	3.26	20.42	15.85	18.90	.58	Yorktown confining unit
62C 12	SOW 172D	364745076004304	228-00253	36 47 47	76 00 44	5.18	22.86	18.29	21.34	3.35	Yorktown confining unit
62A 2	SOW 097A	363537076061001	228-00170	36 33 56	76 06 17	3.05	23.16	20.12	23.16	1.83	Yorktown confining unit
62B 16	na	363812076021202	228-00432	36 38 12	76 02 12	4.27	23.47	19.81	22.86	1.09	Yorktown confining unit
63C 11	na	364728075591401	228-00245	36 47 28	75 59 14	2.77	25.91	21.34	24.38	.47	Yorktown confining unit
62A 5	na	363325076005201	228-00046	36 33 27	76 00 27	1.52	26.82	17.68	25.30	-.53	Yorktown confining unit
63C 5	SOW 173B	364722075591802	228-00243	36 47 22	75 59 18	2.74	28.96	24.38	27.43	.91	Yorktown confining unit
62B 2	SOW 098B	364126076003502	228-00168	36 41 26	76 00 35	3.05	29.87	26.82	29.87	1.83	Yorktown confining unit
61B 8	SOW 134	364231076140801	234-00118	36 42 31	76 14 08	6.10	30.48	25.60	28.65	4.27	Yorktown confining unit
62A 23	na	363714076063502	228-00430	36 37 14	76 06 35	3.17	30.48	26.82	29.87	1.50	Yorktown confining unit
61C 29	SOW 175	364837076092001	228-00318	36 48 37	76 09 21	4.57	32.00	27.43	30.48	2.13	Yorktown confining unit
61B 2	SOW 091A	364227076074701	234-00136	36 42 27	76 07 47	4.57	29.57	28.04	29.57	2.13	Yorktown-Eastover aquifer
62C 2	SOW 092A	364713076030701	228-00132	36 47 14	76 03 07	4.27	31.09	29.57	31.09	.91	Yorktown-Eastover aquifer
61B 17	na	364227076074711	234-00196	36 42 27	76 07 47	4.57	32.92	26.82	29.87	2.44	Yorktown-Eastover aquifer
62B 18	na	364126076013401	228-00269	36 41 26	76 01 34	3.05	41.15	36.58	39.62	1.67	Yorktown-Eastover aquifer
62B 22	na	364325076011501	228-00268	36 43 25	76 01 15	3.05	41.15	36.58	39.62	-.42	Yorktown-Eastover aquifer
62C 4	SOW 083	364711076060001	228-00120	36 47 11	76 06 00	3.96	45.42	35.97	39.01	.91	Yorktown-Eastover aquifer
62C 9	SOW 172A	364745076004301	228-00250	36 47 46	76 00 42	5.18	51.82	47.24	50.29	1.98	Yorktown-Eastover aquifer
62A 22	na	363714076063501	228-00429	36 37 14	76 06 35	3.19	54.25	43.59	51.21	1.52	Yorktown-Eastover aquifer
63C 13	na	364721075591601	228-00364	36 47 21	75 59 16	2.29	62.48	57.91	60.96	.42	Yorktown-Eastover aquifer
62B 15	na	363812076021201	228-00431	36 38 12	76 02 12	4.20	63.40	58.83	61.87	.84	Yorktown-Eastover aquifer
62C 10	SOW 172B	364745076004302	228-00315	36 47 45	76 00 43	5.18	85.34	82.30	85.34	1.52	Yorktown-Eastover aquifer
63C 4	SOW 173A	364722075591801	228-00314	36 47 21	75 59 16	2.50	88.70	85.65	88.70	1.06	Yorktown-Eastover aquifer

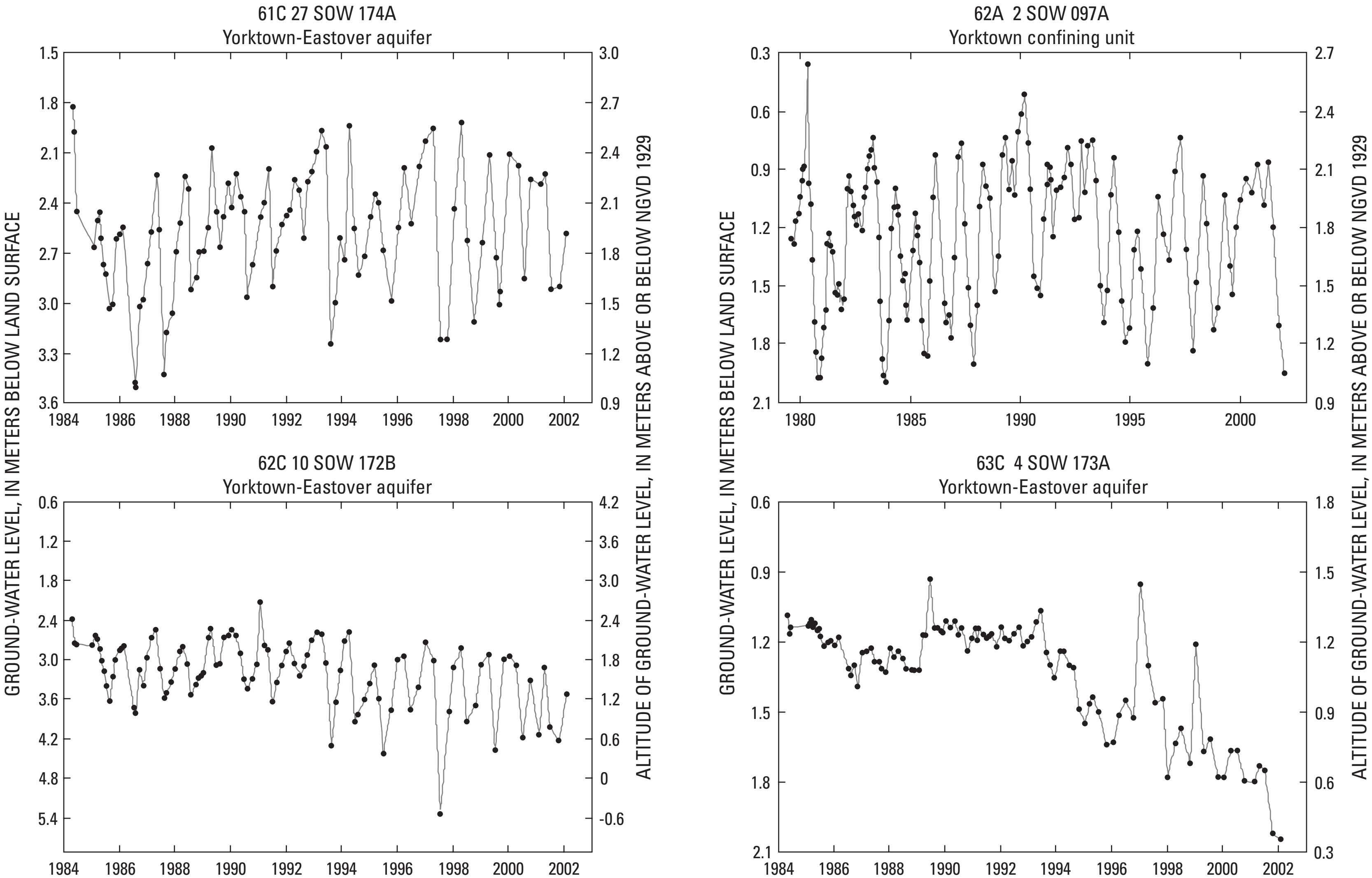


Figure 9. Long-term trends in ground-water levels of the shallow aquifer system in the southern watersheds of Virginia Beach, Virginia.

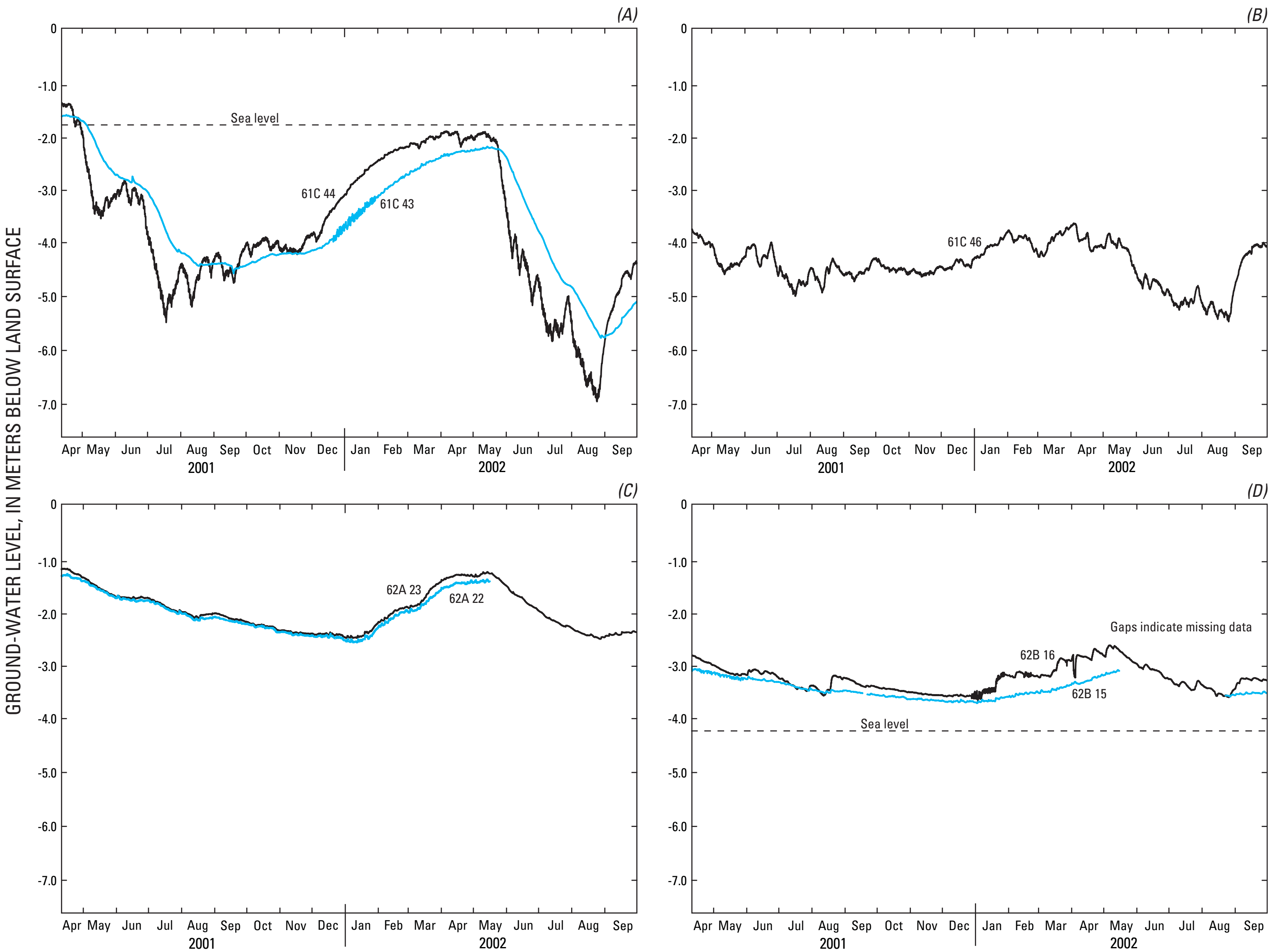


Figure 10. Seasonal trends in ground-water levels at Bellwood Estates Park *(A)*, Bayside High School *(B)*, Blackwater Park *(C)*, and Creeds Elementary School *(D)*, in the southern watersheds of Virginia Beach, Virginia, 2001-2002.

SALINE WATER IN THE SHALLOW AQUIFER SYSTEM

"Water that generally is considered unsuitable for human consumption or for irrigation because of high content of dissolved solids" is called saline (U.S. Geological Survey, 1985, p. 461). Chloride concentrations commonly are used to indicate the proximity or the presence of saline water. In this study, chloride concentrations were contoured by linear Kriging to indicate the general distribution of saline water in the Columbia aquifer, the Yorktown confining unit, and the Yorktown-Eastover aquifer. The chloride concentrations subsequently were used to calibrate a ground-water-flow and solute-transport model.

Definitions

Definitions for water types with regard to seawater are based on dissolved solids concentrations (U.S. Department of the Interior, 1989, p. 22). Water with less than 1,000 mg/L is considered fresh, and water with dissolved solids from 1,000 to 35,000 mg/L is defined as saline. Seawater is assumed to contain approximately 35,000 milligrams of dissolved solids per liter.

A table to relate equivalent concentrations of chloride to those of dissolved solids was made for this report based on the proportion of each to seawater (table 6). Seawater has about 19,000 milligrams of chloride per liter (Hem, 1989, p. 7).

High concentrations of dissolved solids and chlorides can impart an undesirable taste to drinking water. The USEPA (2002, p. 10) recommends a maximum of 250 mg/L for chloride under the Secondary Drinking Water Regulations. People can become accustomed to concentrations in excess of 250 mg/L (World Health Organization, 1993, p. 22). However, a chloride concentration of 400 mg/L renders a salty taste for most people (Hem, 1989, p. 212).

Chloride Concentrations in the Shallow Aquifer System

In the southern watersheds of Virginia Beach, the Columbia aquifer generally contains freshwater and the average chloride concentration is about 25 mg/L (table 7, at end of report). However, water from three wells open to the Columbia aquifer on the eastern edge of the Back Bay watershed had concentrations greater than 200 mg/L (fig. 11). All of the wells in the Columbia aquifer had concentrations less than 250 mg/L. Two wells (not shown) adjacent to a road salt storage area near Pungo were not included on the map because they probably were contaminated by anthropogenic sodium and (or) potassium chloride.

The Yorktown confining unit also contains freshwater in the southern watersheds, similar in distribution to that of the Columbia aquifer, as indicated by chloride concentrations (fig. 12). Chloride concentrations in water from wells open to the Yorktown confining unit were less than the 250 mg/L except for samples from two wells in the northern Back Bay watershed and one other sample from a well west of the southern watersheds and outside of the study area.

The Yorktown-Eastover aquifer contains saline water over much of the southern watersheds, as indicated by chloride concentrations in water from wells open to the aquifer (fig. 13). Freshwater, however, has

Table 6. Definition of water types with regard to seawater and chloride concentrations

Water type[1]			Dissolved solids concentrations (milligrams per liter)	Equivalent chloride concentrations (milligrams per liter)
Freshwater[2]			Less than 1,000	Less than 500
Saline[3] water	Brackish[4] water	Slightly saline[3]	1,000 to less than 3,000	500 to less than 1,600
		Moderately saline[3]	3,000 to less than 10,000	1,600 to less than 5,400
		Very saline[3]	10,000 to less than 35,000	5,400 to less than 19,000
Seawater[1]			35,000	19,000
Brine[3]			Greater than 35,000	Greater than 19,000

[1] U.S. Department of the Interior (1989, p. 22).
[2] Also defined by Davis and Dewiest (1966, p. 118).
[3] Krieger and others (1957, p. 5).
[4] U.S. Geological Survey (1985, p. 460) and Davis and Dewiest (1966, p. 118).

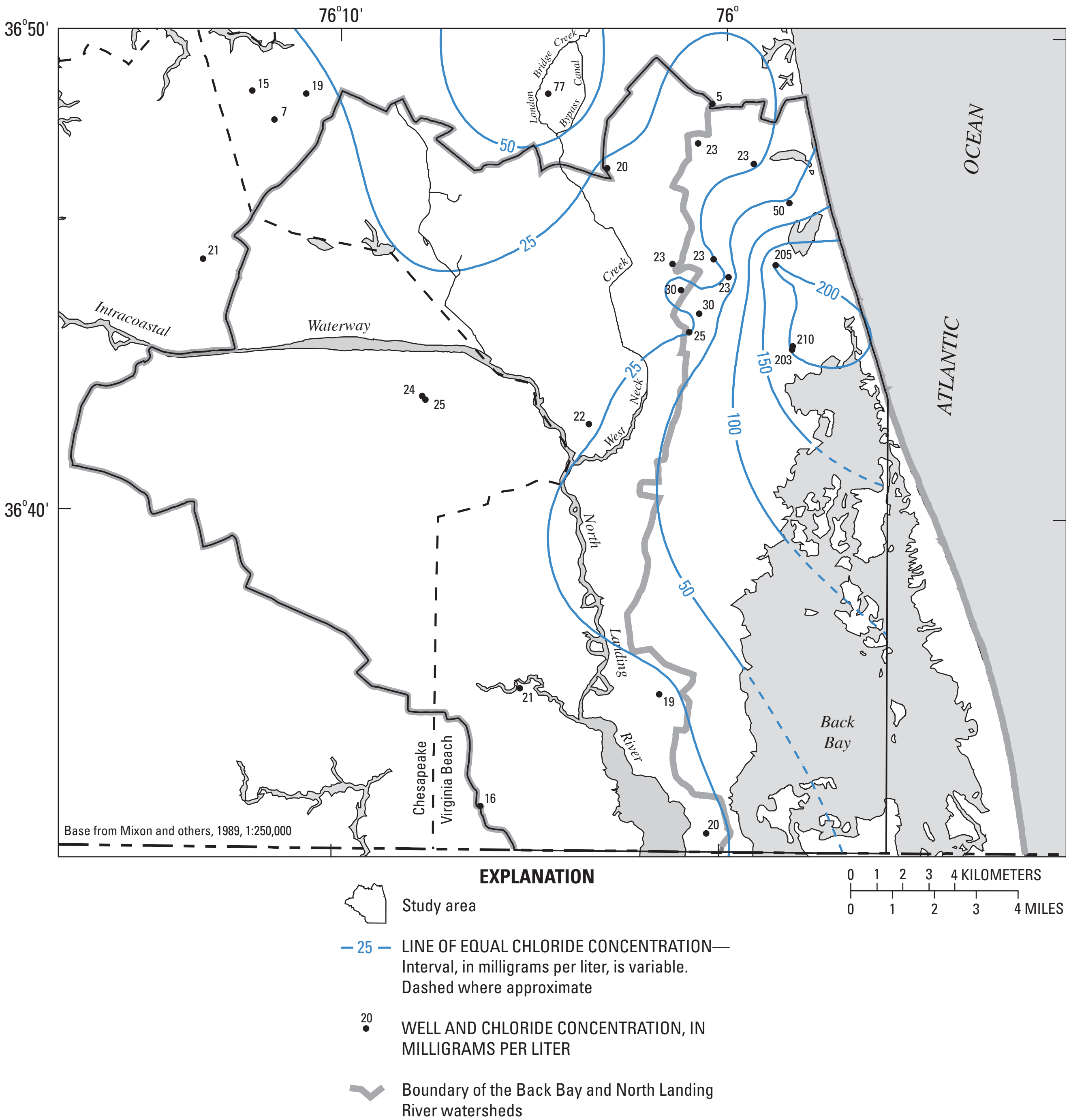


Figure 11. Chloride distribution in the Columbia aquifer of the southern watersheds of Virginia Beach, Virginia.

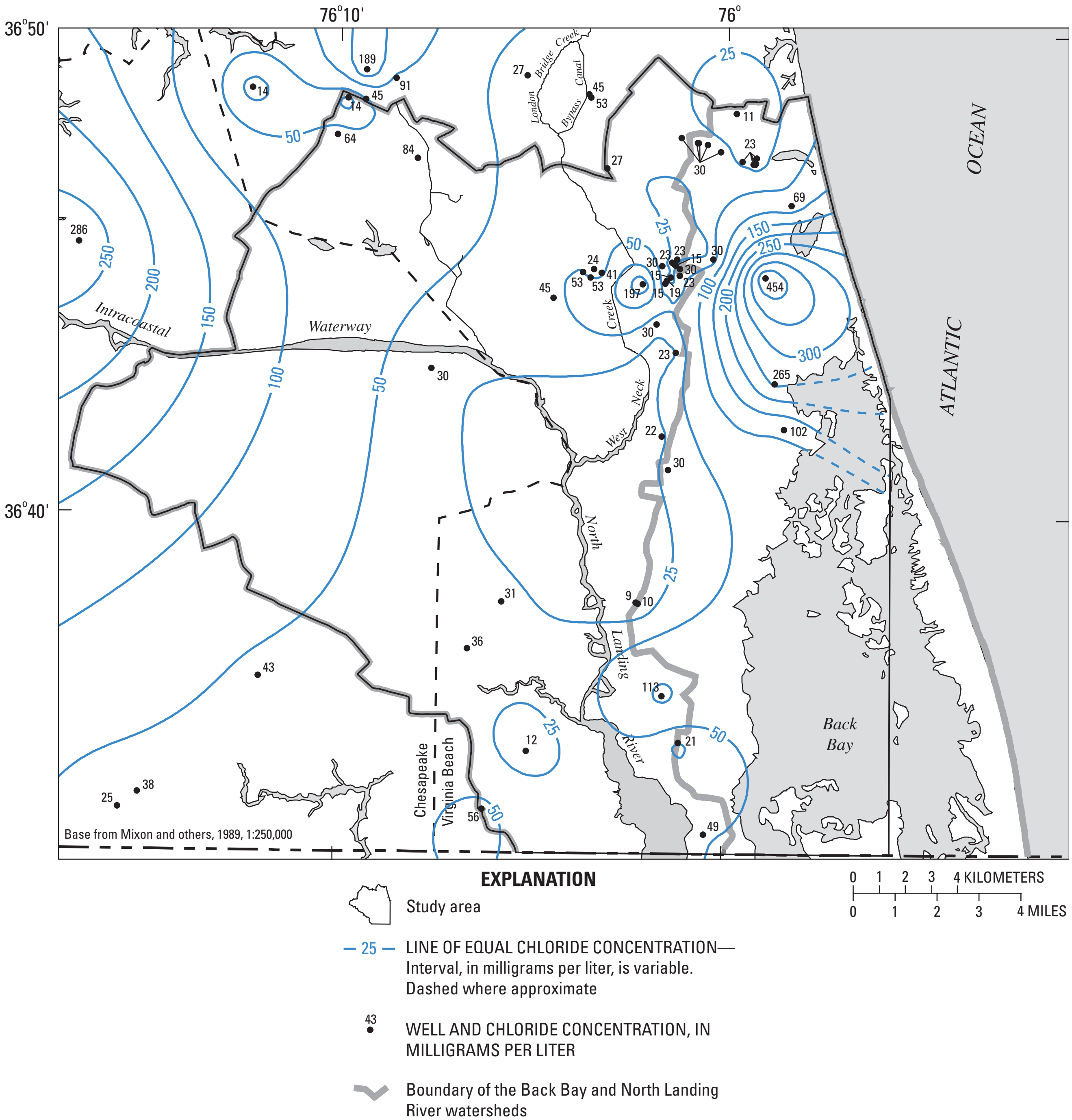
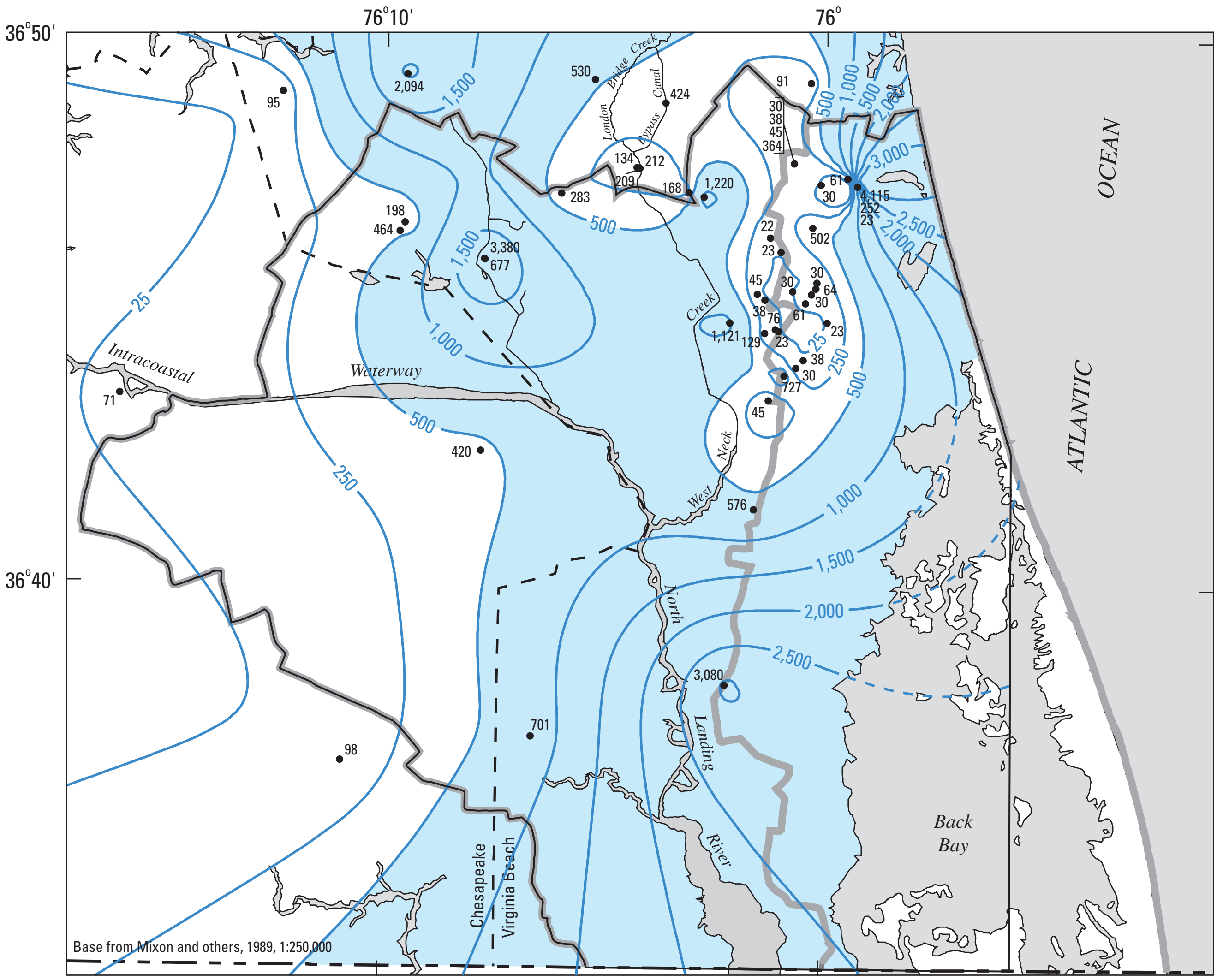


Figure 12. Chloride distribution in the Yorktown confining unit of the southern watersheds of Virginia Beach, Virginia.



EXPLANATION

SALINE WATER—Chloride concentration greater than 500 and less than 19,000 milligrams per liter

Study area

— 25 — LINE OF EQUAL CHLORIDE CONCENTRATION—Interval, in milligrams per liter, is variable. Dashed where approximate

98 WELL AND CHLORIDE CONCENTRATION, IN MILLIGRAMS PER LITER

Boundary of the Back Bay and North Landing River watersheds

0 1 2 3 4 KILOMETERS

0 1 2 3 4 MILES

Figure 13. Chloride distribution in the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

leaked down into the top of the Yorktown-Eastover aquifer, near the watershed divides in the north along Oceana and Pungo Ridges, and possibly along and near the divides in the western parts of the watershed of the North Landing River in Chesapeake, Va. The contour lines around some sites are the average of sample concentrations from two or more wells open to different depths in the aquifer.

Two of the highest concentrations of chloride, 3,080 mg/L in well 61C 43 at Creeds Elementary School and 3,380 mg/L in well 62B 16 at Bellwood Estates Park, were measured in the southern watersheds in the year 2000. Both concentrations were in areas where continuous cores indicated generally fine-grained sediments (Smith and Harlow, 2002, p. 21, fig. 11). These wells were sampled again in 2001, at 2,940 and 3,340 mg/L, respectively, indicating virtually no change in chloride concentration (White and Powell, 2001, p. 313). The highest concentration of chloride measured in the southern watersheds was 4,242 mg/L in water from well 63C 4 at Red Wing Park during an aquifer test in 1981 (Betz-Converse-Murdoch, 1981, v. 2b). That well was sampled again in 2002 at 4,115 mg/L indicating virtually no change in concentration over a period of 21 years.

Virtually of the chloride concentrations measured under natural flow conditions in the shallow aquifers of the southern watersheds, including the highest measurements, showed no changes in concentration through time. These results indicate that the natural freshwater and saline water interfaces probably are in equilibrium in the southern watersheds.

Overall, the maps generally confirm what most previous investigations have indicated; the Columbia aquifer and the Yorktown confining unit generally contain freshwater although concentrations of chloride can be higher than average in places. The top of the Yorktown-Eastover aquifer may contain freshwater in places, but most of the Yorktown-Eastover aquifer contains saline water, particularly with increasing depth.

Conceptual Model of Ground-Water Flow

A general conception of ground-water flow in the shallow aquifer system at Virginia Beach was reported by Smith and Harlow (2002, p. 27). That general conceptual model has been refined in light of the chloride maps and the simulations of ground-water flow documented in this report.

Ground-water-flow patterns in shallow aquifers of Virginia Beach reflect the topography. Tóth defined intergraded local, intermediate, and regional ground-water-flow patterns resulting from undulating topography (Freeze and Cherry, 1979, p. 196). Regional patterns are defined by deep, long concentric paths from the watershed divides to the farthest extent of the discharge areas (fig. 14). Local patterns are shallow, short concentric paths at the nearest edge of the discharge areas and intermediate patterns are the concentric paths between.

The shallow aquifer system at Virginia Beach is recharged by local precipitation. Rainwater or snowmelt that soaks through the soil and is not captured and transpired by plants seeps through the unsaturated zone

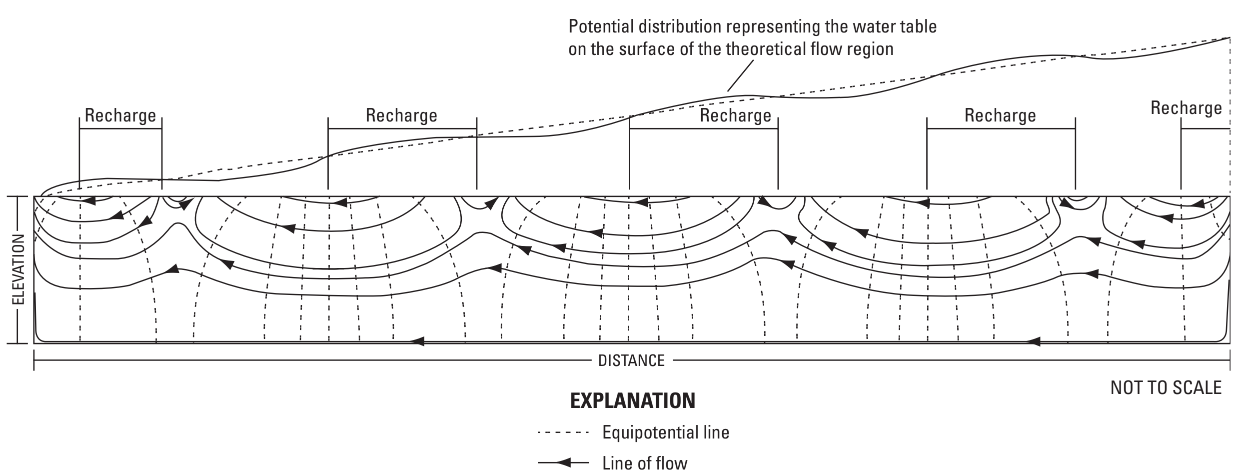


Figure 14. Toth's theoretical ground-water flow patterns effected by topography. (Taken from Sanford, 2002.)

to recharge the water table. During the growing season, ground-water recharge generally is slight because trees and shrubs capture most of the precipitation and transpire that back to the atmosphere. The water table is more readily recharged in the late fall and winter when plants are dormant.

When and where ground-water recharge is ample, the water table rises as a subsurface mound and water begins flowing away from the center of the mound. The mound forces the water beneath to flow downward and outward toward the nearest tidal stream or shore, where the fresh ground water flows into and mixes with saline water (fig. 15). In the humid climate of Virginia Beach, the periodic recharge of freshwater through the shallow aquifer system occurs often enough to create a steady-state balance or a dynamic equilibrium whereby freshwater flows continually down and away from the center of the higher ground and the sand ridges to mix with saline water from the tidal rivers, bays, salt marshes, and the Atlantic Ocean.

Recharge and mounding beneath much of the southern watersheds is limited by the general flatness and low altitude of the terrain and by the proximity and extent of wetlands, bays, open waterways, and tidal rivers, streams, and channels, where ground water readily discharges. Extensive lowlands and wetlands to the west of Virginia Beach and Chesapeake, Va., limit ground-water recharge over much of the southeastern region of Virginia as well. Infiltration of water falling on the land surface is hindered further in much of the southern watersheds of Virginia Beach by shallow layers of clayey soils and the limited depth of permeable sediments beneath the soils (Wolman and others, 1942, p. H-2). Extensive systems of ditches have been built to lower the water table beneath poorly drained soils that cover much of the agricultural areas of Virginia Beach. Paved surfaces, drains, and stormwater sewers, particularly in urban areas along the northern perimeter of the southern watersheds, also inhibit ground-water recharge. Thus, ground-water recharge is limited and ground-water-flow lines tend to be short and shallow in much of the southern watersheds.

The shallow aquifer system is recharged in some places through permeable soils and sand dunes, particularly beneath some of the higher altitudes, such as Pungo Ridge. The areas of greatest recharge are those where the land surface is broad and high.

Semi-confining and confining sediments, particularly those of the Yorktown confining unit, hinder fresh ground-water recharge to deeper units. Pockets of saline water may be trapped within impermeable sediments in some areas (fig. 15). Where recharge of fresh ground water is inhibited, saline water is at shallower depths. The fresh ground water that does recharge the deeper sediments of the shallow aquifer system flows over and above heavier saline water in the bottom of the shallow aquifer system. In the confined and poorly confined aquifers of the southern watersheds, freshwater probably has displaced saline water generally from the higher ground in the north and west toward the south and east so that saline water probably remains in the confined aquifers in the southeast beneath Pungo Ridge. Freshwater from Hickory Ridge to the west probably discharges to the broad flood plain and wetlands of the North Landing River.

SIMULATION OF GROUND-WATER FLOW AND SOLUTE TRANSPORT

The Columbia and Yorktown-Eastover aquifers are poorly confined throughout most of the southern watersheds of Virginia Beach, and the freshwater to saline water distribution is in a dynamic equilibrium (steady state) with average ground-water levels, measured concentrations of dissolved salts (chlorides), and modern sea levels. A three-dimensional, steady-state, ground-water-flow and solute-transport model was used to simulate that dynamic equilibrium.

Model Assumptions and Assumed Properties

A primary goal was to devise the simplest model possible that would meet the objectives of the project. As the number of variables and assumptions in a model increase, errors multiply, creating greater uncertainty. The principle of parsimony (also called the principle of simplicity, or Ockham's razor) suggests that the simpler approach to an objective should be tried first in order to reduce errors and uncertainty. However, there is a tradeoff between the simplicity of design and the complexity of possible realities, because measured data can be more precisely approximated if there are more variables to adjust.

Visual MODFLOW® version V.3.0 (Waterloo Hydrogeologic, Inc., 2002, p. 25) was used to simulate ground-water flow and solute transport. Version V.3.0 incorporates MODFLOW 2000, a finite-difference

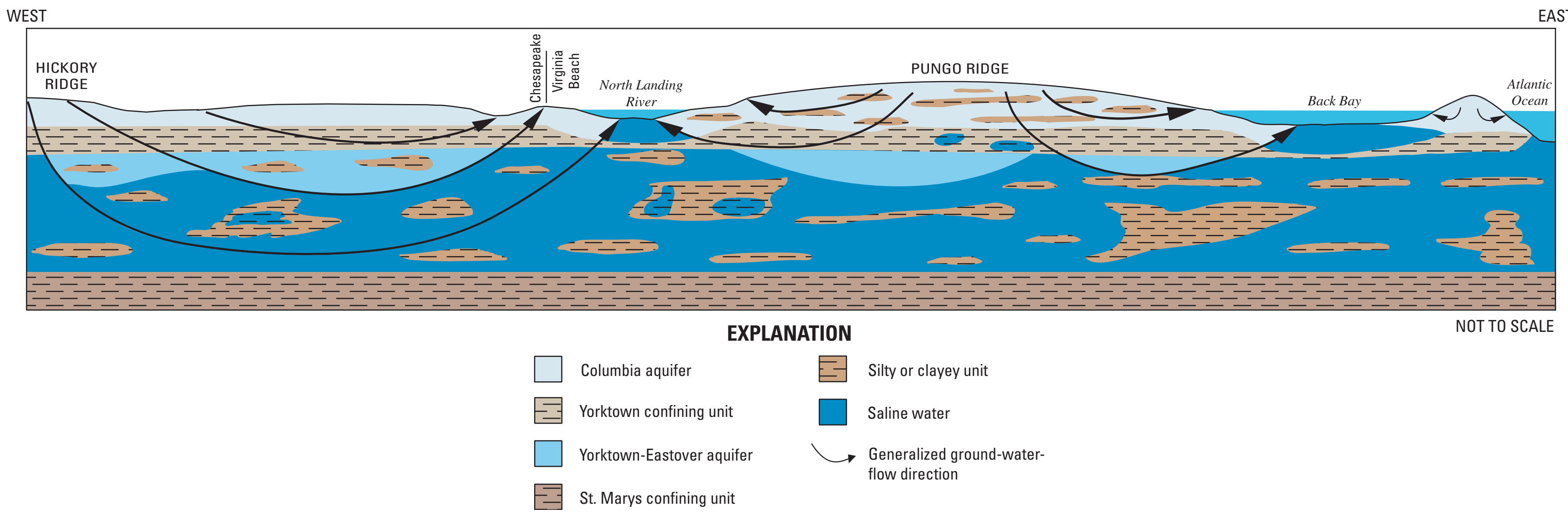


Figure 15. Conceptual model of ground-water flow in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia. (Modified from Johnson, 1999.)

ground-water-flow model (or MODFLOW 96) and MODPATH, a particle-tracking routine designed by the USGS, as well as MT3DMS, a multi-species transport model for simulation of advection, dispersion, diffusion, and some chemical reactions designed at the University of Alabama, and completed, in part, in cooperation with the Army Corps of Engineers Waterways Experiment Station (Zheng and Wang, 1998, p. 1-4). Calibration and sensitivity analyses of the model were aided by the parameter estimator WinPEST and various other mapping, contouring, graphing, and statistical routines that are also incorporated into Visual MODFLOW (Waterloo Hydrogeologic, Inc., 2002, p. 222 and 244). VMOD 3D-Explorer also is incorporated into Visual MODFLOW V.3.0. Except as noted, the default settings of Visual MODFLOW were applied for the model simulations.

The usual assumptions associated with ground-water flow and solute transport simulations of layered aquifer systems as applied to these programs are valid for the objectives of this study. The assumptions are appropriate as used for the system conceptualization of this study; however, before applying the model for other purposes the appropriateness of the assumptions should be evaluated.

Ground-water flow is assumed to be laminar (not turbulent). The aquifers are assumed to be homogeneous (uniform in composition) and isotropic (aquifer properties are directionally uniform) within representative elemental volumes (cells). However, horizontal hydraulic conductivity of each unit was assumed to be higher than vertical because the sediments of the southern watersheds generally were deposited in stratified layers (Jacob, 1963, p. 274).

Temperature and density gradients were assumed to be uniform in the shallow aquifer system. The simulations do not incorporate density-dependent flow— the pressure gradients produced by mixing waters of different mass (weights). Such pressure gradients are negligible because the differences in density between the freshwater and slightly saline water of the southern watersheds is small generally and concentration gradients tend to increase gradually with depth. The greatest chloride concentration measured in a well of the shallow aquifer system was 4,242 mg/L (moderately saline) at Red Wing Park at a depth of 286 m in 1981.

Dispersion in the direction of principal velocity generally is much greater than the dispersion perpendicular to the principal velocity (Henry, 1964, p. C-73). The longitudinal dispersivity of the calibrated model was 1.0 m. The longitudinal dispersivity was assumed to be one order of magnitude (10 times) greater than the transverse dispersivity in the horizontal direction and 2 orders of magnitude (100 times) greater than the transverse in the vertical direction. The diffusion coefficient was assumed to be that of chloride, 20.3×10^{-6} square centimeters per second (Domenico and Schwartz, 1990, p. 369).

Effective porosity of the aquifers was assumed to be 30 percent, representing some shell hash, biofragmental sand, and beach sand in the units; porosity of confining units was assumed to be 40 percent, representing mostly fine sand, silt, and clay deposits (Davis and DeWeist, 1966, p. 375, table 11.1; Todd, 1980, p. 28, table 2.1). Fine-grained sediments such as silt and clay tend to have poorly connected but larger void spaces than sands (Freeze and Cherry, 1979, p. 37).

The simulation method assumes steady state with respect to modern eustatic (average global) sea level, which has fluctuated with regional and global climate changes over the last 70,000 years (Mixon and others, 1982 or See explanation of Sedgefield Member of Tabb Formation from Mixon and others, 1989, Sheet 1). The aquifer system was in equilibrium with measured average water levels. Such a steady state was indicated from numerous hydrographs covering decades of periodic measurements in wells and by continuous records of transducers in wells. A few hydrographs from wells in Virginia Beach, however, were not indicative of steady states, but indicated local anomalies, probably caused by unreported ground-water withdrawal for irrigation, and such water levels were not used to calibrate to the average water levels. It also was assumed that the freshwater-saline-water interfaces were in dynamic equilibrium with modern sea levels, as indicated by the unchanging measurements of chloride in the southern watersheds.

Boundaries and Layers

The boundaries of the southern watersheds of Virginia Beach were derived from hydrologic unit boundaries of Virginia that rely on USGS 1:24,000-scale 7.5-minute topographic maps. The outlines of the southern watersheds of Virginia Beach were imported into Visual MODFLOW® and referenced to known locations on topographic maps using Universal Transverse Mercator coordinates (Waterloo Hydrogeologic, Inc., 1999, p. 20). Maps of land use (fig. 2) and surficial geology (fig. 3) also were overlaid in Visual MODFLOW to guide placement of internal and external boundaries and hydrogeologic properties, including wetland areas and the generally sandy Poquoson Member of the Tabb Formation.

A square finite-difference grid of 80 rows and 80 columns was set over the southern watersheds of Virginia Beach, except for the narrow strip of land adjacent to the Atlantic Ocean east of the Back Bay that was assumed to be isolated with respect to ground-water flow from the rest of the watershed (fig. 16). Each individual cell of the model was 400.0 m (1,312 ft) per side.

The outer perimeters of the southern watersheds were assumed to be no-flow boundaries because of the shallow flowpaths of the aquifer system. The short southern boundaries of the watersheds are drawn at the Virginia-North Carolina State line, which runs perpendicular to the North Landing River and the higher ground on either side, following natural ground-water flowpaths that define no-flow boundaries. The limits of the model area to the east also are assumed to be no-flow boundaries by definition, but those boundaries were set far enough from the land areas to allow unimpeded discharge to the Atlantic Ocean and the Back Bay, which were assumed to be constant water levels. The potential effect of moving the boundary closer to the shore was tested and the simulated water levels were found to be insensitive to the change.

Constant water levels of zero altitude and constant chloride concentrations of 19,000 mg/L were assumed for modern sea levels and maximum salinity representing the Atlantic Ocean in the simulations (Hem, 1989, p. 7, table 2). Constant water levels of 0.3 m (1.0 ft) above sea level and constant chloride concentrations of 10,000 mg/L were used to represent the average tide levels and maximum salinities expected for the Back Bay, the North Landing River, the Intracoastal Waterway, and West Neck Creek (Bales and Skrobialowski, 1994, p. 10, fig. 5; Caldwell, 2001, p. 9, fig. 2, and p. 19, fig. 6).

Flowing non-tidal streams and major ditches were simulated as drain cells in the model. Drain bottoms were determined from points along streams and ditches marked on USGS 7.5-minute, topographic maps. The bottoms of the drain cells were set equal to the altitudes where the land-surface contours crossed over the streams and ditches.

Conductances of the drain cells were estimated by multiplying the hydraulic conductivity by the width and length of the cells and dividing by the thicknesses of the drain bottoms in much the same way as river bottoms for MODFLOW are documented (MacDonald and Harbaugh, 1988, p. 6-4, fig. 34). The length of each drain was assumed to be equal to the length of each cell of the model in which the drain was represented (400 m) the width was assumed to be 3.0 m, and the thickness of the drain bottom was assumed to be 1.0 m. Drain hydraulic conductivities initially were assumed to be 1.0 m/d.

Four contoured surfaces define the conceptual hydrogeologic framework of the shallow aquifer system and constitute the layered geometry of the ground-water-flow and solute-transport model (fig. 17). The contours of the land surface form the limits to the top of the Columbia aquifer. The bottom of the Columbia is the contact with the top of the Yorktown confining unit. The bottom of the Yorktown confining unit is the contact with the top of the Yorktown-Eastover aquifer. The top of the St. Marys confining unit, a regionally continuous marine deposit of low permeability, forms the bottom of the Yorktown-Eastover aquifer, the shallow aquifer system, and the no-flow bottom of the ground-water-flow and solute-transport model.

The four contoured surfaces that form the geometry of the shallow aquifer system were imported into Visual MODFLOW to form the three conceptual units of the model. The three conceptual units of the shallow aquifer system were divided further into seven layers to represent the most common local configuration of shallow aquifers and confining units of the southern watersheds. The model layers representing aquifers (Columbia and the Yorktown-Eastover aquifers) each were divided evenly into two layers, one upper and one lower. The Yorktown confining unit was divided evenly into three layers to approximate two confining units with an aquifer in between, which is the simplest configuration of the local hydrogeology throughout much of the southern watersheds of Virginia Beach.

Most model layers were assigned uniform hydraulic conductivities. The transmissivities of each layer, however, varied with the thickness. The upper layer of the Columbia aquifer was assigned three separate zones for hydraulic conductivities: wetland, upland, or Poquoson (Pungo Ridge), assuming increasing values, respectively (fig. 17). Layer 6, representing the upper layer of the Yorktown-Eastover aquifer, was assigned a single zone of hydraulic conductivity for most of the watersheds. Two areas known to be generally less permeable from test drilling and driller's information, one in and

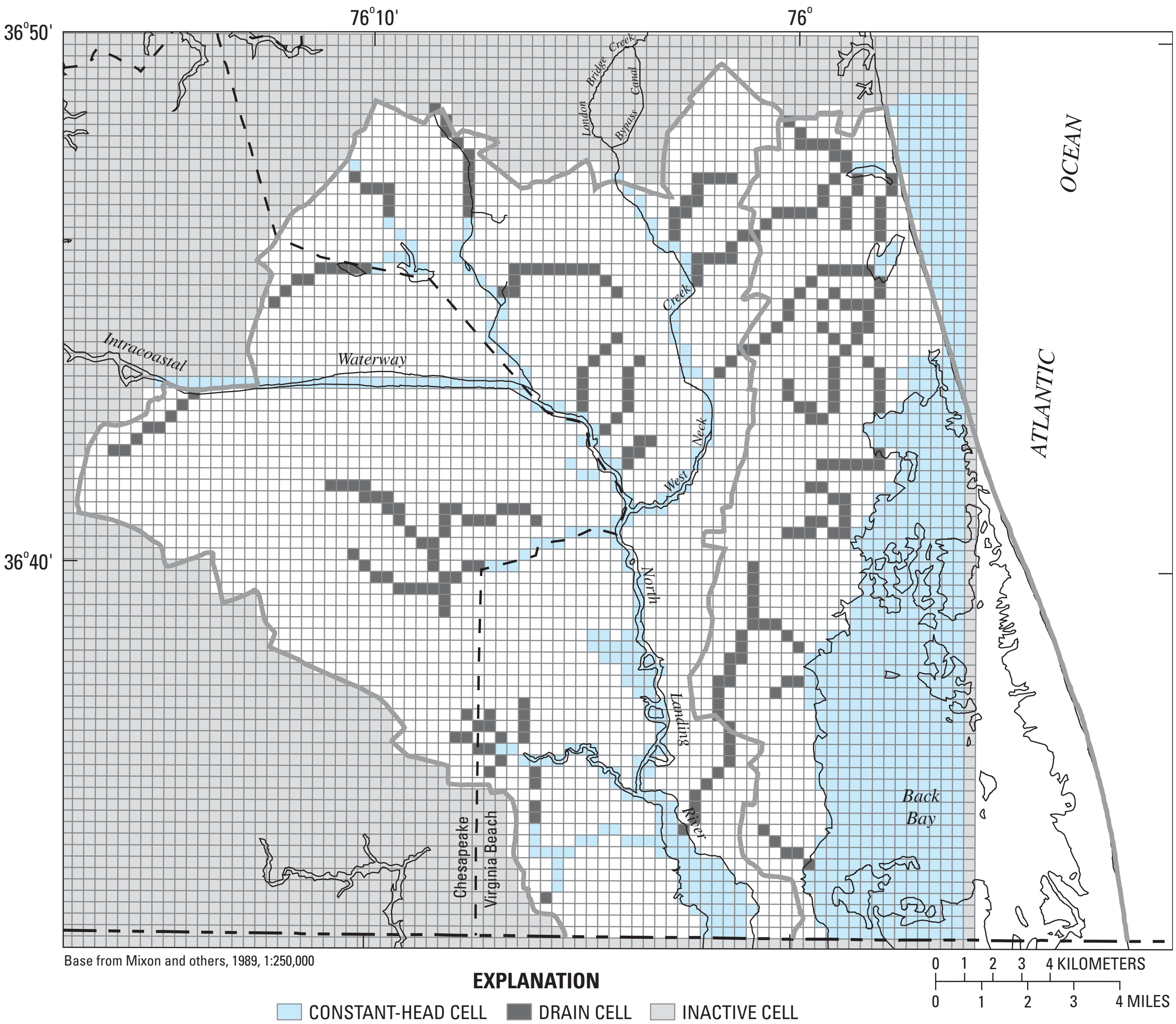


Figure 16. Grid, boundaries, and drains of the ground-water-flow and solute-transport model of the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia.

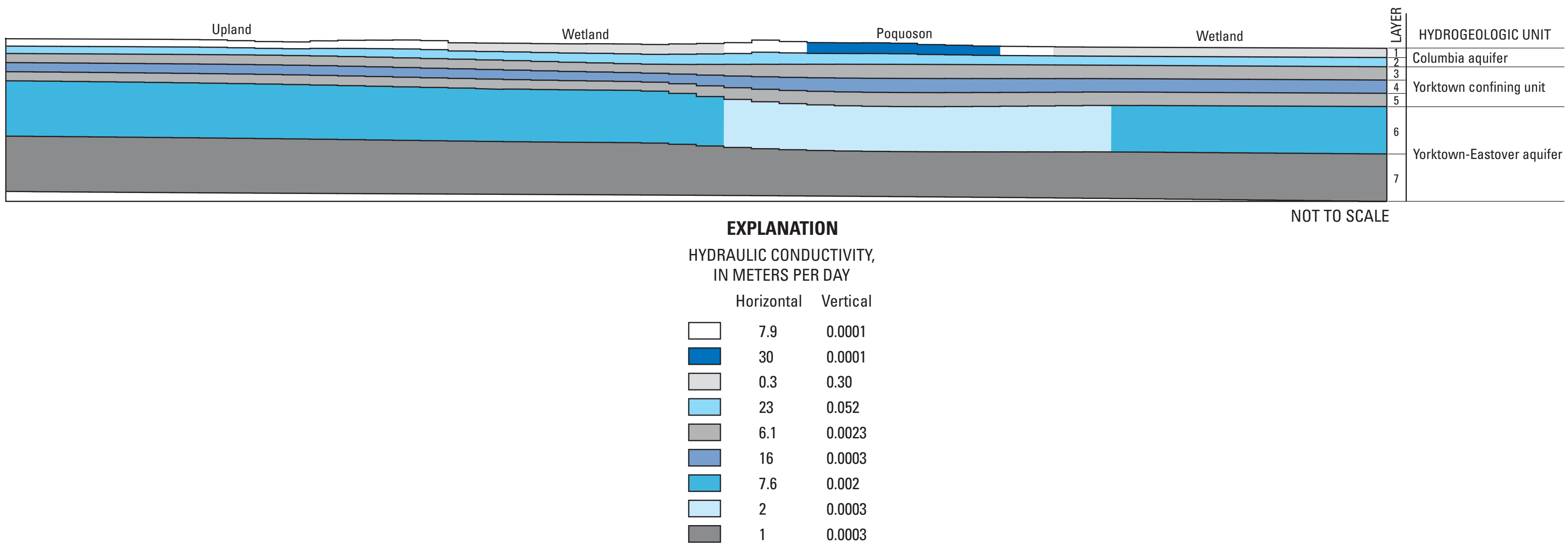


Figure 17. Layers and hydraulic properties of the calibrated model of the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia.

around Bellwood Estates Park and the other in and around Creeds Elementary School, were assigned lower hydraulic conductivities than elsewhere in that layer.

The model layers were designated Type 3 convertible, meaning that the transmissivity was calculated from saturated thickness and hydraulic conductivity (McDonald and Harbaugh, 1988, p. 5-38). Inter-block (cell) conductance was calculated by harmonic means and all cells were non-wettable (Harbaugh and others, 2000, p. 57).

Calibration and Parameter Estimation

Average water levels from 38 wells (table 5), most of which were long-term averages, and chloride concentrations of water sampled from 123 wells (table 7) were used for calibration of the ground-water-flow and solute-transport model. The average water levels were used in WinPEST, a parameter estimation routine for calibrating Visual MODFLOW.

Ground-water-recharge rates were calibrated independently of parameter estimation so that a more unique solution to the ground-water-flow equation could be determined. Recharge rates were taken from previous studies that covered all or parts of southeastern Virginia (table 4). To take advantage of information from digital elevation models, recharge rates were assumed to be dependent on land surface altitudes. Evapotranspiration rates were assumed to be equal to recharge rates at the land surface and to decrease with depth to an extinction point.

Evapotranspiration rates generally reach maximum values at the land surface. The evapotranspiration rates were assumed to be zero where the water table was at land surface. Evapotranspiration rates in the model decrease with depth (and, thus, recharge rates increase) up to a predetermined extinction point. Initially, the extinction point was assumed to be 2.0 m, within the range of 1.8 to 2.4 m commonly assumed–although considerable variation can be expected because of such factors as climate and vegetation (McDonald and Harbaugh, 1988, p. 10-5).

The maximum recharge rate initially was assumed to be about 20 cm/yr, equal to the average annual ground-water discharge for the southern watersheds of Virginia Beach (Richardson, 1994b, p. 12, fig. 5). This initial maximum recharge rate, however, produced simulated water levels much higher than measured. Calibration and subsequent sensitivity tests indicated a better approximation of measured water levels if a maximum recharge rate of 10 cm/yr was assumed for the model with an extinction depth of 3 m.

The model was calibrated to average water levels by adjusting hydraulic conductivities with the aid of the parameter estimator, WinPEST. Minimum and maximum limits for horizontal and vertical hydraulic conductivities for WinPEST were taken from tables 2 and 3, respectively. Much of the calibration process involved checking the limits to WinPEST so that horizontal hydraulic conductivities of individual units always were greater than or equal to vertical. Units known or presumed to be of lower hydraulic conductivity than others—such as the wetlands compared to upland—also were checked and controlled by limiting those parameter limits for WinPest. (Hydraulic conductivities of the wetlands in the southern watersheds are undetermined and a value of 0.3 m/d was presumed.) After calibration, most of the horizontal and vertical conductivities of the calibrated model were at the maximum or minimum limits assigned to WinPEST.

The default values for the mathematical parameters of WinPEST were adequate for almost every model simulation. PCG2, the preconditioned conjugate gradient solution package, version 2.4, was the solver chosen for MODFLOW. Default values for the solver also were adequate for almost every run.

The hydraulic parameters from the WinPEST calibration also were calibrated to measured chloride concentrations. The solute-transport model initially was assumed to contain very saline water (chloride concentrations of 10,000 mg/L) from the late Pleistocene when shallow seas and estuaries covered the study area and saturated the shallow aquifer system. Freshwater displacement of that saline water in the watersheds was simulated until a new steady state with regard to the measured chlorides was reached (fig. 18). Constant concentrations of 10,000 mg/L were assigned to the Back Bay, the North Landing River, and the Intracoastal Waterway, because those tidal waters still are saline to very saline. Constant chloride concentrations of 19,000 mg/L, representing seawater, were assigned to the Atlantic Ocean.

Freshwater recharge was applied to the top layer of the ground-water-flow and solute-transport model until the simulated chloride concentrations approximated measured chloride concentrations as indicated by statistical methods. In the calibrated model, the new steady state was approximated after 31,500 years of freshwater recharge. The solute-transport model approached steady state with regard to measured chloride concentrations after 31,550 years of freshwater recharge. Freshwater displaced saline water that had filled the shallow aquifer system during the last major interglacial period more than 70,000 years ago when the shallow waters and estuaries of the Sedgefield Sea covered the study area (Mixon and others, 1989, sheet 1).

The steady state is indicated by chloride concentrations in the upper layers of the model that show little or no change in concentrations over periods of 10,000 years or more, particularly between times of 30,000 and 40,000 years (fig. 18). Freshwater continued to slowly replace saline water in the lower layers of the model beyond 30,000 years as indicated by simulated chloride concentrations, but few data points are available from those depths as calibration points.

The third-order total variation diminishing (TVD) scheme was selected to solve the advective term of the MT3DMS transport equation because it is mass conservative, minimizes numerical dispersions, and essentially is free of artificial oscillations (Zheng and Wang, 1998, p. 3-6). The TVD scheme uses the ULTIMATE (Universal Limiter for Transient Interpolation Modeling of the Advective Transport Equations) algorithm (Zheng and Wang, 1998, p. 3-5).

The root mean squared errors (RMSE's) of measured to simulated water levels and chloride concentrations were used to calibrate the model (Waterloo Hydrologic, Inc., 2002, p. 250). The RMSE is calculated by subtracting each measured water level and chloride concentration from the equivalent simulated water level and chloride concentration. Each measured to model-simulated difference is squared. All of the squared differences then are summed, divided by the number of measurements, and then the square root is taken. The lower the RMSE, the better the approximation between measured and simulated water levels and chloride concentrations. The RMSE is determined for each simulated run and compared to the last run to determine whether the changes in parameters improve the approximation. The RMSE of measured to simulated water levels for the first run was 161 cm and the RMSE of the calibrated model was 60.7 cm. The normalized RMSE (the RMSE divided by the range between the maximum and minimum observations) was 30.2 percent for the first run and 12.7 percent for the calibrated model.

The solute-transport model approached steady-state conditions with regard to measured chloride concentrations within about 30,000 to 40,000 years depending on simulated hydraulic properties. The model was calibrated after several iterations of adjusting hydraulic properties to water levels followed by calibration to chloride concentrations and then back to water levels. For the transient (chloride) calibration, the calibration time was chosen from the lowest RMSE near the absolute residual mean of the simulated to measured concentrations (nearest zero). The absolute residual mean is calculated by subtracting each measured concentration from the equivalent simulated concentration, dropping the sign (positive or negative), then summing all of the differences and dividing by the number of wells. Positive or negative bias is at a minimum at the lowest absolute residual mean. The residual mean is similar except that the sign is not dropped so that positive and negative values cancel.

The RMSE of measured to simulated concentrations of chloride for the calibrated model was 636 mg/L at the lowest absolute residual mean, which was at 31,550 years (fig. 19A). The normalized RMSE with respect to chloride was 15 percent at that time (fig. 19B).

The calibrated model approximated the measured water levels (13-percent normalized RMSE) slightly more accurately than the chloride concentrations (15-percent normalized RMSE). The simulated chloride concentrations did not approximate the measured concentrations in the water from some wells. In particular, the simulated concentrations of chloride were much greater than those measured for three wells—Pungo1 (62B 22), Pungo 2 (62B 18), and a well at Seneca (62A 6). In contrast, the chloride simulated for one well at Redwing Park (63C 4) and one at Bellwood Estates Park (61B 43) were much less than those measured (fig. 20A). (See figure 8 for well locations.) The differences indicate that these sites do not conform to the simple geometry of the watershed model, or to the hydraulic properties estimated for the model units at those sites, or possibly both. Actual vertical changes in chloride concentrations within the individual units at these locations probably contribute to most of the error. More information or a different model conception and geometry at the local scale would be needed to simulate ground-water flow and solute transport more accurately in those areas.

Calibration of the model to the average annual water levels (fig. 20B) and to most of the measured

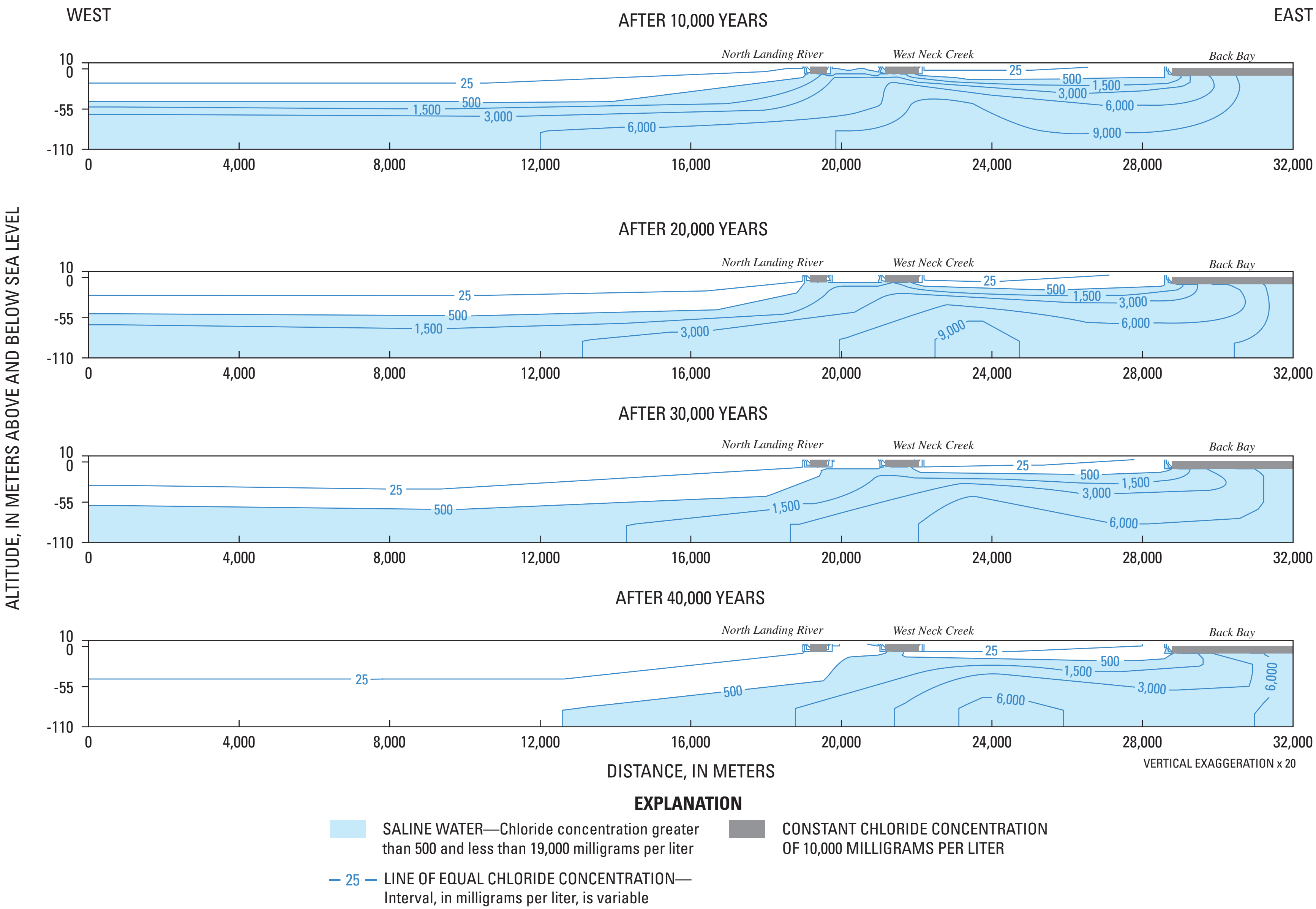


Figure 18. Simulated freshwater displacement of saline water, as indicated by chloride concentrations, in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia.

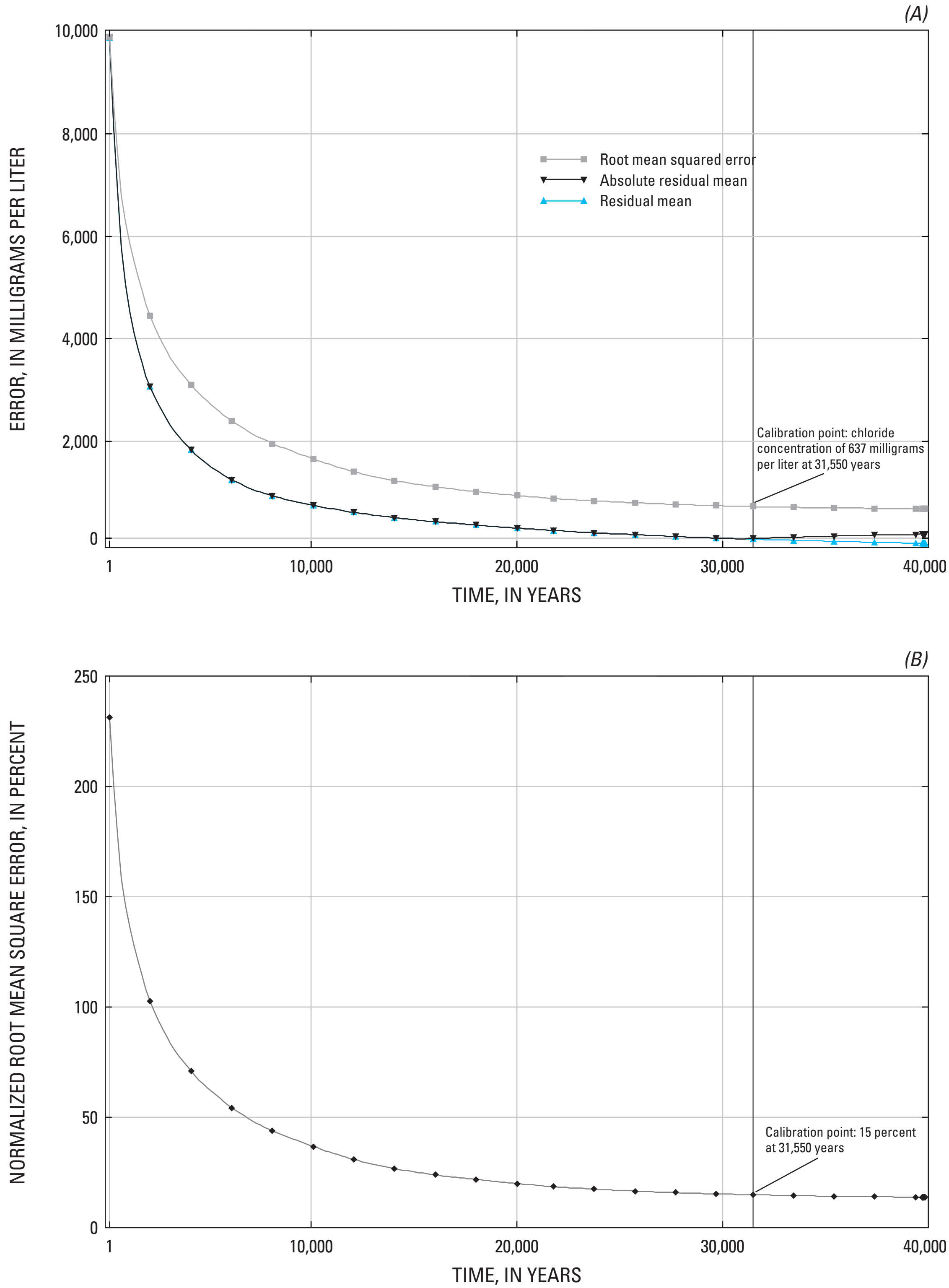


Figure 19. Root mean square errors, absolute residual means, and residual means *(A)* and normalized root mean square errors *(B)* between measured and simulated chloride concentrations approaching equilibrium and the calibration point for the simulation of ground-water flow of the southern watersheds of Virginia Beach, Virginia.

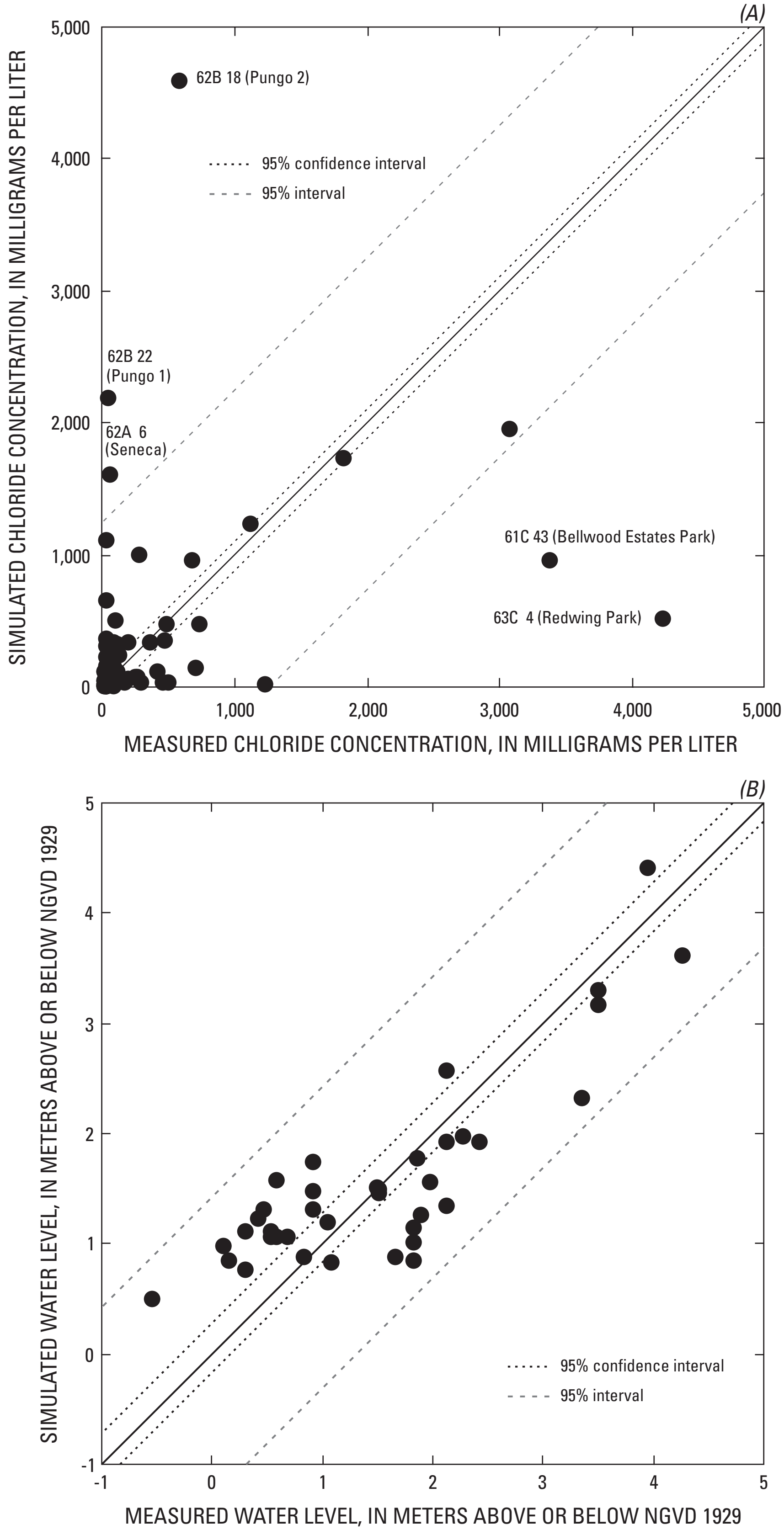


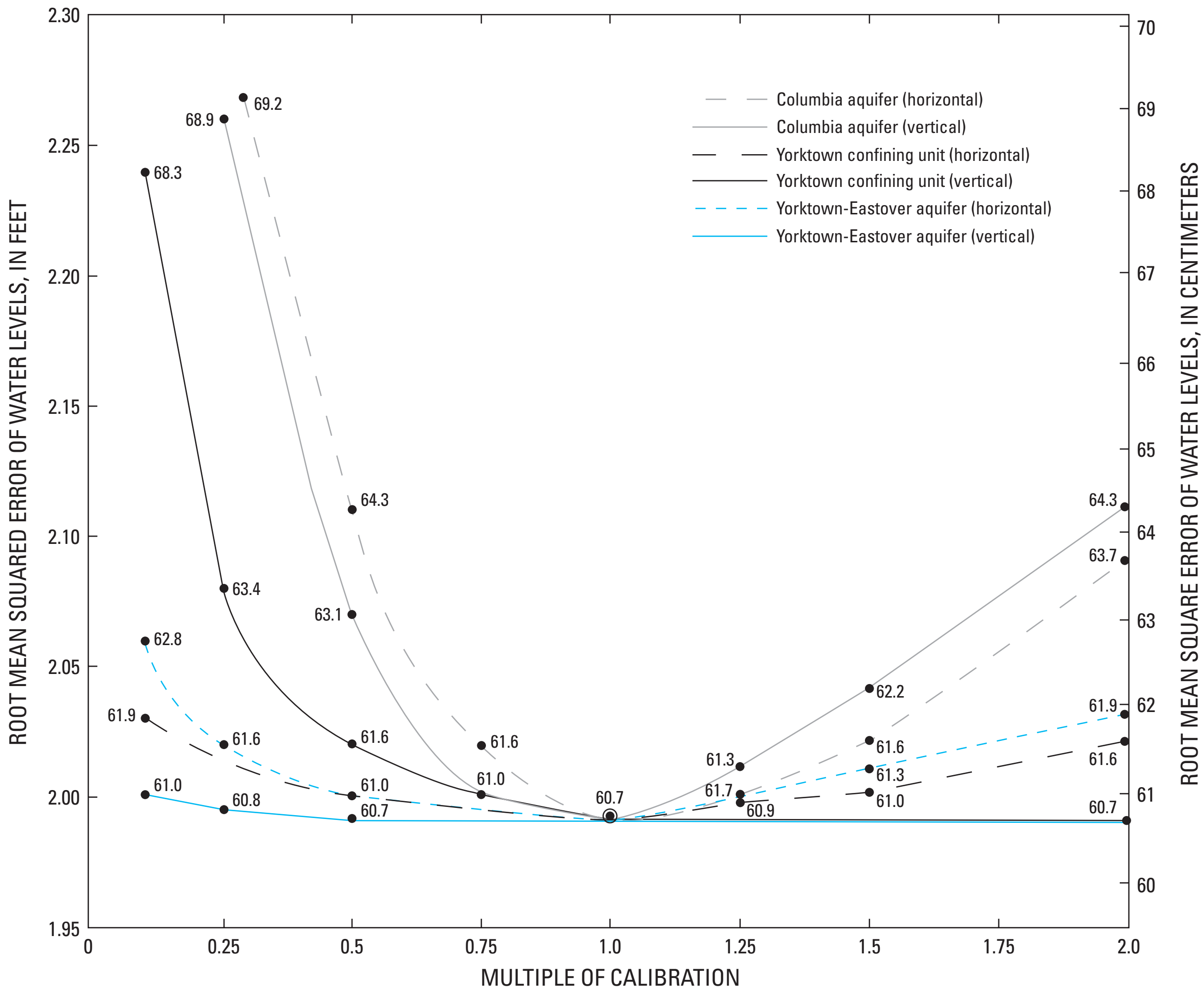
Figure 20. Differences between simulated and measured chloride concentrations *(A)* and simulated and measured water levels *(B)* of the calibrated model of the southern watersheds of Virginia Beach, Virginia.

chloride concentrations, however, indicates that the model is an adequate estimator of ground-water-flow and saline-water movement for watershed planning. Also, approximations of the water levels and chloride concentrations of water sampled from most of the wells indicate that the freshwater and saline water interfaces of the shallow aquifer system probably are in dynamic equilibrium with average water levels and modern sea levels.

Sensitivity Analyses

The RMSE of measured to simulated water levels also was used to test the sensitivity of the calibrated model to changes in aquifer properties. Horizontal and vertical hydraulic conductivities were tested in multiples of the calibrated values. Simulated water levels of the calibrated model were more sensitive to changes in hydraulic conductivity in the Columbia aquifer than in deeper units (fig. 21). Water levels were moderately sensitive to changes in the horizontal hydraulic conductivity of all of the other units. Simulated water levels were sensitive to decreases in the vertical hydraulic conductivity of the Yorktown confining unit, but were not sensitive to increases in the vertical conductivity of the Yorktown confining unit or the Yorktown-Eastover aquifer.

The sensitivity of the ground-water-flow model to mutual changes in recharge rates and evapotranspiration extinction depths was delineated by plotting and contouring RMSE's of the measured to simulated water levels (fig. 22). A recharge rate of 10 cm per year with an extinction depth of 3.0 m was chosen as a reasonable calibration point. Recharge rates less than 10 cm/year were not expected, as indicated by previous studies, and extinction depths greater than 3.0 m, although possible, were considered less likely. However, the model was not sensitive to changes in recharge rates and extinction depths beyond those of the calibration point. Different rates and depths corresponding to the area where RMSE's are less than 61 cm also could have been chosen as calibration points with regard to measured and simulated water levels.



EXPLANATION

60.7 ◉ ROOT MEAN SQUARED ERROR OF MEASURED TO CALIBRATED WATER LEVEL, IN CENTIMETERS, AT THE CALIBRATION POINT

63.4 • ROOT MEAN SQUARED ERROR OF MEASURED TO CALIBRATED WATER LEVEL, IN CENTIMETERS

Figure 21. Sensitivity of the ground-water-flow model of the southern watersheds of Virginia Beach, Virginia, to changes in hydraulic conductivity.

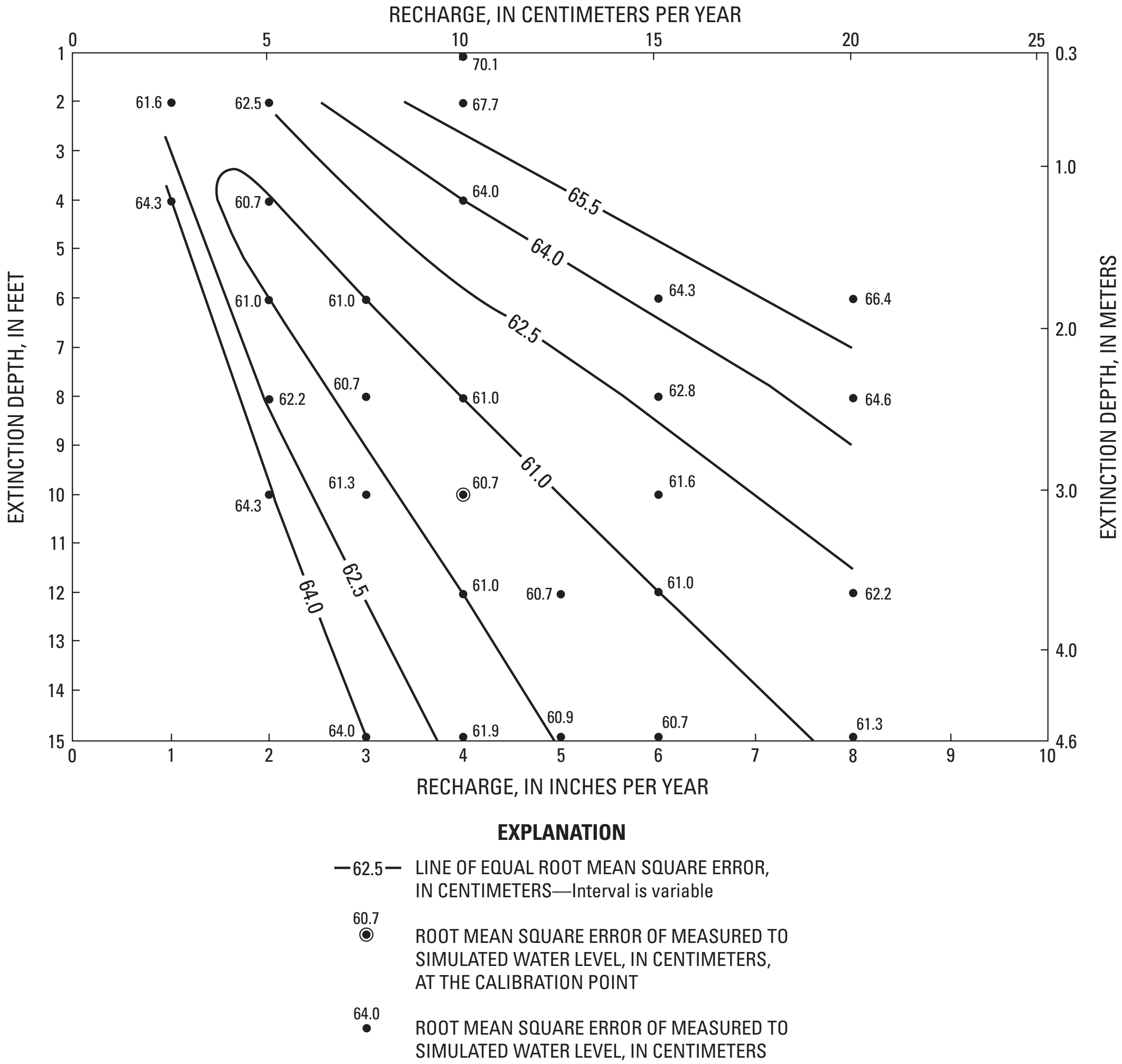


Figure 22. Sensitivity of the ground-water-flow model of the southern watersheds of Virginia Beach, Virginia, to mutual changes in recharge rates and extinction depths.

ANALYSES OF GROUND-WATER FLOW AND SALINE-WATER INTRUSION

The periodic recharge of freshwater to the Columbia aquifer sustains annual ground-water levels in the shallow aquifer system. Steady annual water levels sustain a dynamic equilibrium whereby freshwater flows continually down and away from the center of the higher ground and the sand ridges to mix with saline water from the tidal rivers, salt marshes, inlets, bays, and the Atlantic Ocean. Some freshwater also leaks down through the Yorktown confining unit into the top of the Yorktown-Eastover aquifer, but saline water generally is found in the lower parts of the aquifer.

Once calibrated to the dynamic equilibrium, the ground-water-flow and solute-transport model was used to estimate a ground-water budget of the southern watersheds and to simulate patterns of ground-water flow and the distribution of chloride concentrations in the aquifers. The steady-state ground-water-flow and solute-transport model was used to simulate declines in water levels (drawdowns) around two hypothetical well fields and to simulate the potential movement of chloride concentrations representing saline-water intrusion near one of those hypothetical well fields. The model also was used to simulate drawdowns around two hypothetical open-pit mines.

Ground-Water Budget

A ground-water budget for the southern watersheds can be estimated from the mass balance of the calibrated ground-water-flow model of the shallow aquifer system. Rates of 10 cm/yr applied to the top cells of the calibrated model resulted in a volumetric recharge of 145,000 m^3/d to the watersheds. Evapotranspiration removed 119,000 m^3/d, or about 82 percent of the recharge, leaving 26,000 m^3/d (7 million gal/d), or about 18 percent, as effective recharge to the water table. Inflow from constant heads, representing freshwater lakes and ponds, provided another 400 m^3/d.

Of the water that effectively recharged the shallow aquifer system, 23,000 m^3/d (6 million gal/d) discharged to the tidal zones and open waterways, including the Intracoastal Waterway, North Landing River, West Neck Creek, the Back Bay, and the Atlantic Ocean, represented by constant heads in the model. A smaller portion of recharge–3,700 m^3/d (1 million gal/d)–discharged to drain cells of the model representing non-tidal, freshwater ditches and streams.

Some ground water also is removed from the watersheds by pumping for domestic drinking water and irrigation, but those withdrawals are a negligible percentage of the total annual withdrawals. Domestic ground-water use was small, estimated at 1,400 m^3/d (0.38 million gal/d) for southern Virginia Beach (Johnson, 1999), and irrigation use for agriculture and golf courses was sporadic, estimated at 790 m^3/d (0.21 million gal/d) in all of Virginia Beach in 2000 (U.S. Geological Survey, 2003, Aggregate Water Use Data System).

Ground-Water-Flow Patterns and Chloride Distributions

Ground-water-flow patterns in shallow aquifers reflect the topography. Simulated water levels and flow vectors of the calibrated ground-water model show the general patterns of flow in the aquifers of the southern watersheds. In the Columbia aquifer, water from the higher land surface of the watersheds flows downward and outward toward the nearest drains and tidal streams where the flow changes abruptly upward indicating where most of the ground water discharges (fig. 23).

Along the ground-water divide of the two watersheds, near and along Pungo Ridge, the flow is downward and outward in the Columbia aquifer west to the wetlands along the North Landing River and east to the Back Bay or the Atlantic Ocean where the ground water discharges near the shore. Farther out in the Back Bay and the Atlantic Ocean, negligible flow velocities are indicated by small vectors (dots). Some ground water also leaks downward through the confining units beneath the Columbia into the confined aquifers.

In the model layer representing the sand aquifer between the two confining units of the Yorktown, the flow patterns are similar to that of the Columbia aquifer, but upward leakage over a broader area indicates a more intermediate pattern for the sand unit of the Yorktown (fig. 24). Much of the water that leaks downward into the confined sand unit of the Yorktown leaks back upward into the Columbia aquifer and discharges locally to the nearest wetland or tidal creek, or to the Back Bay and the Atlantic Ocean. Some small amount of water, however, leaks further downward from the sand unit and the confining unit beneath into the Yorktown-Eastover aquifer beneath.

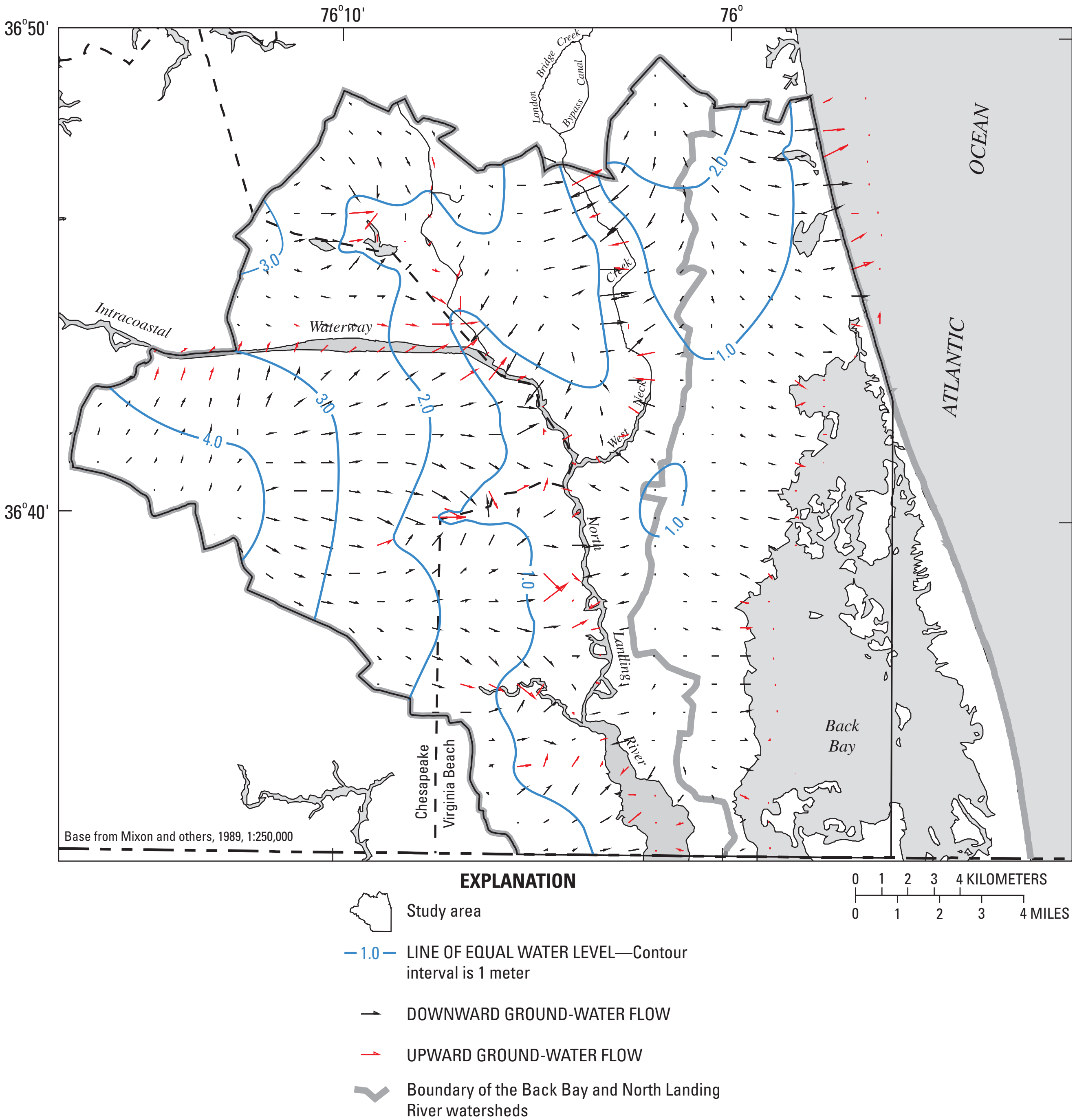


Figure 23. Simulated flow vectors and water levels in the lower half of the Columbia aquifer of the southern watersheds of Virginia Beach, Virginia.

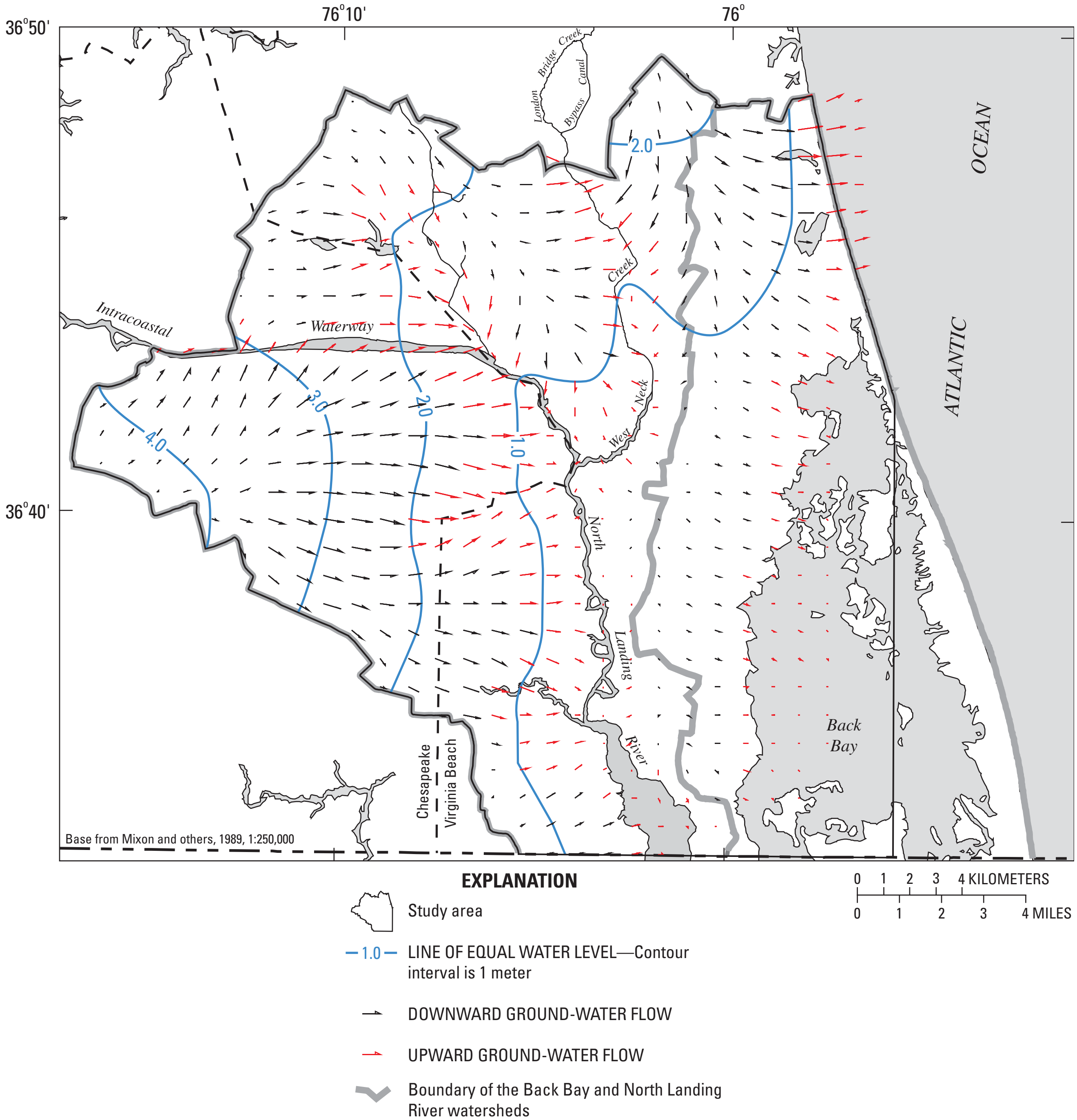


Figure 24. Simulated flow vectors and water levels in the sand aquifer of the Yorktown confining unit of the southern watersheds of Virginia Beach, Virginia.

In the model layer representing the upper half of the Yorktown-Eastover aquifer, the basic flow patterns are more regional than those of the shallower aquifers. Almost all of the flow is from the west and north toward the east or south as opposed to some westward flow paths toward West Neck Creek and the North Landing River in the shallower aquifers (fig. 25). Ground water is leaking upward from the Yorktown-Eastover aquifer over a broad area along the wetlands and tidal rivers of West Neck Creek and North Landing River and to the Atlantic Ocean. To the southeast, negligible flow velocities are indicated by small vectors in and around the Back Bay. Most of the upward leakage from the Yorktown-Eastover aquifer would be expected to discharge within the wetlands of the North Landing River. Saline water, not displaced by freshwater, probably remains in the Yorktown-Eastover aquifer in the south and east, as indicated by the ground-water flow and solute simulations. The simulated flow patterns indicate that the freshwater to saline water components of the shallow aquifer system probably are in or are approaching a dynamic equilibrium.

The simulated distributions of chloride indicate that freshwater has been displaced in some areas in the upper half of the Yorktown-Eastover aquifer (fig. 26), but saline water predominates in the lower half of the Yorktown-Eastover (fig. 27). The simulated distribution of chloride concentrations in the Yorktown-Eastover aquifer approximate those measured and contoured (fig. 13). Both the simulated and measured distributions of chloride indicate that freshwater in the Yorktown-Eastover aquifer probably is limited to isolated areas below the higher altitudes in the west and north along the watershed divide and along the divide of the two southern watersheds beneath the northern parts of Pungo Ridge.

Drawdowns Near Hypothetical Well Fields

The aquifers of the shallow aquifer system were deposited in shifting coastal environments, and the sediments that comprise the aquifers can change over relatively short distances from sand and gravel to fine sand, including some silt, to silt and clay. Recharge to the aquifers is limited in large tracts of the watersheds by clayey soils and extensive wetlands. Also, the quality of the water available from the aquifers can vary considerably from one location to another. All of these factors have limited large-scale production of ground water in the watersheds, and in the rest of Virginia Beach and the surrounding area as well.

One of the most productive well fields in Virginia Beach was at Pembroke about 3 km north of the study area (fig. 1). The Pembroke well field produced sustained freshwater supplies from a depth of about 38 m beginning in 1963. A total of about 1,100 m^3 of water per day (300,000 gal/d) was pumped from seven active wells at Pembroke in 1979 (Geraghty and Miller, 1979, p. 1-3). Well production could have been increased at Pembroke, but the risk of upward movement or intrusion of “brackish water” limited the supply (Wiley and Wilson, Inc., 1979, p. 7).

Using the Pembroke well field as an indicator, about 1,900 m^3/d (0.5 million gal/d) was assumed to be the maximum sustained production for simulating well fields in this report. To compare drawdowns from different permeable zones, two hypothetical well fields, each steadily pumping 1,900 m^3/d from the upper half of the Yorktown-Eastover aquifer, were simulated with the calibrated model (fig. 28). Both well fields were located on the ground-water divide of the two watersheds, but the well field to the north probably would have a higher hydraulic conductivity (7.6 m/d in the model) whereas the well field to the south would be in an area of the Yorktown-Eastover aquifer identified by coring and by local drillers as generally having lower hydraulic conductivity (2 m/d in the model).

The hypothetical well fields pump at the same rates, but the depth and extent of the water-level declines (drawdowns) in and around the well fields would be different at the new steady state, as indicated by the simulated contours. Pumping the hypothetical well field in the north, in more permeable sediments, would result in a smaller drawdown affecting a smaller area in the confined aquifer than the well field in the south. Pumping from the confined aquifer in the south, in less permeable sediments, would result in a deeper drawdown and the area affected would be greater than that in the north. The drawdown in the southern well field also is affected by hydraulic boundaries around the site, causing some elongation in the shape of the simulated concentric contours.

Intrusion of Saline Water Near a Hypothetical Well Field

Beneath the divide of the watersheds along the northern stretch of Pungo Ridge, freshwater recharges

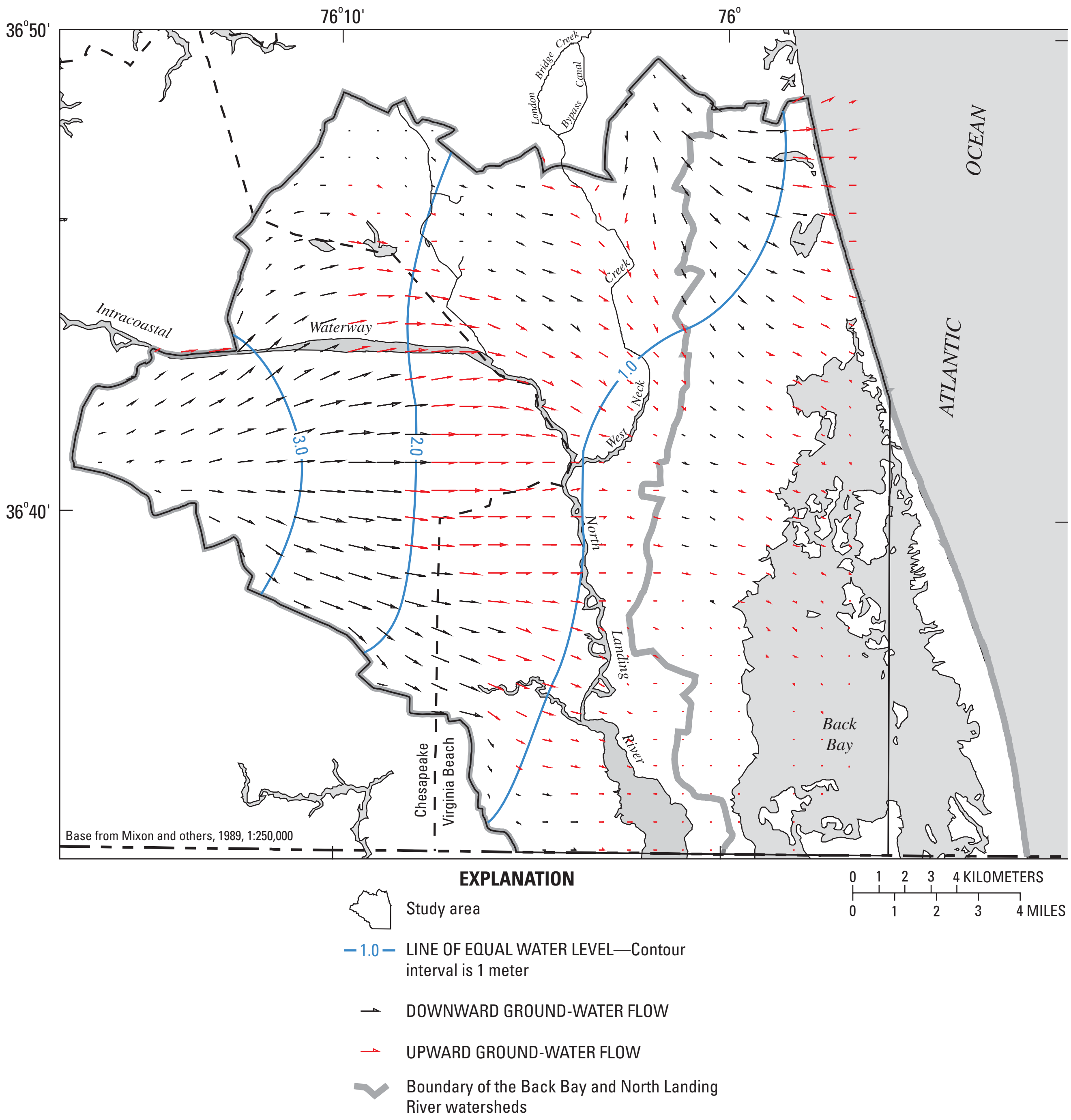


Figure 25. Simulated flow vectors and water levels in the upper half of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

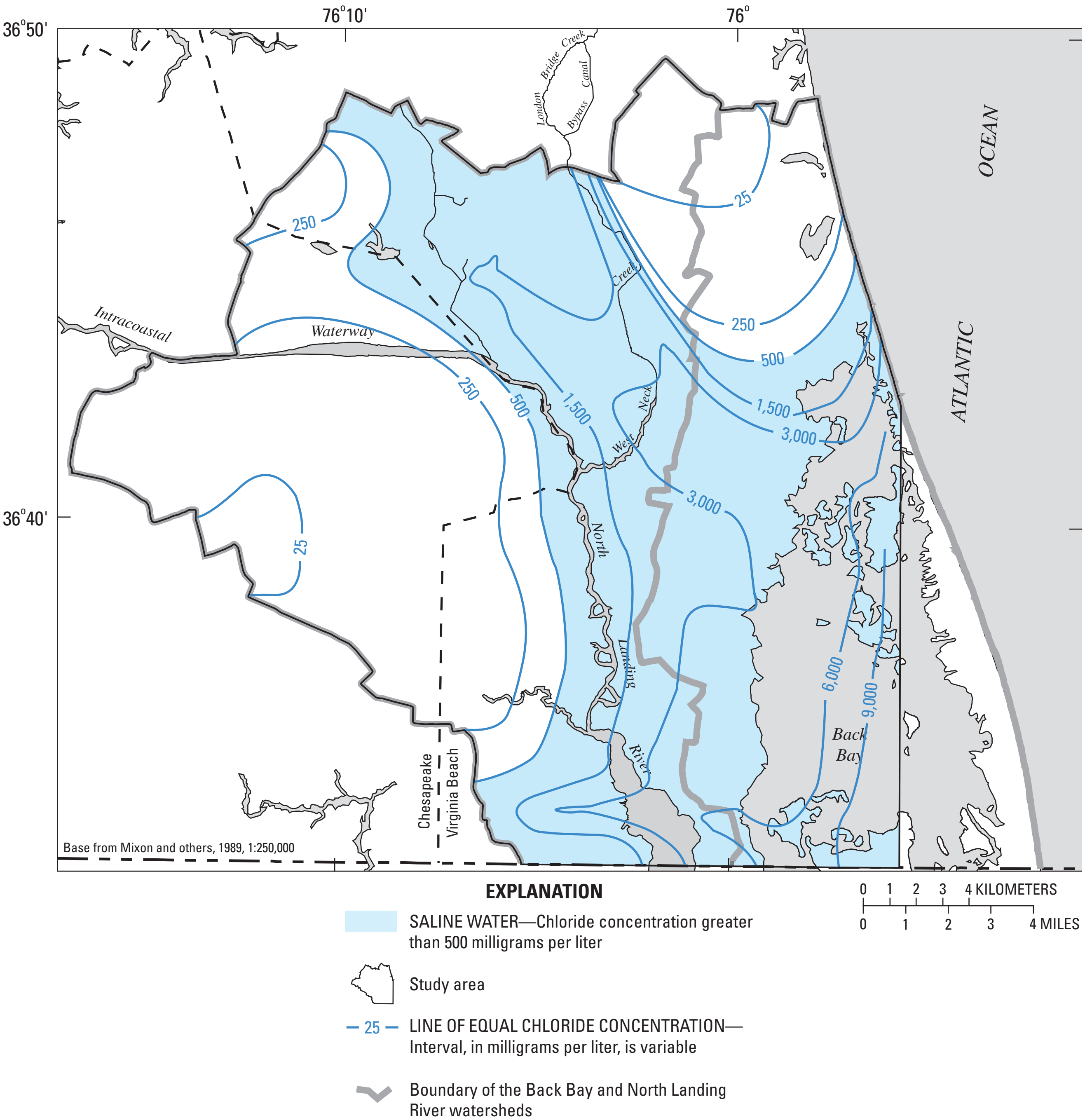


Figure 26. Simulated chloride concentrations in the upper half of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

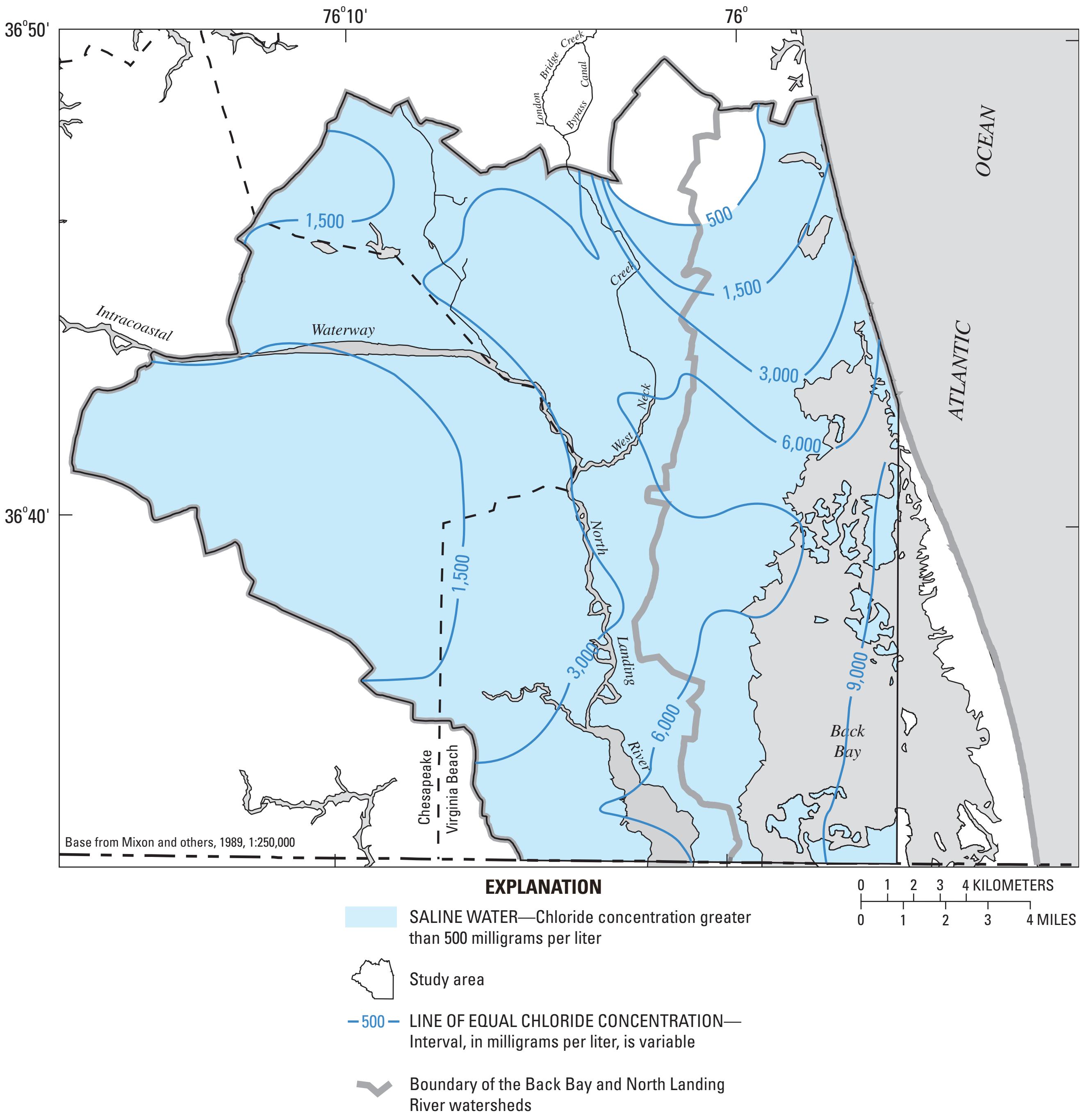
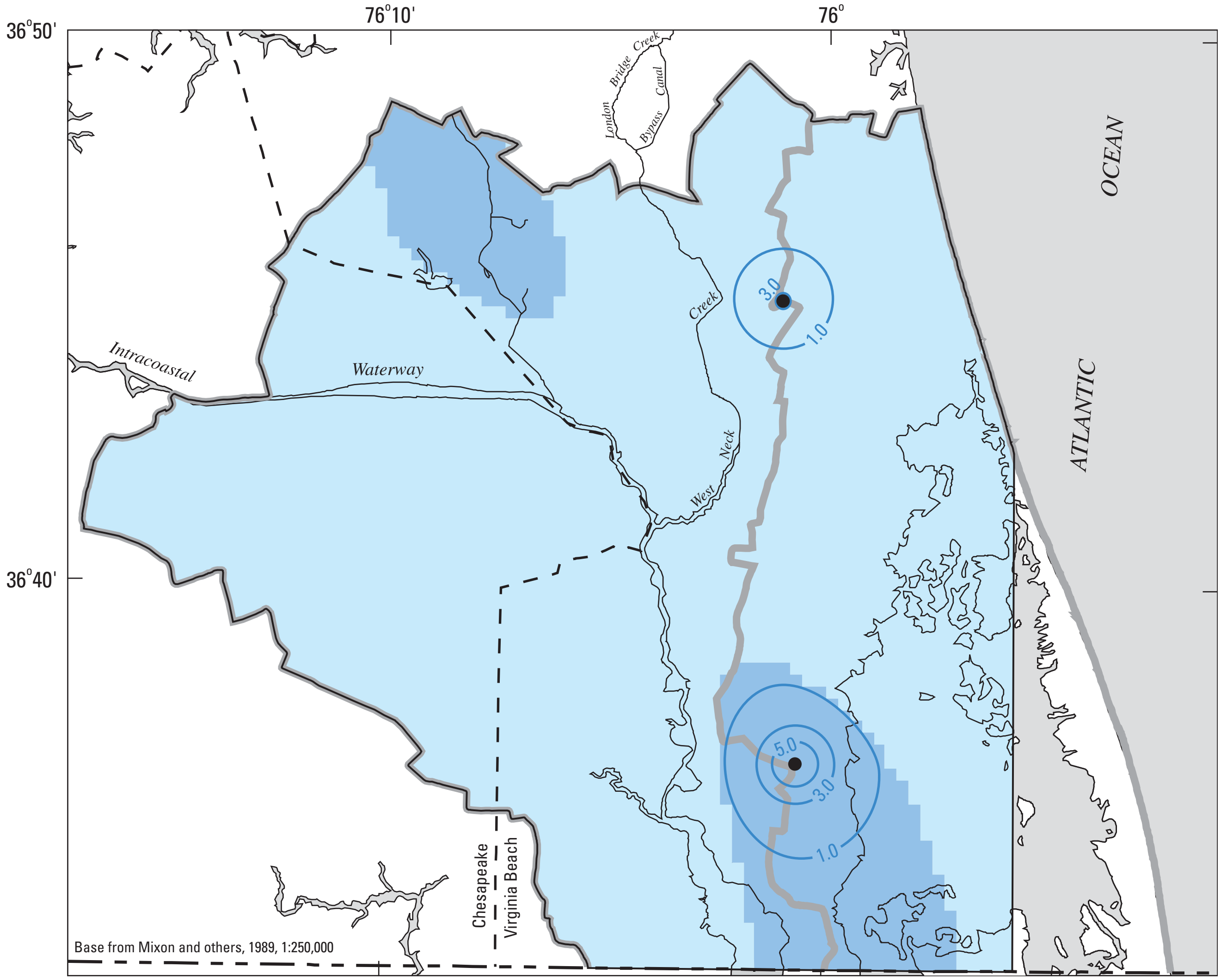


Figure 27. Simulated chloride concentrations in the lower half of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.



EXPLANATION

HYDRAULIC CONDUCTIVITY 2 METERS PER DAY

HYDRAULIC CONDUCTIVITY 7.6 METERS PER DAY

Study area

—1.0— LINE OF EQUAL DRAWDOWN, IN METERS—Contour interval is 2 meters

● HYPOTHETICAL WELL FIELD

Figure 28. Drawdowns around two hypothetical well fields, each pumping 1,900 cubic meters per day (0.5 million gallons per day), on the boundary of the watersheds from the upper half of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

the water table (Columbia aquifer) and, in some places, leaks into the top of the Yorktown-Eastover aquifer. Supplies of freshwater from the Yorktown-Eastover are a possibility in Virginia Beach and in the surrounding area; however, such supplies have been limited because of saline-water intrusion. "With little exception, all large scale pumping operations (> 300,000 gpd [1.1 Ml/day]) have resulted in brackish or saline water intrusion and upconing" (Leahy, 1986, p. 3). The potential intrusion of saline water toward the northern hypothetical well field of the previous scenario was simulated. Intrusion of saline water toward the southern well field was not simulated because of low permeability and the lack of freshwater in the Yorktown-Eastover aquifer there.

Chloride movement toward the hypothetical northern well field of the previous scenario was simulated for 100 years with the calibrated ground-water-flow and solute-transport model to indicate the potential for saline-water intrusion in the confined aquifer. Pumping from the top half of the Yorktown-Eastover aquifer beneath the ridge would remove freshwater. The result would be to allow saline water in the aquifer to begin moving slowly toward the well field, as indicated by simulated chloride concentration gradients in the aquifer from just after the start of pumping (A), after 33 years of pumping (B), after 67 years of pumping (C), and after 100 years of pumping (D) (fig. 29). The nearest source of saline water in the aquifer would be from the southwest beneath West Neck Creek. (Saline water probably was not displaced by freshwater beneath West Neck Creek at the end of the Pleistocene, and the creek is tidal and remains a possible source of saline water.)

After 100 years, the 250-mg/L chloride line would be within the simulated pumping cell approaching the center of the well field and the 500 mg/L chloride line would be close behind. In the simulation, chloride concentrations in the center of the pumping cell changed from 90 mg/L to 150 mg/L over the 100-year span. Saline water to the east also would move toward the well field. The eastern source, however, is farther away than the southwestern source and it would not approach the well field in 100 years.

A vertical view of the simulated pumping cell, exaggerated 10 times, indicates that upward movement of saline water from deeper units beneath the well field probably would not take place in 100 years (fig. 30). Changes in chloride concentrations to the east of the well also were negligible in the vicinity of the well. To the west of the pumping cell, however, the saline water would begin moving slowly eastward toward the well field, as shown by the changes in lines of equal chloride concentrations of 250, 500, and 1,000 mg/L. Much of the apparent upward movement of chloride concentration gradients in this view is an artifact of the vertical exaggeration of the illustration.

The simulation indicates that if freshwater is found in sediments of the Yorktown-Eastover aquifer and if those sediments are permeable enough to supply 1,900 m^3/d (0.5 million gal/d), such a well field could sustain freshwater for a considerable time (possibly decades), but eventually the supply would become more saline. The rate of saline-water intrusion toward the freshwater supply would depend on the rate of pumping, the aquifer properties in and around the site, and the proximity of the well field to saline-water sources. Desalination could, however, extend the use such a well field.

Drawdowns Around Hypothetical Open-Pit Mines

The sand-and-gravel deposits that form some of the most permeable aquifers of the shallow system also are sources of building materials. Open pit mining of sand and gravel has been a common practice in the southern watersheds and throughout Virginia Beach in the recent past. Dewatering of the open pits can affect the water supplies of surrounding areas.

To analyze the potential affects of dewatering from the Columbia aquifer, two cells, each 400 m^2, in the top layer of the calibrated model were pumped steadily. Both cells were on the divide between the two southern watersheds, at the same locations as in the previous simulations, but the dewatering would be from the unconfined Columbia aquifer, which has different hydraulic properties than the deeper confined aquifer. The pumping rates required to dewater each cell to approximately the same depth was determined by trial and error. The simulated well screen was 1.5 m in length at the bottom of each cell.

Differences in the simulated pumping rates required to dewater the cells to approximately the same depth reflect differences in the local hydrogeology, primarily the hydraulic conductivity of the Columbia aquifer at each site (fig. 31). The site to the north is in an upland area that was represented in the model as having a hydraulic conductivity of 7.9 m/d. To dewater the cell to the north, 545 m^3/d (100 gal/min) was required. The

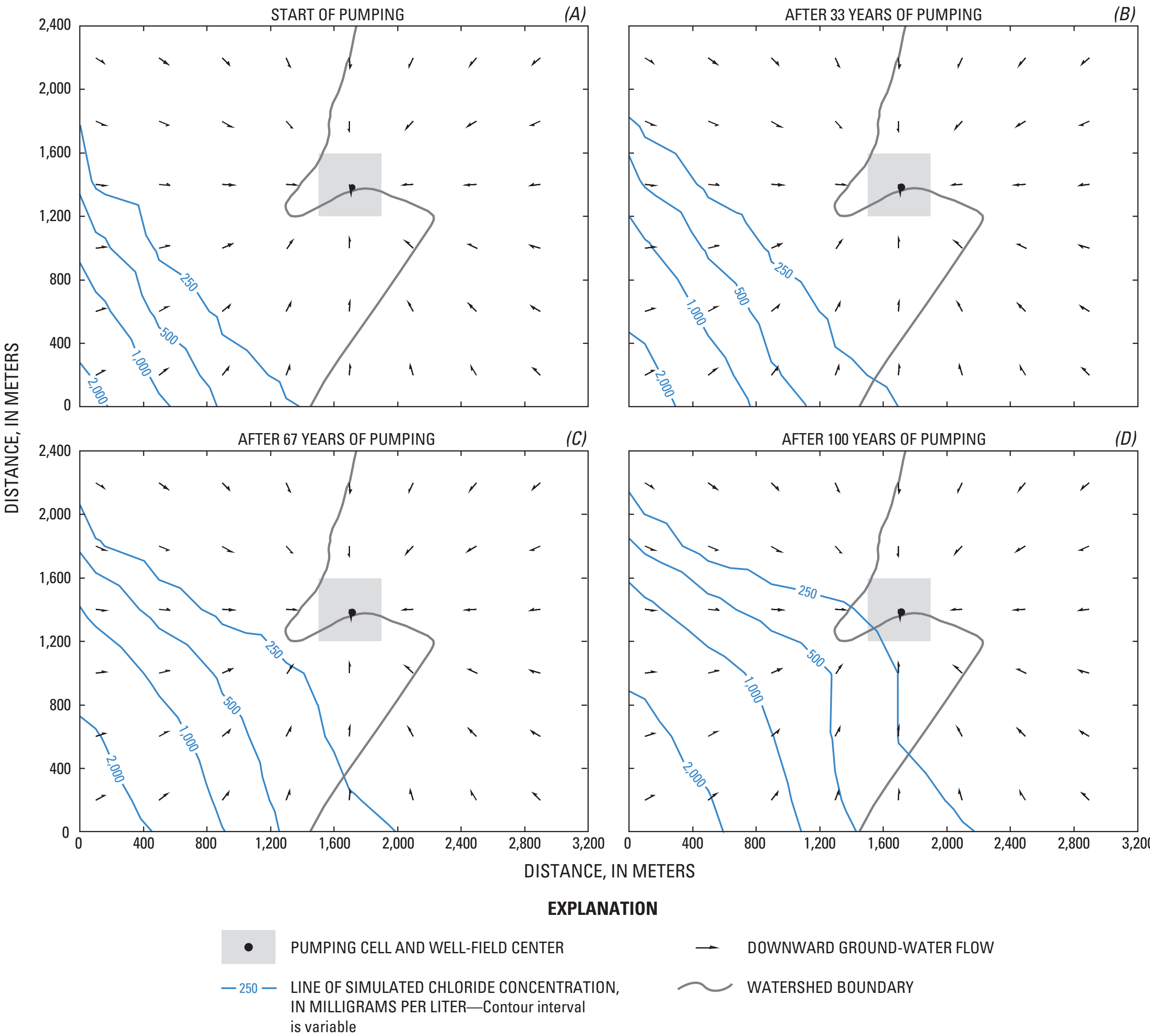


Figure 29. Horizontal view of simulated chloride concentrations approaching a hypothetical well field pumping 1,900 cubic meters per day at start of pumping *(A)*, after 33 years of pumping *(B)*, after 67 years of pumping *(C)*, and after 100 years of pumping *(D)*, on the boundary of the watersheds from the upper half of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

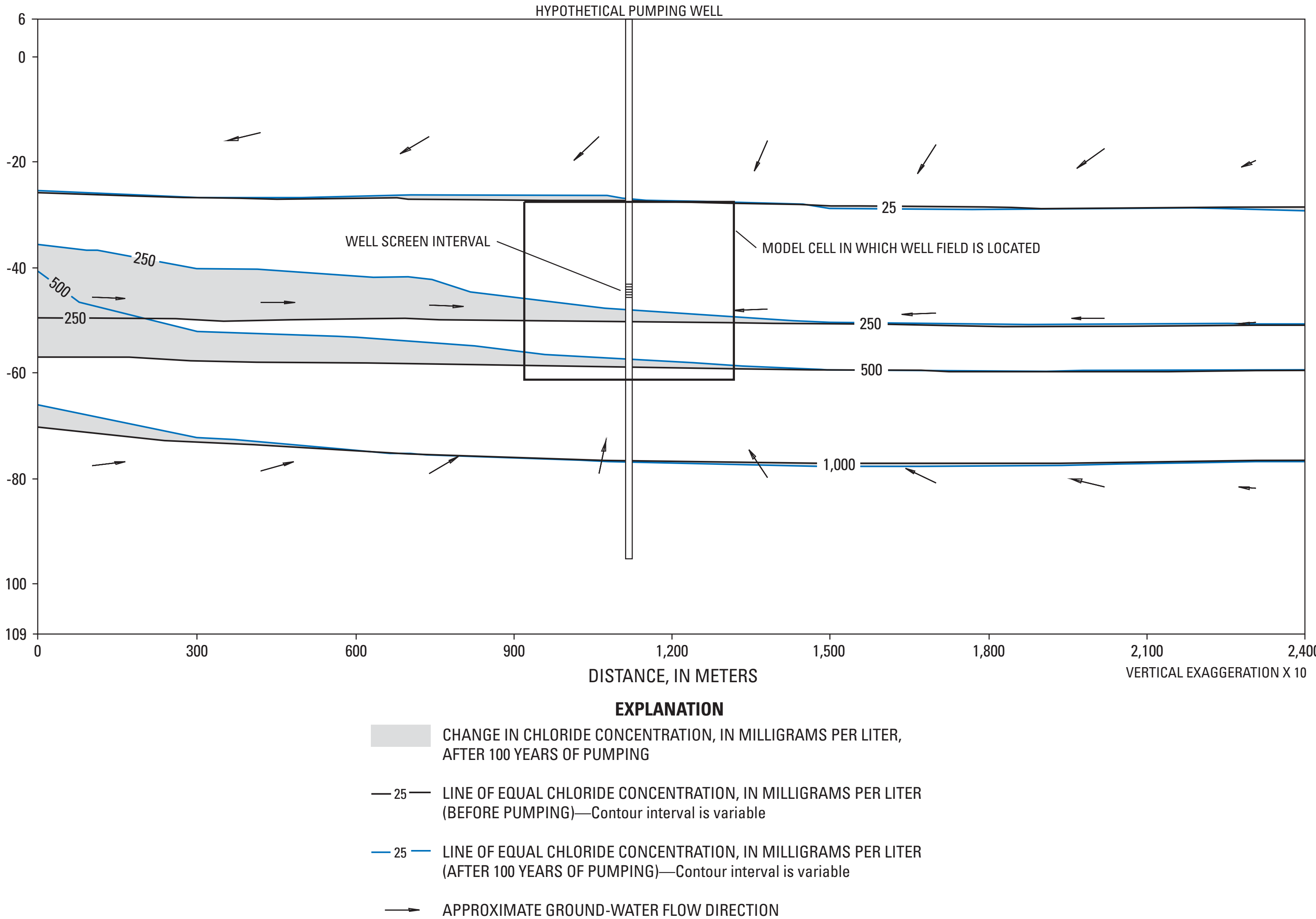


Figure 30. Vertical view of simulated changes in chloride concentrations near a hypothetical well field after 100 years of pumping 1,900 cubic meters per day (0.5 million gallons per day) in the upper half of the Yorktown-Eastover aquifer of the southern watersheds of Virginia Beach, Virginia.

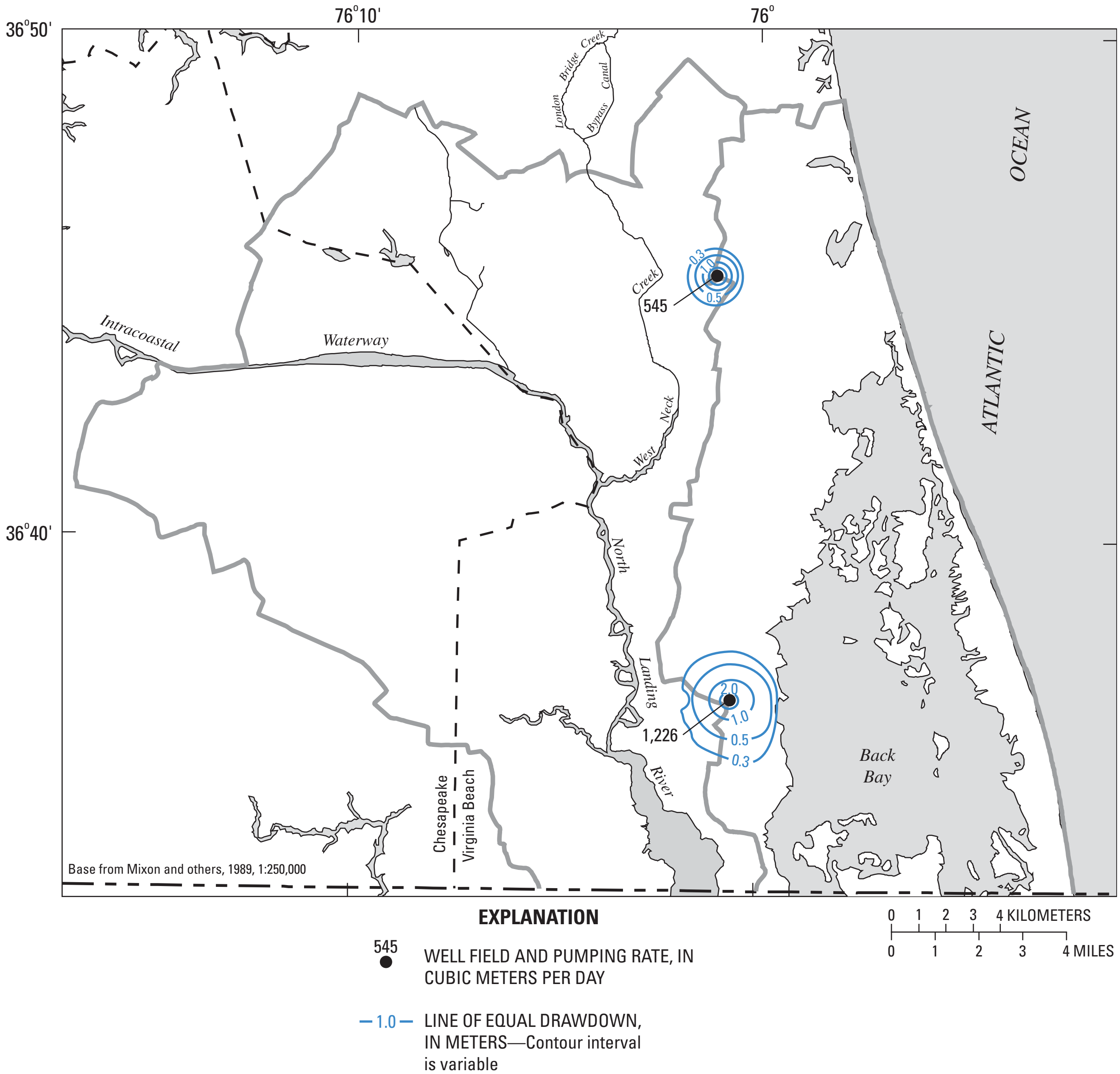


Figure 31. Simulated flow directions and drawdowns around two hypothetical open-pit mines pumping on the watershed boundary from the water table (Columbia aquifer) in the southern watersheds of Virginia Beach, Virginia.

drawdown at the center of the cell was 5 m and the radius of the 0.3-m drawdown contour was about 1 km.

The site to the south was in the Poquoson Member of the Sedgefield Formation that had the highest permeability in the model, a hydraulic conductivity of 30 m/d, almost four times that of the site to the north. To dewater this site would require about 1,200 m^3/d (225 gal/min) or more than twice the pumping rate of the site to the north. The drawdown at the center of the cells was 4.1 m and the radius of the 0.3-m drawdown contour was about 2.5 km at the maximum elongation.

Drawdown at the center of each well was approximately the same but the shape of the cone of depression, indicated by the contoured declines in water levels around each site, was different. The dewatering of the southern site would affect a larger area, as indicated by the 0.3-m (1-ft) drawdown contour. A notch in the 0.3-m drawdown contour to the west resulted from encountering a wetland cell, which was designated with a hydraulic conductivity of 0.3 m/d. To the east, the 0.3-m contour reached the hydraulic boundary of the constant-head cells of Back Bay.

The model simulations indicate that the pumping rate required to dewater a site depend on the aquifer properties and on the hydrologic boundaries in and around the site. More pumping is required to dewater a site where sediments are more permeable, and a larger area around the site would be affected than at a site where materials are less permeable.

SUMMARY AND CONCLUSIONS

Population and tourism continues to grow in Virginia Beach, but the supply of freshwater is limited. A pipeline from Lake Gaston supplies water for northern Virginia Beach, but ground water is widely used to water lawns in the north, and most southern areas of the city rely solely on ground water. Supplies of fresh ground water are limited by high concentrations of chloride, iron, and manganese in some areas. Water from depths greater than 60 m generally is too saline to drink. The city of Virginia Beach and the U.S. Geological Survey began a cooperative study to (1) refine the hydrogeologic framework of the shallow aquifer system, and (2) better understand the distribution of fresh ground water, its potential uses, and its susceptibility to contamination.

Specific objectives of this phase of the investigations were to (1) map chloride concentrations in the shallow aquifers of the southern watersheds of Virginia Beach, (2) determine the patterns of ground-water flow in the shallow aquifers of the southern watersheds, and (3) evaluate potential changes in drawdowns and chloride concentrations, representing saline-water intrusion, resulting from hypothetical withdrawals of ground water in the southern watersheds of Virginia Beach.

The Columbia aquifer, the Yorktown confining unit, and the Yorktown-Eastover aquifer compose the hydrogeologic units of the shallow aquifer system of Virginia Beach. The top altitudes of these units were extended from continuous core sites reported previously, to other sites in the southern watersheds, where geophysical logs and lithologic descriptions of sediments had been recorded. The top altitudes of the units were contoured by linear Kriging. Chloride data collected during this investigation and from previous studies were contoured also by linear Kriging to map the general distribution of chlorides for each unit.

The Columbia and Yorktown-Eastover aquifers are poorly confined throughout most of the southern watersheds of Virginia Beach and the freshwater-to-saline-water distribution is in a dynamic equilibrium with average ground-water levels, measured concentrations of dissolved salts (chlorides), and modern sea levels. The chloride concentrations measured in water from wells open to the shallow aquifers and confining units of the southern watersheds showed virtually no changes in concentration through recent time.

In the humid climate of Virginia Beach, the periodic recharge of freshwater through the shallow aquifer system occurs often enough to create a steady-state balance or a dynamic equilibrium whereby freshwater flows continually down and away from the center of the higher ground and the sand ridges to mix with saline water from the tidal rivers, bays, salt marshes, and the Atlantic Ocean. Fresh ground water from the Columbia aquifer also leaks down through the Yorktown confining unit into the upper half of the Yorktown-Eastover aquifer and then flows within the Yorktown-Eastover above saline water that remains in the lower half of the shallow aquifer system.

Ground-water-flow patterns in shallow aquifers of Virginia Beach reflect the topography. Ground-water recharge is limited in much of the southern watersheds because the land surface generally is low and flat, whereas bays, wetlands, tidal rivers, and tidal streams where fresh ground water discharges extend throughout the watershed area. Also, soils over much of the watersheds are rich in clay and ditching has been used to lower the water table for agriculture. Where sand ridges do allow greater recharge, generally unconfined conditions prevail. Ground-water flow can be deeper below the ridges, but discharge areas are nearby in wetlands, tidal creeks, or just off shore in the Back Bay or the Atlantic Ocean. Thus, ground-water-flow lines tend to be short and shallow in much of the southern watersheds.

A three-dimensional, steady-state, ground-water-flow and solute-transport model was used to simulate the dynamic equilibrium between freshwater and saline water in the shallow aquifer system as indicated by water-level hydrographs and chloride concentrations. The equilibrium was approached after 31,550 years of freshwater recharge and displacement of saline. Saline water saturated the shallow aquifer system during the last major interglacial period more than 70,000 years ago when estuaries and shallow seas covered the area. At model calibration, average water levels were approximated slightly more accurately than chloride measurements (13-percent normalized RMSE of 38 water levels compared to 15-percent normalized RMSE of 123 chloride measurements). The chloride concentrations in the model did not approximate the measured concentrations for some wells, indicating sites where local hydrogeologic units or unit properties do not conform to the simple hydrogeology simulated with the model.

The calibrated steady state, ground-water-flow and solute-transport model was used to simulate hypothetical scenarios. The simulation indicates that if freshwater is found in sediments of the Yorktown-Eastover aquifer, and if those sediments are permeable enough to supply 1,900 m^3/d (0.5 million gal/d), such a well field could sustain freshwater, possibly for decades, but eventually the water would become more saline. The rate of saline-water intrusion toward the freshwater supply would depend on the rate of pumping, aquifer properties, and the proximity of the well field to saline water sources.

Steady-state simulations with the calibrated model also indicate that a pumping rate of 545 m^3/d (100 gal/min) would be required to dewater to a depth of 5 m in a hypothetical open-pit mine in the upland part of the Columbia aquifer and that the 0.3-m drawdown contour around the site would be about 1 km in radius. A pumping rate of 1,200 m^3/day (225 gal/min) would be needed to dewater an open-pit mine about 4.1 m deep in the Columbia aquifer where materials are more permeable, and a large area around the site, about 2.5 km at the maximum elongation, would be drawn down about 0.3 m.

The aquifers of the shallow aquifer system were deposited in shifting coastal environments, and the sediments that comprise the aquifers can change over relatively short distances from sand and gravel to fine sand, including some silt, to silt and clay. Also, the quality of water available from the aquifers can vary considerably from one location to another. Because it is difficult to correlate the discontinuous sediments from one site to another, the hydrogeologic framework of the shallow aquifer system is not well defined in many areas of the southern watersheds, as well as the rest of the city of Virginia Beach. Additional field information such as geophysical logs, coreholes, water-level observations, and water-quality data could improve the conceptual framework at the local (site-specific) scale in many areas of Virginia Beach. Such detailed information would be needed for any field explorations or site-specific ground-water-flow and solute-transport simulations.

The usual assumptions associated with ground-water-flow and solute-transport simulations of layered aquifer systems as applied to the models used in this study are valid for the objectives of this study. The assumptions are appropriate as used for the system conceptualization; however, before applying the model for other purposes, the appropriateness of the assumptions, particularly the boundary conditions, should be evaluated.

The ground-water-flow and solute-transport model of the southern watersheds documented in this report is a simple representation of a complex, and in some places, an uncertain hydrogeologic framework. The calibrated steady-state ground-water flow and solute-transport model does, however, combine a large amount of field information with sound hydraulic and transport principles to produce reasonable results on the watershed scale.

REFERENCES CITED

Bales, J.D., and Skrobialowski, S.C., 1994, Flow and salinity in West Neck Creek, Virginia, 1989-92, and salinity in North Landing River, North Carolina, 1991-92: U.S. Geological Survey Water-Resources Investigations Report 94-4097, Albemarle-Pamlico Estuarine Study Report No. 94-04, 36 p.

Betz-Converse-Murdoch, Inc., 1981, Development of fresh 10 MGD ground water supply—engineering report for the City of Virginia Beach: Vienna, Va., Betz-Converse-Murdoch, Inc., Potomac Group, variously paged.

Betz-Converse-Murdoch, Inc. by Converse-Ward-Davis-Dixon, 1981, Virginia Beach groundwater development project supporting data, vols. 1a, 1d, 2b, and 2c, Caldwell, N.J., Converse, Ward, Davis, Dixon, Inc, variously paged.

Caldwell, W.S., 2001, Hydrologic and salinity characteristics of Currituck Sound and selected tributaries in North Carolina and Virginia, 1998-99: U.S. Geological Survey Water-Resources Investigations Report 01-4097, 36 p.

City of Virginia Beach Department of Economic Development, 2002, City of Virginia Beach 2001-2002 Data Sheet, accessed August 23, 2002, at http://www.vbgov.com/dept/econdev/datasheets/2001ds.pdf).

City of Virginia Beach Department of Planning, 1996, Statistical and development information package, January 1, 1966, 117 p.

Converse-Ward-Davis-Dixon, Inc, for Betz-Converse-Murdoch, Inc., 1981, Report of hydrogeologic investigation, groundwater development phase, Virginia Beach fresh groundwater project for City of Virginia, Virginia: Caldwell, N.J., Converse, Ward, Davis, Dixon, Inc, 199 p., 1 attachment, 2 app.

Davis, S.N. and Dewiest, R.J.M., 1966, Hydrogeology: New York, John Wiley and Sons, 118 p.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley and Sons, 824 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Geotrans, Inc., 1981, Final report on the quantitative evaluation of ground-water resources in the Virginia Beach area, Virginia-Attachment I to report Hydrogeologic investigation groundwater development phase Virginia Beach fresh groundwater project for City of Virginia Beach prepared for Converse, Ward, Davis, Dixon, Inc.: Caldwell, N.J., 107 p.

Geraghty & Miller, Inc., 1978, Availability of ground water for public supply in the City of Virginia Beach, Virginia-Prepared at the request of Wiley & Wilson, Inc., for the City of Virginia Beach: Tampa, Fl., Geraghty & Miller, Inc., 57 p.

Geraghty & Miller, Inc., 1979, Evaluation of pumping test on Yorktown Aquifer, City of Virginia Beach, Virginia-Prepared for Wiley & Wilson, Inc.: Annapolis, Md., Geraghty & Miller, Inc., 49 p.

Hamilton, P.A., and Larson, J.D., 1988, Hydrogeology and analysis of the ground-water flow system in the Coastal Plain of southeastern Virginia: U.S. Geological Survey Water-Resources Investigations Report 87-4240, 175 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model --User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Harsh, J.F. and Laczniak, R.J., 1990, Conceptualization and analysis of the ground-water flow system in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina, Regional Aquifer-System Analysis-Northern Coastal Plain: U.S. Geological Survey Professional Paper 1404-F, 100 p.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p., 3 pl.

Henry, H.R., 1964, Effects of dispersion on saltwater encroachment in a coastal aquifer, *in* Cooper, H., and others, eds., Sea water in coastal aquifers: U.S. Geological Survey Water-Supply Paper 1613-C, p. 70-84.

Jacob, C.E., 1963, Correction of drawdowns caused by a pumped well tapping less than the full saturated thickness, *in* Bental, Ray, comp., Methods of determining permeability, transmissivity, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 272-282.

Johnson, G. H. and Berquist, C.R., Jr., 1989, Geology and mineral resources of the Brandon and Norge quadrangles, Virginia: Virginia Division of Mineral Resources Publication 87, 28 p., 1 pl.

Johnson, G. H., Kruse, S.E., Vaughn, A.W., Lucey, J.K., Hobbs, C.H. III, and Powars, D.S., 1998, Postimpact deformation associated with late Eocene Chesapeake Bay impact structure in southeastern Virginia: Geology, v. 26, no. 6, p. 506-510.

Johnson, H.M., IV, 1999, The Virginia Beach shallow ground-water study: U.S. Geological Survey Fact Sheet 173-99, 2 p.

Krieger, R.A., Hatchett, J.L. and Poole, J.L., 1957, Preliminary survey of the saline-water resources of the United States: U.S. Geological Survey Water Supply Paper 1374, 172 p.

Laczniak, R.J., and Meng, A.A., III, 1988, Ground-water resources of the York-James Peninsula of Virginia: U.S. Geological Survey Water-Resources Investigations Report 88-4059, 178 p.

Leahy, T. M., III, 1986, The potential for desalting in Hampton Roads, Virginia: City of Virginia Beach, Va., 48 p.

Malcolm Pirnie, 1997a, Application for a Permit to Withdraw Ground Water, PGA Tour Construction Services, 3279-001, TCP of Virginia Beach, Virginia: Virginia Department of Environmental Quality Permit Parts 11-14, variously paged.

Malcolm Pirnie, 1997b, Application for a Permit to Withdraw Ground Water, Heron Ridge Golf Club 3309-001, West Neck Creek, Virginia Beach, Virginia: Virginia Department of Environmental Quality Permit Parts 11-14: Malcolm Pirnie, variously paged.

MacDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water-flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, variously paged.

Meng, A.A., III, and Harsh, J.F., 1988, Hydrogeologic framework of the Virginia Coastal Plain-Regional Aquifer-System Analysis: U.S. Geological Survey Professional Paper 1404-C, 82 p., 4 pls.

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, 1989: U.S. Geological Survey Miscellaneous Investigations Series Map I-2033, 2 sheets, scale 1:250,000.

Mixon, R.B., Szabo, B.J., and Owens, J.P., 1982, Uranium-series dating of mollusks and corals, and age of Pleistocene deposits, Chesapeake Bay area, Virginia and Maryland: U.S. Geological Survey Professional Paper 1067-E, 18 p.

National Climatic Data Center, 2002, Climate at a Glance, Climate Monitoring, Norfolk Climate Summary, National Climatic Data Center Asheville, N.C., accessed August 28,2002, at http://www.ncdc.noaa.gov/cgi-bin/cag3/hr_display3.pl.

Oaks, R.Q., Jr., and Coch, N.K., 1973, Post-Miocene stratigraphy and morphology, southeastern Virginia: Virginia Division of Mineral Resources Bulletin 82, 135 p., 2 pls.

Peebles, P.C., Johnson, G.H., and Berquist, C.R., 1984, The Middle and Late Pleistocene stratigraphy of the outer Coastal Plain, southeastern Virginia: Virginia Minerals, v. 30, no. 2, p. 13-22.

Powars, D. S., 2000, The effects of the Chesapeake Bay impact crater on the geologic framework and the correlation of hydrogeologic units of southeastern Virginia, south of the James River: U.S. Geological Survey Professional Paper 1622, 54 p., 1 pl.

Richardson, D.L., 1994a, Hydrogeology and analysis of the ground-water-flow system of the Eastern Shore, Virginia: U.S. Geological Survey Water-Supply Paper 2401, 108 p., 1 pl.

Richardson, D.L., 1994b, Ground-water discharge from the Coastal Plain of Virginia: U.S. Geological Survey Water-Resources Investigations Report 93-4191, 15 p.

Robinson, M.A. and Reay, W.G., 2002, Ground water flow analysis of a Mid-Atlantic outer Coastal Plain watershed, Virginia, U.S.A.: Groundwater, v. 40, no. 2, p. 123-131.

Siudyla, E.A., May, A.E., and Hawthorne, D.W., 1981, Ground water resources of the Four Cities Area-Norfolk, Portsmouth, Virginia Beach, Chesapeake: Virginia State Water Control Board Planning Bulletin 331, 167 p., 25 pl.

Sanford, Ward, 2002, Recharge and ground-water models: an overview: Hydrogeology Journal, v. 10, p. 110-120.

Smith, B.S. and Harlow G. E., Jr., 2002, Conceptual hydrogeologic framework of the shallow aquifer system at Virginia Beach, Virginia: U.S. Geological Survey Water-Resources Investigations Report 01-4262, 32 p.

Smith, B.S., 2001, Ground-water flow in the shallow aquifer system at the Naval Weapons Station Yorktown, Virginia: U.S. Geological Survey Water-Resources Investigations Report 00-4077, 33 p.

Spruill, T.B., Harned, D.A., Ruhl, P.M. Eimers, J.L. McMahon, G., Smith, K.E., Galeone, D.R. and Woodside, M.D., 1998, Water quality in the Albemarle-Pamlico Drainage Basin, North Carolina and Virginia, 1992-95: U.S. Geological Survey Circular 1157, 36 p.

Todd, D.K.,1980, Groundwater hydrology: New York, John Wiley and Sons, 535 p.

Toth, J. 1963, A theoretical analysis of ground-water flow in a small drainage basin: Journal of Geophysical Resources, vol. 68, p. 4795-4812.

U.S. Department of the Interior, 1989, Subsurface-water flow and solute transport—Federal glossary of selected terms: Reston, Va., U.S. Geological Survey, Office of Water Data Coordination, 38 p.

U.S. Environmental Protection Agency, Summer 2002, 2002 Edition of drinking water standards and health advisories: EPA 822-R-02-038, Office of Water, USEPA, Washington, D.C., 12 p.

U.S. Geological Survey, 2002, National Elevation Database Digital Elevation Model, 30-meter resolution.

U.S. Geological Survey, 1985, National water summary 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 460 p.

Virginia Council on the Environment, 1992, Virginia Beach West, 1:100,000.

Waterloo Hydrogeologic, Inc., 2002, Visual MODFLOW V 3.0 User's Manual: Waterloo, Ontario, Canada, Waterloo Hydrogeologic, Inc., 370 p.

Waterloo Hydrogeologic, Inc., 1999, User's Manual for Visual MODFLOW: Waterloo, Ontario, Canada, Waterloo Hydrogeologic, Inc., 274 p.

Watermark Numerical Computing & Waterloo Hydrogeologic Inc., 1999, User's manual for WinPEST: Waterloo, Ontario, Canada, Waterloo Hydrogeologic Inc., 154 p.

White, R.K., and Powell, E.D., 2001, Water resources data, Virginia, water year 2000, v. 2, ground-water level and ground-water quality records: U.S. Geological Survey Water-Data Report VA-00-2, 337 p.

Wiley & Wilson, Inc., 1979, City of Virginia Beach Department of Public Utilities comprehensive potable groundwater report: Virginia Beach, Va., Wiley & Wilson, Inc., 109 p.

Wolman, Abel, Geyer, J.C., and Day, W. F., 1942, Hampton Roads regional water supply study: Washington, D.C., Executive Office of the President, National Resources Planning Board, 15 p., 1 pl.

World Health Organization, 1993, Guidelines for drinking water quality, 2nd ed: Vol.1 Recommendations, extracted, Geneva, World Health Organization, variously paged, accessed September 22, 2000, at http://www.who.int/water_sanitation_health/GDWQ/acceptability.htm.

Zheng, C., and P.P. Wang, 1998, MT3DMS, A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems (Release DoD _3.00.A): Documentation and User's Guide, University of Alabama, Tuscaloosa, variously paged.

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; mg/L, milligrams per liter; na, not applicable; –, sampled between November 1, 1980, and March 10, 1981]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
61C 52	na	364846076121701	228-00008	364846	761217	-12.96	15	3.66	29.87	Columbia aquifer	3/11/80	Siudyla and others, 1981, app. E.
62C 71	na	364836076002201	228-00033	364836	760022	2.59	5	6.10	21.95	Columbia aquifer	1/13/77	Siudyla and others, 1981, app. E.
61C 49	na	364843076105301	228-00051	364843	761053	-11.89	19	8.23	18.29	Columbia aquifer	10/31/72	Siudyla and others, 1981, app. E.
62A 25	na	363623076051001	228-00055	363623	760510	-5.49	21	3.66	26.21	Columbia aquifer	4/12/78	Siudyla and others, 1981, app. E.
63B 6	na	364330075581401	228-00057	364330	755814	-12.20	203	.91	20.12	Columbia aquifer	4/12/78	Siudyla and others, 1981, app. E.
63B 7	na	364334075581301	228-00058	364334	755813	-9.15	210	.91	9.14	Columbia aquifer	4/12/78	Siudyla and others, 1981, app. E.
63C 27	na	364633075582001	228-00128	364633	755820	-6.10	50	1.52	7.92	Columbia aquifer	12/28/77	Siudyla and others, 1981, app. E.
62A 26	na	363324076001901	228-00137	363324	760019	-3.96	20	3.05	9.14	Columbia aquifer	4/06/78	Siudyla and others, 1981, app. E.
62A 27	na	363617076013401	228-00138	363617	760134	-1.52	19	3.05	7.62	Columbia aquifer	4/06/78	Siudyla and others, 1981, app. E.
62B 36	na	364154076032801	228-00147	364154	760328	-3.81	22	3.05	7.32	Columbia aquifer	10/27/78	Siudyla and others, 1981, app. E.
62C 67	na	364714076030401	228-00169	364714	760304	-2.29	20	4.27	7.32	Columbia aquifer	1979	Siudyla and others, 1981, app. E.
62A 3	SOW 097B	363537076061002	228-00171	363355	760617	-3.66	16	3.05	20.73	Columbia aquifer	7/26/79	Siudyla and others, 1981, app. E.
61C 57	na	364810076114201	228-00182	364810	761142	-13.41	7	6.10	3.96	Columbia aquifer	6/15/79	Siudyla and others, 1981, app. E.
62C 69	na	364846076043701	228-00195	364846	760437	-.15	77	3.35	9.14	Columbia aquifer	4/03/81	Siudyla and others, 1981, app. E.
62C 21	na	364515076012101	228-00288	364515	760121	-2.90	23	3.96	19.81	Columbia aquifer	3/9/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
63B 5	na	364459075595401	228-00294	364459	755954	-13.72	23	3.05	17.37	Columbia aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 70	na	364522076001701	228-00298	364522	760017	-12.96	23	3.66	19.81	Columbia aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
63C 12	na	364515075584101	228-00359	364515	755841	-15.24	205	1.52	.00	Columbia aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 11	SOW 172C	364745076004303	228-00257	364746	760043	-1.52	23	6.09	9.14	Columbia aquifer	2/13/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
63C 19	na	364721075591701	228-00248	364721	755917	-5.64	23	2.74	19.81	Columbia aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 27	na	364443076010702	228-00280	364443	760107	-12.96	30	4.57	18.29	Columbia aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 11	na	364414076003901	228-00260	364414	760039	-13.57	30	2.44	20.42	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
62B 29	na	364352076004301	228-00262	364352	760043	-14.02	15	3.35	20.42	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia—Continued

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; mg/L, milligrams per liter; na, not applicable; –, sampled between November 1, 1980, and March 10, 1981]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
62B 9	na	364352076005401	228-00263	364352	760054	-14.02	23	3.26	19.81	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
62B 21	na	364353076005401	228-00264	364353	760054	-13.72	23	3.11	19.81	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
62B 7	na	364354076005401	228-00265	364354	760055	-14.02	23	2.59	9.14	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
62B 24	na	364352076005402	228-00266	364352	760054	-3.51	38	3.20	15.24	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
62B 32	na	364352076005404	228-00267	364352	760054	-13.72	15	3.05	20.12	Columbia aquifer	3/14/81	Betz-Converse-Murdoch, Inc., 1981, vol. 1 and vol.2
61B 21	na	364223076074201	234-00026	364223	760742	-12.65	25	3.96	19.20	Columbia aquifer	1/13/77	Siudyla and others, 1981, app. E.
61C 58	na	364515076133001	234-00040	364515	761330	-10.67	21	7.01	6.71	Columbia aquifer	2/13/74	Siudyla and others, 1981, app. E.
61B 7	SOW 091D	364227076074704	234-00067	364227	760747	-1.40	24	4.57	32.31	Columbia aquifer	3/22/89	USGS
62C 1	na	364945076051401	228-00007	364945	760514	-26.83	14	3.66	35.66	Yorktown confining unit	12/09/80	Siudyla and others, 1981, app. E.
63C 6	na	364824075594601	228-00044	364824	755946	-21.95	11	4.57	31.09	Yorktown confining unit	12/28/77	Siudyla and others, 1981, app. E.
62A 6	na	363325076005202	228-00047	363325	760052	-22.41	49	1.52	28.65	Yorktown confining unit	8/10/72	Siudyla and others, 1981, app. E.
61C 22	na	364812076094701	228-00050	364812	760947	-20.12	64	6.10	25.91	Yorktown confining unit	10/19/72	Siudyla and others, 1981, app. E.
62A 24	na	363617076013301	228-00053	363617	760133	-21.95	113	2.44	18.90	Yorktown confining unit	4/06/78	Siudyla and others, 1981, app. E.
62B 33	na	363813076021501	228-00056	363813	760215	-15.70	9	2.44	28.65	Yorktown confining unit	4/06/78	Siudyla and others, 1981, app. E.
61C 53	na	364725076080001	228-00076	364725	760760	-23.17	84	3.96	24.08	Yorktown confining unit	9/28/76	Siudyla and others, 1981, app. E.
61C 55	na	364904076083401	228-00105	364904	760834	-18.75	91	4.57	27.43	Yorktown confining unit	7/17/58	Siudyla and others, 1981, app. E.
62C 13	na	364508076032501	228-00107	364508	760325	-18.60	24	3.05	18.29	Yorktown confining unit	3/25/74	Siudyla and others, 1981, app. E.
63C 26	na	364629075582001	228-00127	364629	755820	-15.24	69	1.52	17.68	Yorktown confining unit	12/28/77	Siudyla and others, 1981, app. E.
62C 3	SOW 092B	364715076030801	228-00133	364714	760307	-16.92	27	4.27	19.81	Yorktown confining unit	12/12/77	Siudyla and others, 1981, app. E.
62C 5	SOW 093	364504076031301	228-00135	364456	760301	-16.92	41	4.27	18.29	Yorktown confining unit	12/19/77	Siudyla and others, 1981, app. E.
62B 34	na	363813076054301	228-00136	363813	760543	-13.41	31	3.35	18.29	Yorktown confining unit	4/06/78	Siudyla and others, 1981, app. E.
62A 28	na	363507076050201	228-00139	363507	760502	-13.72	12	3.05	19.81	Yorktown confining unit	4/20/78	Siudyla and others, 1981, app. E.
63B 8	na	364247075584301	228-00140	364247	755843	-17.53	255	1.52	19.81	Yorktown confining unit	4/21/78	Siudyla and others, 1981, app. E.

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia—Continued

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; mg/L, milligrams per liter; na, not applicable; –, sampled between November 1, 1980, and March 10, 1981]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
63B 9	na	364247075584302	228-00141	364247	755843	-17.53	261	1.52	18.29	Yorktown confining unit	4/21/78	Siudyla and others, 1981, app. E.
63B 10	na	364150075582801	228-00144	364150	755828	-15.85	102	.91	24.38	Yorktown confining unit	9/13/79	Siudyla and others, 1981, app. E.
62B 35	na	364140076013701	228-00146	364140	760137	-19.05	22	4.57	31.09	Yorktown confining unit	4/20/78	Siudyla and others, 1981, app. E.
62A 29	na	363519076010701	228-00148	363519	760107	-26.52	21	3.05	22.56	Yorktown confining unit	10/27/78	Siudyla and others, 1981, app. E.
61C 56	na	364839076094801	228-00164	364839	760948	-12.80	14	7.62	23.16	Yorktown confining unit	6/28/79	Siudyla and others, 1981, app. E.
62A 2	SOW 097A	363537076061001	228-00170	363356	760617	-18.60	56	3.05	22.86	Yorktown confining unit	7/26/79	Siudyla and others, 1981, app. E.
62C 34	na	364909076051101	228-00357	364921	760521	-17.68	27	3.05	20.73	Yorktown confining unit	7/18/02	USGS
62C 25	na	364515076012001	228-00283	364515	760120	-14.33	30	3.99	28.04	Yorktown confining unit	3/12/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 35	na	364521076011601	228-00284	364521	760116	-21.04	23	4.08	27.74	Yorktown confining unit	3/9/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 30	na	364514076012001	228-00285	364514	760120	-20.73	23	3.90	27.43	Yorktown confining unit	3/14/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 20	na	364516076012102	228-00286	364516	760121	-20.43	15	3.99	27.43	Yorktown confining unit	3/9/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 26	na	364517076012401	228-00287	364517	760124	-20.43	23	3.84	30.33	Yorktown confining unit	3/9/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 23	na	364515076012102	228-00289	364515	760121	-21.13	30	4.02	27.43	Yorktown confining unit	3/13/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62B 17	na	364400076014701	228-00363	364400	760147	-21.04	30	3.05	24.38	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
61C 28	SOW 174B	364920076093202	228-00317	364914	760919	-16.77	194	4.57	32.00	Yorktown confining unit	7/19/02	USGS
61C 29	SOW 175	364837076092001	228-00318	364837	760921	-24.39	45	4.57	35.05	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 37	na	364522076002001	228-00292	364522	760020	-27.59	30	3.66	29.57	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
63B 3	na	364459075585901	228-00360	364459	755859	-25.00	454	1.52	27.43	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 54	na	364455076013201	228-00273	364455	760132	-21.04	19	3.35	33.53	Yorktown confining unit	3/12/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 55	na	364459076012601	228-00274	364459	760126	-25.91	15	4.57	27.43	Yorktown confining unit	3/9/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 41	na	364451076013401	228-00275	364451	760134	-21.04	15	3.44	27.43	Yorktown confining unit	3/9/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 42	na	364501076011201	228-00276	364501	760112	-21.04	45	3.47	23.47	Yorktown confining unit	3/9/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 28	na	364513076013901	228-00277	364513	760139	-17.07	30	3.41	28.65	Yorktown confining unit	3/12/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia—Continued

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; mg/L, milligrams per liter; na, not applicable; –, sampled between November 1, 1980, and March 10, 1981]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
62C 56	na	364505076034201	228-00346	364505	760342	-21.04	53	4.57	22.86	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 25	na	364458076033001	228-00347	364458	760330	-15.24	53	4.57	22.86	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 58	na	364744076003001	228-00251	364744	760030	-14.94	30	4.88	22.86	Yorktown confining unit	2/14/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 12	SOW 172D	364745076004304	228-00253	364747	760044	-14.63	30	5.18	24.38	Yorktown confining unit	2/13/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 60	na	364747076004601	228-00254	364747	760046	-16.16	30	5.18	25.91	Yorktown confining unit	2/13/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 46	na	364753076011101	228-00255	364753	760111	-17.07	30	5.79	25.91	Yorktown confining unit	2/13/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 47	na	364736076001001	228-00256	364736	760010	-18.29	30	4.79	20.42	Yorktown confining unit	2/14/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62C 61	na	364846076033501	228-00344	364846	760335	-12.80	45	4.57	24.99	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 62	na	364842076033201	228-00345	364842	760332	-17.38	53	4.57	54.86	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 37	na	364450076020902	228-00355	364450	760209	-18.29	197	3.05	21.34	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 19	na	364059076012701	228-00270	364059	760127	-13.72	30	1.52	20.42	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 13	na	364325076011701	228-00271	364325	760117	-15.55	23	3.05	28.96	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
63C 5	SOW 173B	364722075591802	228-00243	364722	755918	-23.17	17	2.74	25.30	Yorktown confining unit	7/17/02	USGS
63C 22	na	364724075593701	228-00244	364724	755937	-18.90	23	3.35	25.91	Yorktown confining unit	2/6/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
63C 11	na	364728075591401	228-00245	364728	755914	-20.12	23	2.77	23.47	Yorktown confining unit	2/6/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
63C 14	na	364720075591701	228-00246	364720	755917	-18.29	15	2.13	23.77	Yorktown confining unit	2/6/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
63C 23	na	364720075591901	228-00247	364720	755919	-18.60	23	2.13	27.13	Yorktown confining unit	2/6/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
63C 25	na	364721075591602	228-00249	364721	755916	-19.21	23	2.44	22.86	Yorktown confining unit	2/6/81	Betz-Converse-Murdoch, Inc., 1981,vol. 1 and vol. 2
62B 20	na	364432076042701	228-00362	364432	760427	-15.55	45	4.27	30.48	Yorktown confining unit	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62A 23	na	363714076063502	228-00430	363714	760635	-25.19	36	3.17	23.47	Yorktown confining unit	9/11/01	USGS
62B 16	na	363812076021202	228-00432	363812	760212	-17.07	10	4.27	16.76	Yorktown confining unit	8/15/00	USGS
61A 6	na	363620076120001	234-00015	363620	761200	-9.91	43	4.57	29.26	Yorktown confining unit	10/28/74	Siudyla and others, 1981, app. E.
60A 4	na	363352076153501	234-00028	363352	761535	-10.67	25	6.40	30.48	Yorktown confining unit	4/10/75	Siudyla and others, 1981, app. E.

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia—Continued

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; mg/L, milligrams per liter; na, not applicable; –, sampled between November 1, 1980, and March 10, 1981]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
60A 7	na	363413076151101	234-00034	363413	761511	-20.42	38	5.79	21.64	Yorktown confining unit	8/03/70	USGS
61B 22	na	364303076073501	234-00045	364303	760735	-16.16	30	4.27	31.70	Yorktown confining unit	2/05/79	Siudyla and others, 1981, app. E.
60C 29	na	364536076164301	234-00051	364536	761643	-23.17	286	2.44	36.58	Yorktown confining unit	10/17/61	Siudyla and others, 1981, app. E.
62C 64	na	364740076041801	228-00002	364740	760418	-35.82	134	2.13	35.66	Yorktown-Eastover aquifer	6/19/64	Siudyla and others, 1981, app. E.
62C 65	na	364739076041401	228-00003	364739	760414	-34.91	209	1.52	36.58	Yorktown-Eastover aquifer	6/30/64	Siudyla and others, 1981, app. E.
62C 66	na	364739076041701	228-00004	364739	760417	-35.82	212	2.13	36.58	Yorktown-Eastover aquifer	7/18/64	Siudyla and others, 1981, app. E.
61C 42	na	364900076122201	228-00009	364900	761222	-31.40	95	2.13	45.11	Yorktown-Eastover aquifer	12/09/80	Siudyla and others, 1981, app. E.
61C 5	na	365221076121301	228-00101	365221	761213	-31.71	464	3.96	38.10	Yorktown-Eastover aquifer	12/04/78	Siudyla and others, 1981, app. E.
61C 54	na	364637076093301	228-00103	364637	760933	-33.38	198	2.44	45.42	Yorktown-Eastover aquifer	12/04/78	Siudyla and others, 1981, app. E.
62C 4	SOW 083	364711076060001	228-00120	364711	760600	-33.54	283	3.96	31.09	Yorktown-Eastover aquifer	10/13/78	Siudyla and others, 1981, app. E.
62C 2	SOW 092A	364713076030701	228-00132	364714	760307	-26.07	168	4.27	60.96	Yorktown-Eastover aquifer	12/18/79	Siudyla and others, 1981, app. E.
62C 68	na	364624076011501	228-00192	364624	760115	-55.34	22	4.57	41.15	Yorktown-Eastover aquifer	11/19/80	Siudyla and others, 1981, app. E.
62C 24	na	364916076051601	228-00356	364916	760516	-35.06	530	3.05	45.72	Yorktown-Eastover aquifer	7/18/02	USGS
62C 27	na	364522076013201	228-00282	364522	760132	-39.02	45	3.66	72.54	Yorktown-Eastover aquifer	3/9/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62C 36	na	364516076012101	228-00368	364516	760121	-41.01	38	3.90	53.34	Yorktown-Eastover aquifer	3/9/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
61C 27	SOW 174A	364920076093201	228-00316	364920	760930	-45.73	2,094	4.57	35.05	Yorktown-Eastover aquifer	7/19/02	USGS
63C 15	na	364535076001001	228-00290	364535	760010	-28.96	30	3.05	42.67	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
63C 16	na	364528076001201	228-00291	364528	760012	-36.59	64	3.05	35.97	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 38	na	364512076002601	228-00293	364512	760026	-29.88	61	3.05	39.62	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
63B 2	na	364451075595601	228-00295	364451	755956	-33.54	23	3.05	36.58	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 53	na	364525076004401	228-00296	364525	760044	-28.96	30	4.57	41.76	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 39	na	364522076001801	228-00297	364522	760018	-35.06	30	3.66	38.10	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 57	na	364608076010001	228-00348	364608	760100	-28.96	23	6.10	36.58	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia—Continued

[USGS, U.S. Geological Survey; SWCB, State Water Control Board; Latitude and longitude in degrees, minutes, and seconds in NAD27; mg/L, milligrams per liter; na, not applicable; –, sampled between November 1, 1980, and March 10, 1981]

USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
62C 43	na	364635076001701	228-00350	364635	760017	-29.27	502	1.83	59.44	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62C 15	na	364708076024501	228-00358	364708	760247	-51.83	1,220	4.57	51.82	Yorktown-Eastover aquifer	7/17/02	USGS
62C 9	SOW 172A	364745076004301	228-00250	364746	760042	-43.60	45	5.18	42.67	Yorktown-Eastover aquifer	2/13/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62C 59	na	364722076000601	228-00252	364722	760006	-35.37	30	4.30	48.77	Yorktown-Eastover aquifer	2/14/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62C 48	na	364914076002101	228-00352	364914	760021	-39.63	91	6.10	85.34	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table2)
62C 10	SOW 172B	364745076004302	228-00315	364745	760043	-77.74	364	5.18	44.20	Yorktown-Eastover aquifer	2/13/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62C 22	na	364746076004301	228-00369	364746	760043	-35.91	30	5.24	42.67	Yorktown-Eastover aquifer	2/13/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62C 63	na	364746076004302	228-00258	364746	760043	-32.93	38	5.18	54.86	Yorktown-Eastover aquifer	2/14/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62C 50	na	364851076033901	228-00343	364851	760339	-47.26	424	4.57	54.86	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 26	na	364450076020901	228-00354	364450	760209	-48.78	1,121	3.05	41.15	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 22	na	364325076011501	228-00268	364325	760115	-35.06	45	3.05	41.15	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 18	na	364126076013401	228-00269	364126	760134	-34.15	576	3.05	56.39	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
63C 21	na	364729075593001	228-00242	364729	755930	-49.63	61	3.66	88.70	Yorktown-Eastover aquifer	2/6/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
63C 4	SOW 173A	364722075591801	228-00314	364721	755916	-84.70	4,115	2.50	62.48	Yorktown-Eastover aquifer	7/16/02	USGS
63C 13	na	364721075591601	228-00364	364721	755916	-57.01	252	2.29	53.34	Yorktown-Eastover aquifer	7/15/02	USGS
63C 24	na	364721075591702	228-00365	364721	755917	-47.87	23	2.44	38.10	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 14	na	364441076010201	228-00278	364441	760104	-30.49	23	4.57	51.82	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 12	na	364443076010701	228-00279	364443	760107	-44.21	76	4.57	54.86	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 28	na	364439076012201	228-00281	364439	760122	-47.26	129	4.57	35.05	Yorktown-Eastover aquifer	–	Converse-Ward-Davis-Dixon, Inc, 1981, table 2)
62B 23	na	364410076002801	228-00259	364410	760028	-28.96	38	3.05	40.23	Yorktown-Eastover aquifer	3/14/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62B 8	na	364401076003801	228-00261	364401	760038	-34.45	30	2.68	65.23	Yorktown-Eastover aquifer	3/14/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
62B 30	na	364352076005403	228-00366	364352	760054	-61.74	727	3.32	60.20	Yorktown-Eastover aquifer	3/14/81	Betz-Converse-Murdock, Inc., 1981,vol. 1 and vol. 2
61C 43	na	364558076074501	228-00426	364558	760745	-55.43	3,380	1.73	32.61	Yorktown-Eastover aquifer	8/10/00	USGS

Table 7. Chloride concentrations in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia—Continued

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USGS well number	SWCB well number	USGS well identifier	Storet identifier	Latitude	Longitude	Sample altitude (meters below NGVD 1929)	Chloride (mg/L)	Land-surface altitude (meters above NGVD 1929)	Well depth (meters below land surface)	Hydrogeologic unit	Sample date	Chloride data source
61C 44	na	364558076074401	228-00427	364558	760744	-27.81	677	1.76	54.25	Yorktown-Eastover aquifer	8/09/00	USGS
62A 22	na	363714076063501	228-00429	363714	760635	-44.22	701	3.19	63.40	Yorktown-Eastover aquifer	8/16/00	USGS
62B 15	na	363812076021201	228-00431	363812	760212	-56.16	3,080	4.20	36.27	Yorktown-Eastover aquifer	8/16/00	USGS
60B 26	na	36432707616001	234-00001	364327	761600	-25.76	71	2.74	42.67	Yorktown-Eastover aquifer	5/10/78	Siudyla and others, 1981, app. E.
61A 9	na	363637076104901	234-00041	363637	761049	-34.15	98	3.96	29.57	Yorktown-Eastover aquifer	12/15/78	Siudyla and others, 1981, app. E.
61B 2	SOW 091A	364227076074701	234-00136	364227	760747	-24.00	420	4.57	29.87	Yorktown-Eastover aquifer	3/22/89	USGS