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

The Potential for Saltwater Intrusion in the Potomac Aquifers of the York-James Peninsula, Virginia

Water-Resources Investigations Report 98-4187

Prepared in cooperation with the
HAMPTON ROADS PLANNING DISTRICT COMMISSION

USGS
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By Barry S. Smith

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Richmond, Virginia
1999

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square meter (m^2)	10.76	square foot
liter (L)	33.82	ounce, fluid
liter (L)	0.2642	gallon
cubic meter per day (m^3/d)	0.0002642	million gallons per day
meter per second (m/s)	3.281	foot per second
meter per day (m/d)	3.281	foot per day
kilogram per second (kg/s)	2.205	pound per second
meter per year (m/yr)	3.281	foot per year
cubic meter per day (m^3/d)	264.2	gallon per day
cubic meter per second (m^3/s)	22.83	million gallons per day
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	0.0685	slug
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot
kilogram per cubic meter (kg/m^3)	0.00194	slug per cubic foot
kilogram per meter-second (kg/m-s)	67.2	pound per foot -second
meter per day (m/d)	3.281	foot per day
meter squared per day (m^2/d)	10.76	foot squared per day
meter per second squared (m/s^2)	3.281	foot per second squared

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (° F) may be converted to degrees Celsius (° C) as follows:

$$°C = (°F - 32) / 1.8$$

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

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

Transmissivity: The standard unit for transmissivity is cubic meter per day per square meter times meter of aquifer thickness $[(m^3d)/m^2]m$. In this report, the mathematically reduced form, meter squared per day (m^2/d), is used for convenience.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

The Potential for Saltwater Intrusion in the Potomac Aquifers of the York-James Peninsula, Virginia

By Barry S. Smith

ABSTRACT

The most productive aquifers of the Virginia Coastal Plain are in the Potomac Formation. Water supplies in the Potomac aquifers are impaired, however, by saltwater in some areas. A two-dimensional, density-dependent, solute-transport model was used to investigate saltwater movement in the Potomac aquifers and the potential for saltwater intrusion or upward migration of saltwater.

The model was designed to represent a simplified section of the Potomac aquifers and associated confining units near Lee Hall, Va. Solute-transport simulations show that the direction of ground-water flow and the hydrogeologic properties, particularly the permeability of aquifers and the distribution of confining sediments in the Potomac Formation, control the system hydrodynamics and saltwater movement in the Potomac aquifers. The simulations indicate lateral intrusion for the Lower Potomac aquifer near Lee Hall, Va. Velocity vectors of the simulations indicate that a hypothetical, but typical, production well in the Middle Potomac aquifer could induce upconing only within the immediate vicinity of the well. Migration of saltwater from the Middle and Lower Potomac aquifers east of the hypothetical well also was indicated by the simulations.

INTRODUCTION

The Coastal Plain aquifers supplied 89 Mgal/d of water to the counties, cities, industries, and utilities of Virginia in 1990. Most of that water, 79 Mgal/d, came from the Potomac aquifers (McFarland and Focazio, 1993). The population of the Coastal Plain of Virginia has increased since 1990, primarily along interstate highways from the suburbs of Washington, D.C., southward to Richmond, and southeastward to Hampton and Norfolk (fig. 1). Demands for freshwater have increased with the population. More production wells have been added to supplement existing demands and expected needs; however, supplies of freshwater in the most productive aquifers are impaired by saltwater in some areas.

In coastal areas, ground-water pumping can cause saltwater intrusion—the movement of saltwater into freshwater aquifers. Pumping of water from the Potomac aquifers and from shallower aquifers has lowered ground-water levels substantially and has changed the direction of ground-water flow over much of the region. These changes, and the proximity of some pumping centers to saltwater sources in and near the aquifers, has increased the potential for saltwater intrusion.

Brackish (slightly saline) water generally comprises a transition zone between freshwater and saltwater in the Coastal Plain aquifers. Where the aquifers are brackish, they are nevertheless usable. Freshwater can be injected and stored temporarily in brackish aquifers; an Aquifer Storage and Recovery (ASR) system is operated in Chesapeake, Va. (fig. 2). Desalination systems also can be designed to pump brackish water that can then be reduced by electrolysis or reverse osmosis. Brackish water pumped from wells completed in the Potomac aquifers in Chesapeake and in Newport News is desalinated before distribution.

Very saline water, however, is more expensive to desalinate. The city of Virginia Beach, which is underlain by the most saline parts of the Potomac aquifers, receives freshwater through a pipeline from Lake Gaston, a reservoir more than 70 mi away.

Purpose and Scope

The Chloride Project is a cooperative program of the U.S. Geological Survey (USGS) and the Hampton Roads Planning District Commission (HRPDC) that began in 1995. The first objective of the Chloride

Project was to evaluate the spatial and temporal distribution of concentrations of chloride (assuming that chloride is a potential indicator of saltwater intrusion) in the Cretaceous (Potomac) and early Tertiary (Chickahominy-Piney Point) aquifers. In 1996, about 80 observation wells were selected from existing wells in the Coastal Plain for the Chloride Project network. Wells greater than 2 in. in diameter with discrete screened intervals open to a single aquifer in and near brackish-water and saltwater zones were generally selected for the network. A quality-assurance plan for sampling and analysis of the network also was written in 1996. Under the plan, a part of the network is sampled each year and new wells are added to the network where possible or deleted from the network when necessary.

A second objective of the Chloride Project, which is the focus of this report, was to evaluate the factors that affect the distribution of chloride (or more specifically, the distribution of saltwater as determined by dissolved-solids concentrations) in the aquifers, and a third objective, also addressed in this report, was to assess the potential for lateral intrusion and(or) upconing of saltwater in the aquifers.

In 1997, a two-dimensional solute-transport model was tested as a possible means of evaluating hydrogeologic controls on saltwater movement in the Potomac aquifers, and whether saltwater intrusion or upconing of saltwater should be of concern to the management of ground-water supplies in the Coastal Plain. Preliminary results from the solute-transport model indicated that the hydrogeologic framework was an important control on the potential for saltwater intrusion, and in 1998, a revision to the geologic framework in the vicinity of a recently discovered peak-ring crater (fig. 1) beneath the mouth of the Chesapeake Bay (Poag and others, 1994) was proposed and accepted as a new cooperative study by the USGS and the HRPDC. A revision of the geologic framework in the vicinity of the buried crater would be a first step toward a refinement of the hydrogeologic framework of the entire Coastal Plain.

Approach

The potential for lateral intrusion or upconing of saltwater in the Potomac aquifers, and the factors that affect the distributions of saltwater in those aquifers,

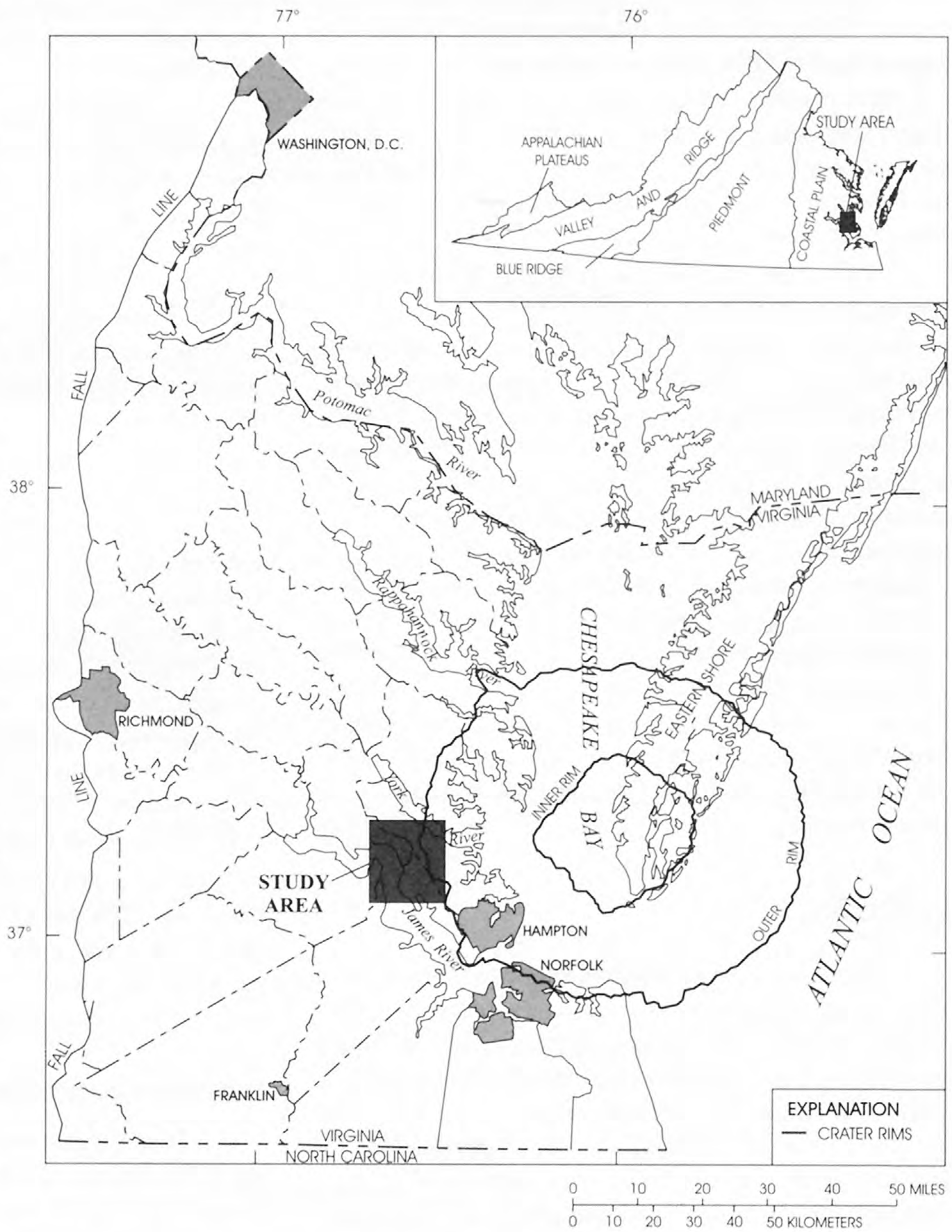

Figure 1. Location of the study area in the Coastal Plain of Virginia.

were evaluated with the aid of a two-dimensional, density-dependent, ground-water flow and solute-transport model. The USGS solute-transport model SUTRA (Voss, 1984) was used to represent a simplified vertical section of the Potomac aquifers and the hydraulic properties of the aquifers and associated confining units near Lee Hall, Va. The Lee Hall section was selected because more information about the aquifers and confining units was available there than elsewhere and because data collected during and prior to the Chloride Project indicated that saltwater could be moving in the Lower Potomac aquifer, but not in the shallower aquifers, near Lee Hall.

Location of the Study Area

The Lee Hall area is a narrow strip of land between the York and James Rivers in Virginia (fig. 3). The U.S. Naval Weapons Station, Fort Eustis Military Reservation, and Colonial National Historic Park are in the Lee Hall area. The boundaries of James City County, York County, and the City of Newport News, Va., intersect at Interstate 64 just 2 mi northwest of the town of Lee Hall. The City Reservoir of Newport News is also near Lee Hall.

Acknowledgments

The initial hydraulic properties of the aquifers and confining units simulated for the section near Lee Hall were from aquifer tests during Phase II of the Brackish Ground-Water Development (BGD) Project of Newport News, Va. (Camp Dresser and McKee, and Russnow, Kane, and Assoc., 1995, p. 4-4 and 4-10). Some of the dissolved-solids concentrations used in the Lee Hall simulations also were collected in collaboration with test drilling and well installations of the Phase II BGD Project. Art Russnow of Russnow, Kane, & Associates was particularly helpful in coordinating those activities.

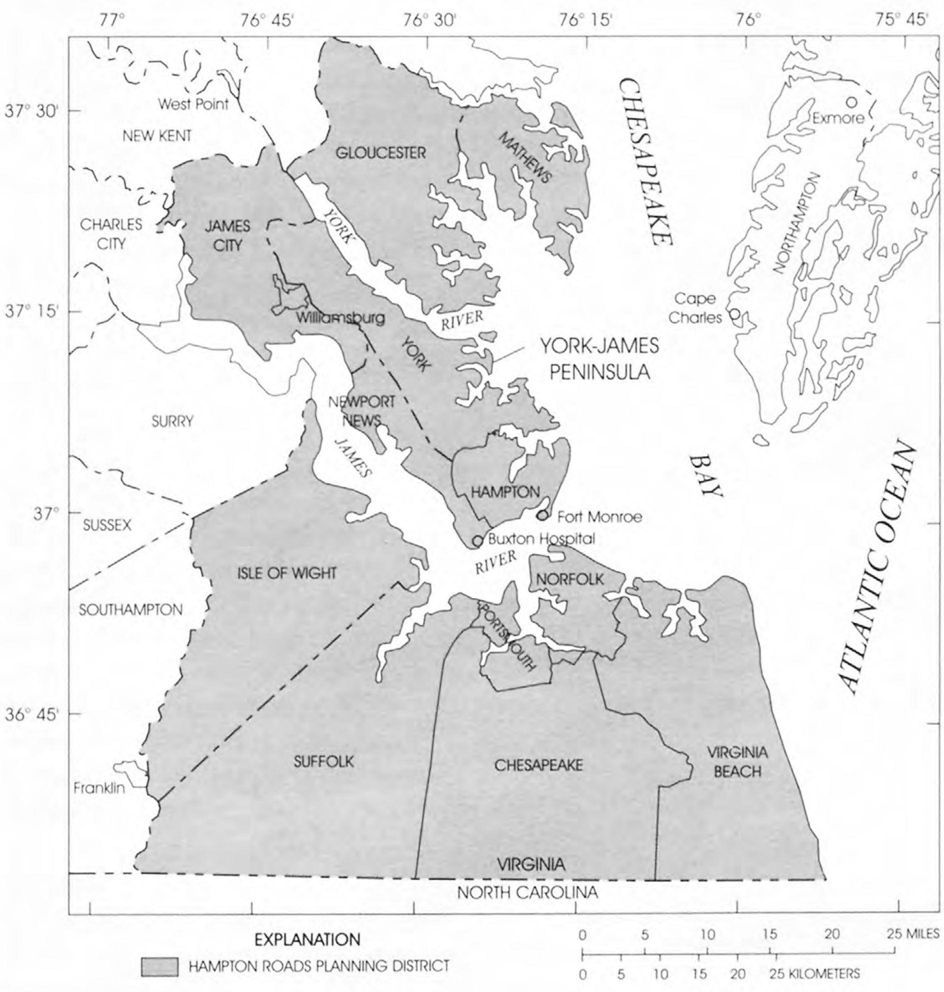

Figure 2. Location of the Hampton Roads Planning District in southeastern Virginia.

PREVIOUS STUDIES

Sanford (1913, pl. 1) mapped the probable chlorine (chloride) content of artesian waters from 200 to 700 ft below sea level in the southeastern part of the Virginia Coastal Plain. He reported that the mineralization of the deep artesian waters increased toward the southeast. He noted that the increase was not due directly to increase of depth nor to changes in the chemical composition of the enclosing beds (p. 51). Sanford (1911, p. 82 and 83) noted that saltwater was flowing from Potomac Formations that were not marine in origin. He believed that this saltwater had invaded from above during high stands of the sea but had not been flushed as well as beds further to the west, where the Potomac Formations contained freshwater (Sanford, 1913, p. 114). He noted that one possible cause of the incomplete flushing or poor circulation was the decrease in permeability of the artesian aquifers downdip, caused by fining of the sediments or pinching out of water beds.

Cederstrom (1943, pl. 3) mapped a broad wedge of high concentrations of chloride in the artesian aquifers beneath the Coastal Plain of Virginia. Chloride concentrations were greater than 250 mg/L at the apex of the wedge just north of Williamsburg, Va., on the York-James Peninsula (p. 10); however, he did not know why the high chloride area was in the form of a wedge (Cederstrom, 1957, p. 40).

Cederstrom (1943, p. 13 and 1957, p. 40 and pl. 5) also reported that increases of mineralization in the artesian aquifers were not necessarily a function of depth, but he noted that the increase was coincident with a downwarping in the geologic structure of the water-bearing sands beneath the York-James Peninsula. He agreed with Sanford (1911; 1913) that the movement of freshwater eastward through the artesian beds had not been sufficient to completely remove the seawater that had previously saturated the aquifer. Cederstrom (1957, p. 41) also agreed that water-bearing sands of lower permeability generally have higher chloride concentrations because they have not been flushed as well as more permeable sands. He noted that marked changes in mineralization over relatively small distances in some areas of the York-James Peninsula defied a reasonable explanation (Cederstrom, 1943, p. 10 and 11).

Cederstrom (1943, p. 16-18) reported marked initial increases in chloride concentrations with increased pumping rates at Yorktown and Fort Eustis, Va., and thought it possible that gradual increases in concentrations would continue if water levels in the aquifers continued to decline. He noted that increased pumping in the Fort Eustis area during the drought of 1941-42 resulted in temporary increases in chloride concentrations in those wells and thought that brackish water had migrated to the well field from downdip or from depth (Cederstrom, 1945, p. 119).

Back (1966, fig. 2) mapped 350-mg/L isochlors in the Cretaceous and in the Tertiary sediments from New Jersey to Virginia. He quoted Sanford (1911) regarding the post-depositional submergence of sediments and infiltration of seawater as the origin of saltwater in the aquifers but also believed that some of the deep saltwater could have come from the solution

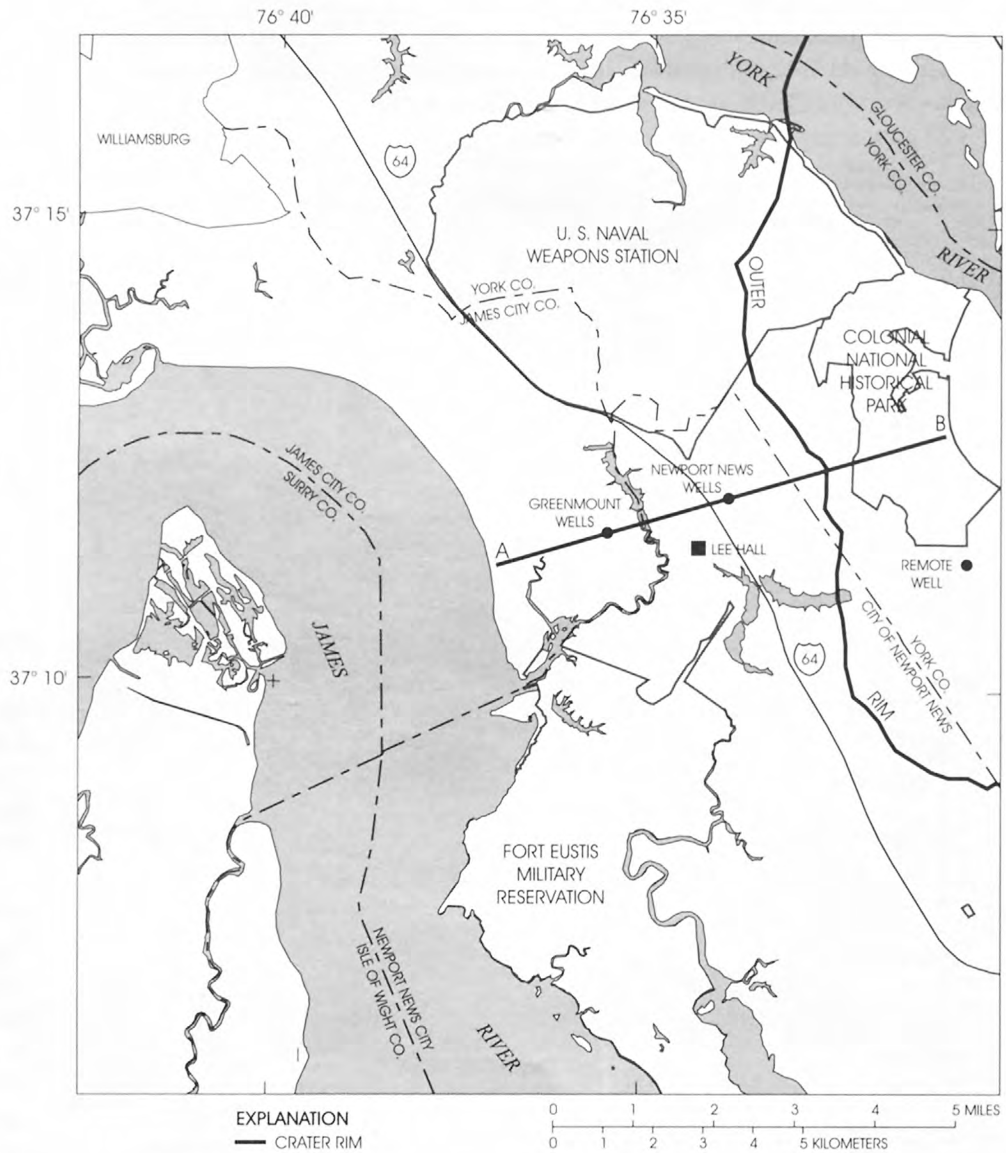

Figure 3. Lee Hall area, Virginia.

of minerals and the concentration of ions by filtration through clays (Back, 1966, p. A9).

Litchler and Wait (1974, fig. 9 and 10) contoured chloride concentrations in vertical sections of the Lower Cretaceous (Potomac) aquifer(s) north and south of the James River. They believed that saltwater was slowly, but surely, encroaching westward in the aquifers because of "heavy" pumping (p. 51).

Larson (1981, figs. 2-8) contoured chloride concentrations along several vertical sections of the Coastal Plain and areally mapped the depth to the 250 mg/L chloride concentration (pl. 2). He noted that a wedge of saltwater at shallow depth coincided with the mouth of the Chesapeake Bay near the York-James Peninsula (p. 13). He also reported increases in the chloride content of some wells over time and attributed those increases to local infiltration from nearby bays or estuaries (p. 20) rather than a regional phenomenon (p. 22).

Laczniak and Meng (1988, p. 36 and fig. 29) reported that the hydrochemistry of aquifers changed with depth at Newport News Park near Lee Hall, Va. The water in the aquifers changed from a calcium-bicarbonate type near the land surface to a sodium bicarbonate and then a sodium-chloride type with increasing depth. They attributed the change to increasing residence time of the water with depth, noting longer ground-water flow paths from the Fall Line for the deeper ground water. Laczniak and Meng (1988, p.77) also simulated ground-water flow of the York-James Peninsula from 1890, before pumping began, through 1983.

Focazio and others (1993, pl 1-5) mapped the major ions, including chloride and dissolved solids, in the Coastal Plain aquifers of Virginia.They described different zones of ground-water types based on the general chemical evolution from shallow recharge areas in the west to deeper discharge areas eastward (p. 12). They agreed with earlier investigators that the sources of chloride in the mostly stream-deposited Potomac sediments were probably from submergence of the sediments during marine transgressions, and they believed that another possible source of chloride was "offshore" evaporite deposits (p. 13).

Potential ground-water velocities from proposed withdrawals near saltwater interfaces were estimated in a technical memorandum prepared for the city of Chesapeake, Va. (CH2M Hill, 1993, table 4-1). Those velocities ranged from 6 to 10 ft/yr (2 to 3 m/yr) in the Upper Potomac aquifer and from 9 to 23 ft/yr (3 to 7 m/yr) in the Middle Potomac aquifer depending on the proposed withdrawal rates. The potential for the vertical migration of saltwater between aquifers from the proposed wells also was discussed.

Richardson (1994) investigated the saltwater-freshwater interfaces of the Yorktown-Eastover and Columbia aquifers of the Eastern Shore of Virginia. She found no changes in the movement of the saltwater-freshwater interfaces from historical pumping through 1988, as simulated by the USGS computer model SHARP (p. 62). Hypothetical increases in simulated pumping near the shore, however, resulted in slow movement of the interfaces landward over a period of 50 years (p. 100 and 107). Richardson also warned of the possibilities of inducing downward leakage of saltwater from the Chesapeake Bay or the Atlantic Ocean into shallow aquifers.

Potential changes in the concentrations of chloride, dissolved solids, and other constituents from proposed ground-water pumping in the Lee Hall area were investigated for the city of Newport News, Va., by Camp Dresser and McKee (1994 and 1996). Those studies assumed that low vertical permeabilities in the confining units would inhibit vertical flow. They believed that the horizontal transport of constituents was more important than vertical transport in affecting potential changes in water quality (p. 2-35). Traveltimes for vertical flow through the Middle and Upper Potomac confining units were estimated at greater than 100 years.

Poag and others (1994, p. 691) presented evidence of a buried peak-ring impact crater 85 km wide and up to 2 km deep cutting through the upper Eocene and Cretaceous sediments, beneath the mouth of the Chesapeake Bay and the surrounding area (fig. 1). The outer ring of the crater beneath the York-James Peninsula conformed with changes in chemical-concentration gradients that had been mapped previously by Focazio and others (1993). The association of the inland saltwater wedge to the structure of the crater was confirmed by Bruce and Powars (1995, p. 8).

THE POTOMAC AQUIFERS AND CONFINING UNITS

Sediments beneath the Coastal Plain of Virginia have been divided into a layered sequence of aquifers and intervening confining units. Sand, gravel, and shell deposits of sufficient saturated thickness to yield significant quantities of water have been defined as aquifers. Continuous clay and silt deposits of low permeability have been defined as confining units (Meng and Harsh, 1988).

Hydrogeologic Framework

The Potomac Formation is an eastward thickening wedge of alternating sand, silt, and clay deposits of Cretaceous age beneath the Coastal Plain of Virginia. The sands of the Potomac Formation are primarily gray, poorly sorted, fine to coarse grained, quartzofeldspathic and are interbedded with grey to green sandy clays and silt or laminated carbonaceous clays (Mixon and others, 1989, Sheet 1). Three confined aquifers were mapped in the sediments of the Potomac Formation by the USGS during the Regional Aquifer System Analysis (RASA) of the Virginia Coastal Plain. These aquifers were named the Upper, Middle, and Lower Potomac aquifers, and the confining sediments above each aquifer were similarly called the Upper, Middle, and Lower Confining Units (Meng and Harsh, 1988, table 1, p. c12 and c13). Fractured basement rocks, an extension of those from the Piedmont of Virginia, lie beneath the Lower Potomac aquifer.

The sediments of the Lower and Middle Potomac aquifers were deposited by streams and have similar stratigraphy. The Lower Potomac aquifer typically consists of coarse, arkosic quartz sands with intervening clays that were deposited by low-gradient rivers and meandering streams flowing across a broad alluvial plain (Harsh and Laczniak, 1990, p. F10). The Middle Potomac aquifer typically consists of intercalated lenses of medium sand, silt, and clay, which were deposited by low-gradient streams in fluvial and deltaic environments (p. F9). The Lower and Middle Potomac aquifers are separated by sequences of finely laminated, usually brown, grey, or dark green carbonaceous clays interbedded with thin, sandy clays, which collectively are known as the Lower Potomac confining unit. The Lower and Middle Potomac aquifers are not, however, easily distinguishable or completely separated everywhere by a confining unit because fluvial and deltaic deposits are generally discontinuous over relatively short distances. The confining unit above the Middle Potomac aquifer is predominantly a massive, red montmorillonitic clay but is finely laminated in places (p. F9). The Upper and Middle Potomac aquifers also are not completely separated everywhere by confining sediments.

The sediments of the Upper Potomac aquifer are of marine origin and were deposited either in a marginal outer-delta or a near-shore marine environment. They are typically medium to very fine quartzose sand interbedded with dark micaceous clay, varying amounts of shell material, lignite, and glauconite (Harsh and Laczniak, 1990, p. F9). The sediments of the Upper Potomac confining unit are dark green to black, highly micaceous silty clays, interbedded with red to yellow clay (p. F9).

A recently discovered, peak-ring crater buried beneath the Chesapeake Bay, the Eastern Shore of Virginia, and the eastern half of the York-James Peninsula (fig. 1) has altered some previous concepts of the hydrogeologic framework of the Coastal Plain. In the Lee Hall area, the confining unit above the Upper Potomac aquifer, which was previously believed to be primarily sediments of a marginal outer-delta or a near-shore marine environment, is also in large part an Eocene deposit of disturbed beds, coarse breccia, and tsunami deposits above which are finer ejecta material (Poag and others, 1994, p. 692). The tsunami-breccia and ejecta deposits are known as the "Exmore beds," or the "Exmore tsunami deposits," from the type area near Exmore, Va. In the Lee Hall area, the Exmore deposits are thicker to the east within the buried rim of the crater and thinner west of the rim (D.S. Powars, U.S. Geological Survey, and T.S. Bruce, Virginia Department of Environmental Quality, written commun., 1997).

Aquifer and confining-unit properties

Permeabilities of the Potomac aquifers and confining units (table 1) were derived initially from aquifer tests conducted by the City of Newport News in the Lee Hall area during the BGD Project (Camp Dresser and McKee and Russnow, Kane, and Assoc., 1995, p. 4-4 and 4-10). Transmissivity data from those aquifer tests were divided by aquifer thickness to derive a hydraulic conductivity for each unit. The hydraulic conductivity of each unit was converted to metric units and then to "intrinsic" permeability by use of the equation derived by Hubbert (1940), as described by Freeze and Cherry (1979, p. 27) and rearranged:

Table 1. Horizontal hydraulic conductivities and simulated permeabilities of the Potomac aquifers and confining units

Unit	Hydraulic conductivity (meters per day)	Hydraulic conductivity (meters per second)	Simulated permeability: Initial (square meters)	Simulated permeability: Resultant (square meters)
Upper Confining unit	1.3	1.5×10^{-5}	1.5×10^{-12}	3.6×10^{-15}
Upper Potomac aquifer	22.6	2.6×10^{-4}	2.7×10^{-11}	2.7×10^{-11}
Middle Potomac confining unit	1.3	1.5×10^{-5}	1.5×10^{-12}	1.4×10^{-11}
Middle Potomac aquifer	12.2	1.4×10^{-4}	1.4×10^{-11}	1.4×10^{-11}
Lower Potomac confining unit	.27	3.1×10^{-6}	3.2×10^{-13}	3.6×10^{-15}
Lower Potomac aquifer	2.1	2.4×10^{-5}	2.4×10^{-12}	2.4×10^{-12}

$$k = K\frac{\mu}{\rho g} \qquad (1)$$

where k is permeability, in square meters,

K is hydraulic conductivity, in meters per second,

μ is fluid viscosity, in kilograms per meter second,

ρ is fluid density, in kilograms per cubic meter, and

g is the acceleration of gravity, in meters per square second.

A fluid viscosity of 0.001 kg/m-s, an acceleration of gravity of 9.8 m/s^2, and a fluid density of 1,000 kg/m^3 were assumed and used to convert from the hydraulic conductivities to permeabilities. Ground-water temperature was assumed to be uniform.

Most aquifers of water-deposited sediments are stratified and consequently are anisotropic (Jacob, 1963, p. 274). Because of the lenticular geometry of the Potomac sediments, the horizontal permeabilities of all units were assumed to be 10 times the vertical permeabilities.

Initial permeabilities of the confining units were tested and changed during solute-transport simulations so that simulated pressures would conform more closely to measured water levels. The Middle Potomac confining unit was "removed" during these tests by assigning the resultant permeability a value equal to that of the Middle Potomac aquifer. The resultant permeabilities were then used for subsequent simulations and for the results of this report.

The porosity of the Potomac aquifers and confining units was assumed to be 30 percent. Brown and Silvey (1977, p. 17) used an effective porosity of 0.30 for analyses of Cenomanian and Albian Age sands (Upper and Middle Potomac aquifers) in the Norfolk, Va., area. The porosity was based on core analyses and interpretation of compensated gamma-gamma density logs, which had indicated porosities from 35 to 40 percent.

The dispersivity of the units is not known and probably changes with the rate and direction of solute movement at all scales (Domenico and Schwartz, 1990, p. 369). It was assumed that the horizontal dispersivity was 1 to 2 orders of magnitude greater than the vertical dispersivity, because the magnitude of dispersion is generally much greater in the direction of the principal velocity than perpendicular to it (Henry, 1964, p. C-73). A horizontal dispersivity of 100 m and a vertical dispersivity of 1 m were used in initial simulations, and in subsequent solute-transport tests those values provided acceptable results.

Ground-Water Flow and Saltwater Contamination

Before wells were installed to withdraw water from the Coastal Plain, freshwater in the confined aquifers flowed from the higher altitudes along the Fall Line eastward toward the coast (Harsh and Laczniak, 1990, p. F10 and F-12 and figs. 38, 39, and 40). Some freshwater discharged beneath the major river valleys of the Coastal Plain. Near the coast, fresh ground water from the confined aquifers discharged by upward leakage through the confining units and bottom sediments into the estuaries, tidal rivers, and inlets of the Chesapeake Bay and the Atlantic Ocean. Some freshwater also would have discharged by diffusion and dispersion into saltwater zones at the seaward limits of the aquifers.

The first deep water well in coastal Virginia was drilled at Fort Monroe (fig. 2). Drilling began in 1864, but the well was abandoned as a failure in 1869 (Sanford, 1913, p. 99). Water described as "very saline" rose from a depth of 599 ft in the well to the surface of the parade ground at the fort. Saltwater was flowing from the non-marine Potomac Formation, as noted by Sanford (1911, p.82 and 83), and must have invaded the formations during higher stands of the sea and(or) invaded during the cataclysmic aftermath of the Eocene bolide that left a crater buried beneath the mouth of the Chesapeake Bay and the surrounding area (Poag and others, 1994, p. 691).

Fresh flowing water was encountered by wells drilled elsewhere in the Coastal Plain of Virginia, and by the late 1800's, the deep confined aquifers of coastal Virginia were recognized as an important source of freshwater. Before 1945, annual rates of ground-water withdrawals from the confined aquifers were probably less than 10 Mgal/d (Harsh and Laczniak, 1990, p. F13). By the mid-1940's, increased well construction to meet demands for water and decades of unrestricted artesian-well flows had lowered water levels in the deep confined aquifers, and pumps were generally required to lift water to the surface (Cederstrom, 1945, p. 76).

After production wells began pumping in the mid- to late 1940's, water levels in the deep confined aquifers were lowered, which resulted in coalescing cones of depression centered on major pumping centers (Harsh and Laczniak, 1990, p. F12 and figs. 55, 56, and 57). From the 1950's through the 1970's, withdrawals from the confined aquifers increased substantially, peaking at about 103 Mgal/d in the late 1970's (Kull and Laczniak, 1987, p. 11 and fig. 4).

As pumping increased and water levels declined forming coalescing cones of depression, ground water from surrounding areas was captured and began flowing toward the major pumping wells. Consequently, the directions of flow changed in many areas and reversed in some areas of the Coastal Plain. Near the coast, where freshwater had previously discharged by upward leakage through confining sediments into estuaries, tidal rivers, inlets, and bays, saltwater could begin leaking downward from those sources. Where freshwater had dispersed and diffused into saltwater at the seaward edges of the confined aquifers, saltwater could begin moving landward.

Through the 1980's, ground-water withdrawals stayed just below the historically high rates. About 100 Mgal/d were withdrawn from the Virginia Coastal Plain in 1980 (Harsh and Laczniak, 1990, p. F13) and about 92 Mgal/d were withdrawn in 1983. Most of that withdrawal, 83 Mgal/d, came from the Potomac aquifers (Kull and Laczniak, 1987, table 2, p. 14). In 1990, the Coastal Plain aquifers supplied 89 Mgal/d, of which 79 Mgal/d came from the Potomac aquifers (McFarland and Focazio, 1993).

Production wells were completed in some shallow aquifers adjacent to tidal rivers and bays. In some areas, such as at Buxton Hospital on the north shore of the James River in Newport News and in the town of Cape Charles on the Eastern Shore of Virginia (fig. 2), wells became contaminated with brackish water within months after production began (Cederstrom, 1943, p. 21). A few wells open to shallow confined aquifers near coastal areas were still flowing in 1990, but most were producing salty water (Harsh and Laczniak, 1990, p. F13).

POTENTIAL FOR SALTWATER INTRUSION

The USGS and the HRPDC began the Chloride Program in 1995 to collect and sample water from the Cretaceous and Tertiary aquifers at selected sites in the Coastal Plain in order to determine the spatial and temporal distribution of chloride in the aquifers and to determine which aspects of saltwater intrusion, if any, could be of concern to present and future ground-water supplies. Dissolved-solids and chloride concentrations in the aquifers of the Virginia Coastal Plain had indicated that saltwater was present in the Cretaceous and Tertiary deposits toward the east, particularly near the tidal rivers, inlets, bays, and estuaries of the Chesapeake Bay and the Atlantic Ocean.

Definition of Saltwater and Saltwater Intrusion

Saltwater has been defined by the amount of solute dissolved in the water as measured by concentrations of dissolved solids in milligrams per liter or parts per million (Krieger and others, 1957 p. 5):

Description	Dissolved solids (milligrams per liter)
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	Greater than 35,000

Under this classification, freshwater would be defined as water with dissolved-solids concentrations less than 1,000 mg/L. Residents of some areas of the United States have used water with more than

1,000 mg/L dissolved solids all their lives, however, without any notable adverse health effects (Hem 1989, p. 212).

Seawater generally has a dissolved-solids concentration near 35,000 mg/L. Chloride ions comprise more than half of the total dissolved solids of seawater. About 19,000 mg/L of chloride are found in average seawater (Hem, 1989, table 2, p. 7), and increasing concentrations of chloride can be early indicators of saltwater intrusion.

Saltwater intrusion is the movement of saltwater into freshwater aquifers (U.S. Dept. of the Interior, 1989, p. 22). Saltwater intrusion, also called saltwater encroachment or seawater intrusion, has been described as having two aspects: (1) lateral encroachment, which is the horizontal movement of saltwater toward a pumping well, and (2) upconing, which is the vertical upward movement of saltwater beneath a pumping well or well field (fig. 4). Downward vertical leakage toward a pumping well from saltwater sources above a leaky or poorly confined aquifer could be considered another aspect of saltwater intrusion.

Upconing of saltwater beneath a well or well field is generally a more imminent phenomenon than lateral encroachment, because less freshwater is displaced by upconing than by lateral intrusion (Heath, 1983, p. 69). Upconing of saltwater beneath a well or well field would be considered a local phenomenon, whereas lateral encroachment of saltwater could be either a local or a regional phenomenon. Local upconing of saltwater was probably the mechanism that caused the brackish-water intrusion of pumping wells within months after installation of wells at Buxton Hospital on the south end of York-James Peninsula and at Cape Charles on the Eastern shore of Virginia reported by Cederstrom (1943, p. 16-18, 21, and 1945, p. 119.)

Saltwater in the Virginia Coastal Plain

Saltwater in coastal aquifers could be derived from the sea, from water of earlier seas trapped below ground, from brines more mineralized than seawater, from evaporite deposits of earlier salt lakes and seas, or possibly, as a result of the cataclysmic aftermath of the impacts of bolides (large meteors) or comets. An inland wedge of saltwater in the aquifers of the Virginia Coastal Plain was evident as early as 1913, as indicated by "chlorine" (chloride) concentration gradients (Sanford, 1913, pl 1). Sanford (1911, p. 82 and 83) noted that saltwater was flowing from Potomac Formations that were not marine in origin. The chloride wedge had been explained as possibly related to a structural depression by Cederstrom (1943, p. 13 and 1957, p. 40), and the structural depression was substantiated by the discovery of the peak-ring crater beneath the mouth of the Chesapeake Bay and the surrounding area (Poag and others, 1994, p. 691). The association of the

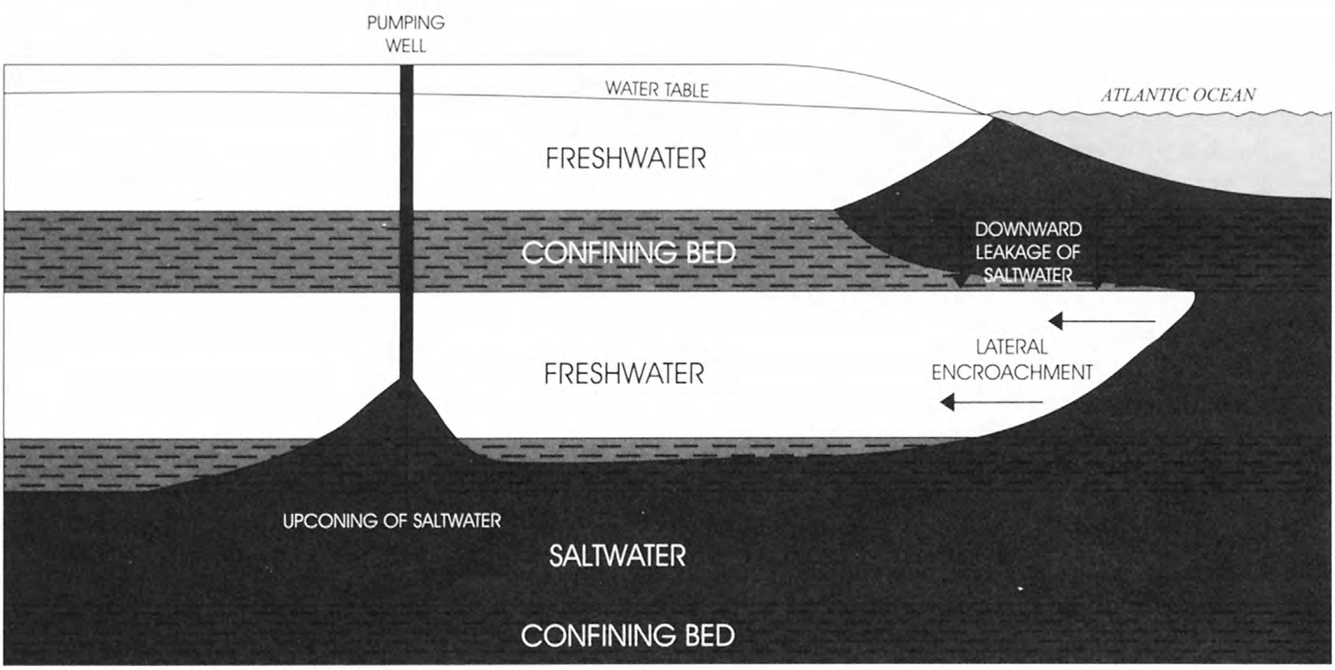

Figure 4. Aspects of saltwater intrusion.

inland saltwater wedge to the structure of the crater was confirmed by Bruce and Powars (1995, p. 8).

The most recent and most detailed maps of the inland saltwater wedge included contours of concentrations of the common ions in ground water and concentrations of dissolved solids in the Potomac aquifers (Focazio and others, 1993, pl. 3-5). The transition zone between freshwater and saltwater is delineated by concentrations of dissolved solids greater than 1,000 mg/L in the Middle Potomac aquifer (fig. 5). North of the James River, the transition zone generally conforms in configuration and location relative to the outer rim of the buried peak-ring crater. The contours of dissolved-solids concentrations were drawn before the discovery of the crater, and the hydrochemical and geologic data that were used to draw the respective map lines were determined independently.

The inland saltwater wedge is a regional phenomenon that is spatially related to the geologic structures associated with the buried peak-ring crater. The saltwater wedge in the Potomac Formation was intruded as a result of the Eocene bolide and(or) during high stands of the seas afterwards. Local variations in the concentration gradients of dissolved solids (and chloride) may be superimposed on the regional gradients. Saltwater also is found in association with Triassic rocks in Virginia, some of which are buried beneath the Coastal Plain. Residual seawater is trapped in some bedrocks beneath the Coastal Plain (Subitzky, 1961, p. D71).

Indicators of Saltwater Intrusion

Water samples collected from the chloride observation-well network in 1995 and 1996 indicated virtually no change in dissolved-solids or chloride concentrations from those recorded for previous years with one exception. An increase in dissolved-solids and chloride concentrations was detected in one well in the Lower Potomac aquifer at Newport News Park. The concentration of dissolved solids had increased 15 percent (from 3,860 mg/L in 1984 to 4,430 mg/L in 1993) and the concentration of chloride had increased 20 percent (from 2,000 to 2,400 mg/L) since shortly after the installation of the well in 1984. Other wells at the same site open to the Upper and Middle Potomac aquifers showed no changes in concentration since 1984 (fig. 6).

The Lower Potomac well at Newport News Park was installed in a deeper test hole. The bottom of the hole was not sealed by grout during construction of the well but was allowed to collapse and seal naturally, which raised the possibility of upward migration of saltwater from an unsealed hole. Standard groundwater procedures however require that field parameters, including specific conductivity, remain unchanged for at least one half hour before any water sample is collected for analysis. Field notes indicate that specific conductance in water from the well generally remained stable for several hours during purging before water samples were collected, which indicates that the

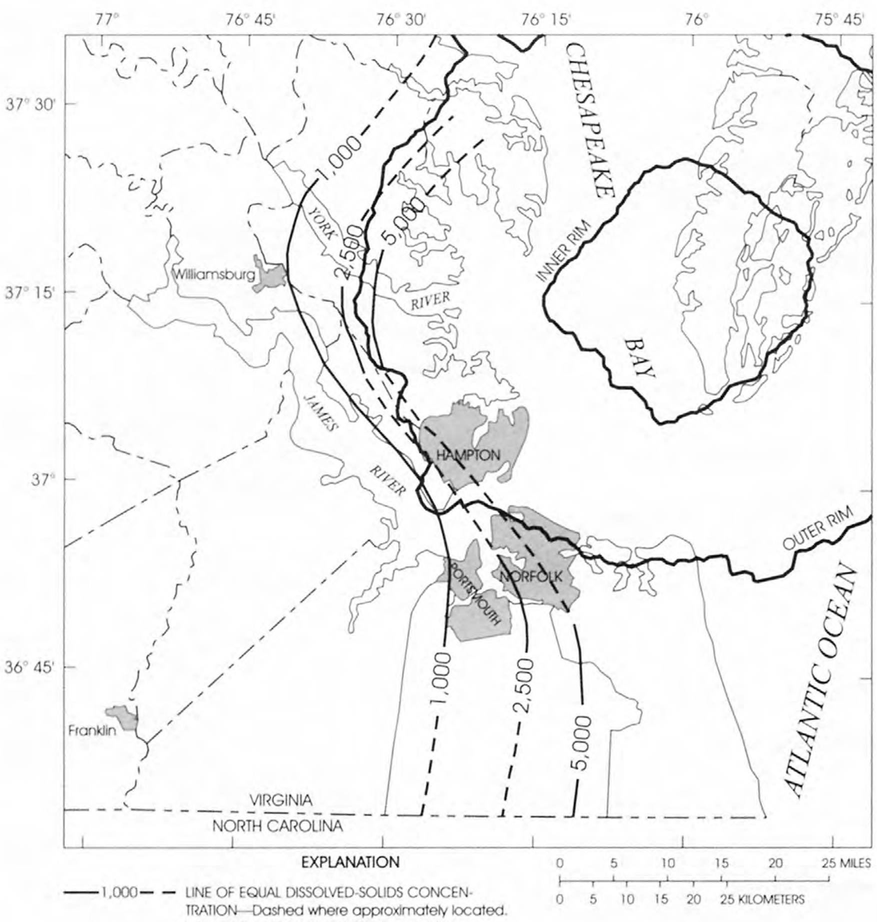

Figure 5. Concentrations of dissolved solids in the Middle Potomac aquifer.

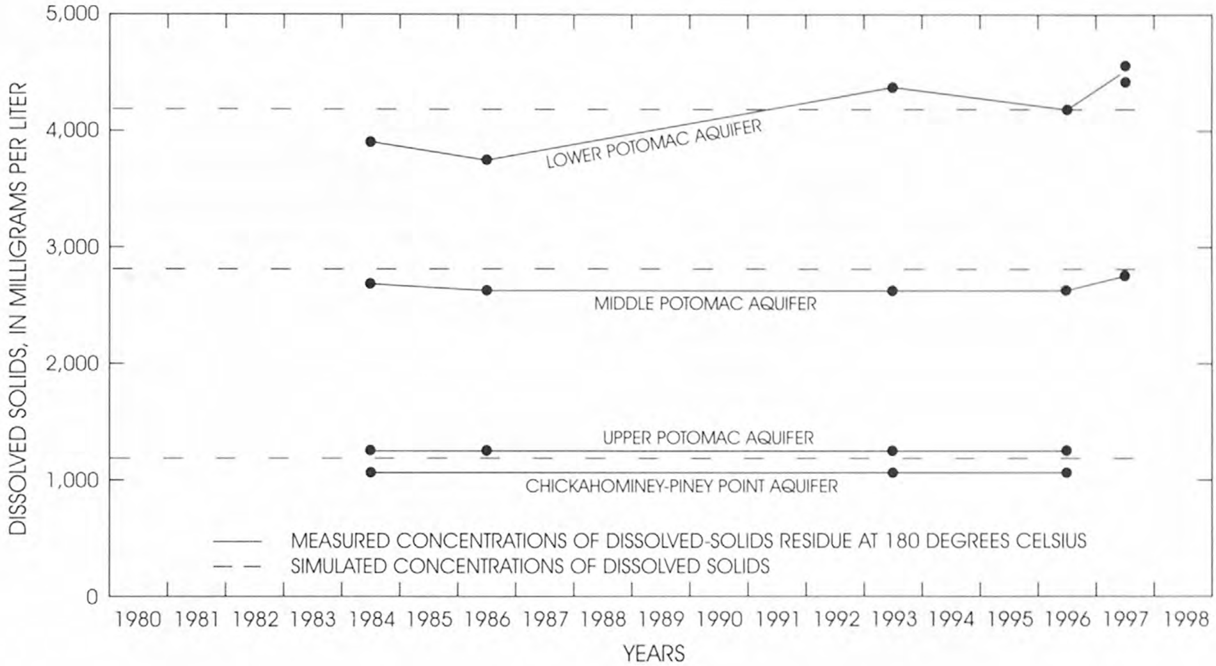

Figure 6. Concentrations of dissolved solids in wells at Newport News Park.

well bore probably was not an avenue for upward movement of saltwater from a deeper source.

The increase in dissolved-solids and chloride concentrations in the Lower Potomac well at Newport News Park coincided with declining water levels in that well during the same period (fig. 7). Beginning in 1994, however, water levels in the Lower Potomac well began a 3-year recovery. The water levels continued to recover until August 1996, when the levels dropped precipitously to the same depths as those before the recovery began, probably indicating renewed withdrawals. A water sample from the well in August of 1996 showed slightly lower concentrations of 4,330 mg/L; however, when the well was sampled again in 1997, a small increase in the concentration of dissolved solids to 4,580 mg/L was detected and confirmed by analysis of a replicate sample at 4,680 mg/L.

Water-use records from the Virginia Department of Environmental Quality (VADEQ) indicated the nearest withdrawals from the Potomac aquifers in the Lee Hall area were from an industrial plant on the James River at the western edge of the Lee Hall section. The records of ground-water use did, in fact, show a substantial decline in pumpage at the plant from more than 3.0 Mgal/d in previous years to less than 0.3 Mgal/d in 1994. This reduction in pumpage coincided with the water-level recovery in the Lower Potomac well.

The increases in dissolved-solids concentrations before 1993 could possibly be related to pumping at the plant in combination with regional pumping. Wells at the plant were, however, reported to be pumping from the Upper Potomac aquifer and should have produced greater declines and subsequent recoveries in water levels in that aquifer. The recovery of water levels in the Upper and Middle Potomac wells at Newport News Park were much smaller than those in the Lower Potomac well. The change in water levels in the Lower Potomac well from 1994 through 1997 has not been satisfactorily explained by the hydrogeologic and water-use data from Federal, State, or local records.

Changes in chloride concentrations with increased pumping were reported previously in the Lee Hall area by Cederstrom (1943, p 16-19). When newly installed wells near Fort Eustis began pumping in the early 1940's, concentrations of chloride increased substantially (up to 16 percent in one well) but then remained generally constant as long as the pumping remained steady. Cederstrom warned, however, that chloride concentration could increase gradually if pumping in the area increased. He believed that pumping during the drought of 1941-42 caused brackish water to migrate into the well field from downdip or from depth (Cederstrom, 1945, p.119).

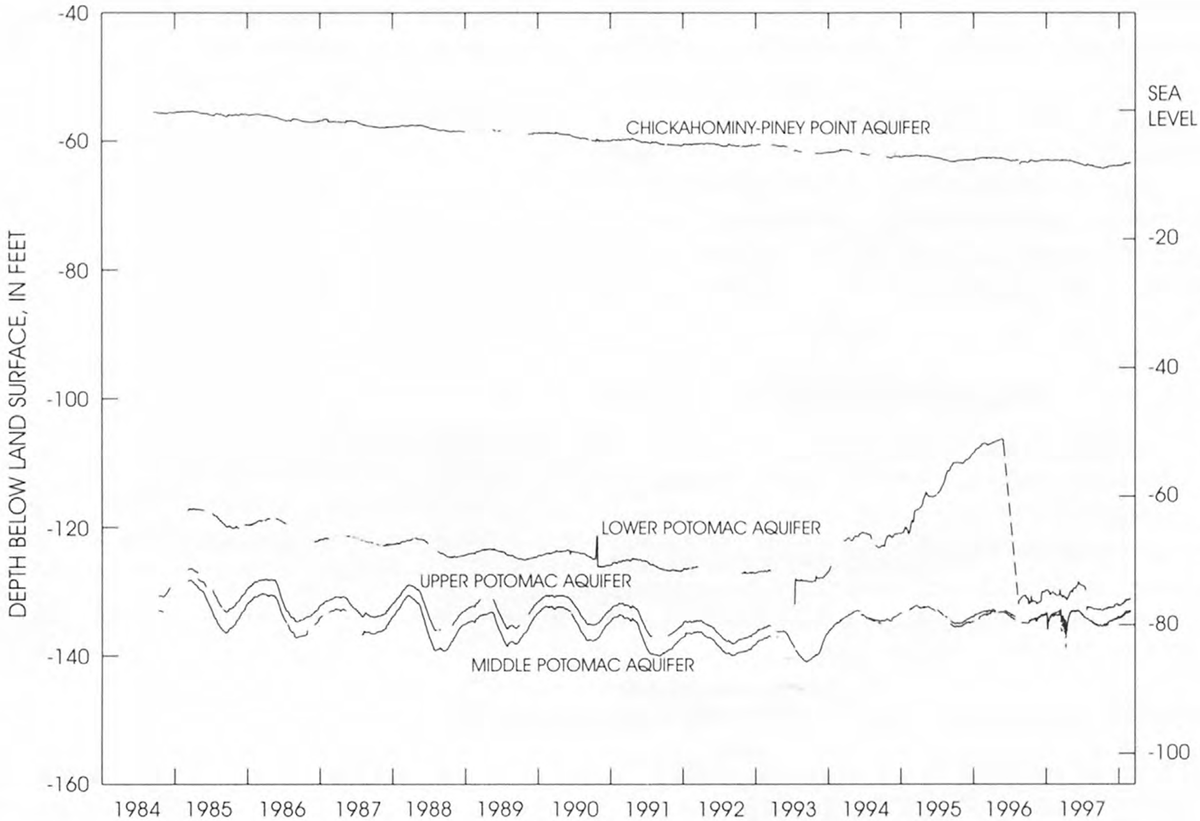

Figure 7. Water levels in wells at Newport News Park.

SIMULATION OF SALTWATER INTRUSION IN THE POTOMAC AQUIFERS

Data collected during the Chloride Project indicated that saltwater could be moving in the Lower Potomac aquifer but not in the shallower aquifers at Newport News Park near Lee Hall, Va. A two-dimensional, density-dependent, ground-water flow and solute-transport model was used to analyze whether the increase in dissolved-solids concentrations in the Lower Potomac aquifer before 1993 was caused by (1) upconing of saltwater at nearby pumping centers in the Upper Potomac aquifer, even though the Upper and Lower Potomac aquifers were believed to be separated by continuous confining layers, or (2) a more regional, lateral intrusion of saltwater, or (3) some combination of local and regional pumping. The Lee Hall area was studied because the data from no other sites sampled in the Chloride Project indicated possible saltwater movement. Additionally, more information about the aquifers and confining units was available in the Lee Hall area than elsewhere in the Coastal Plain of Virginia, which made the simulation of that area more feasible.

It was assumed that the Potomac aquifers and confining units had contained saltwater at some time in the past and that freshwater from the west had displaced the saltwater to the extent shown by the dissolved-solids concentrations that were unchanged in modern times. The solute-transport simulations were begun with a freshwater sweep of saltwater from the aquifers. The freshwater sweep was stopped when the simulated concentrations of dissolved solids approximated the measured concentrations in the Upper and Middle Potomac aquifers, which had not changed in modern times. Flow was then reversed in the aquifers to represent the effect of historical pumping. The hydrogeologic framework was evaluated by changing the permeability of the confining units and re-running the simulations from the beginning (freshwater sweep) through the historical pumping period. A hypothetical pumping well was simulated to indicate the potential for lateral intrusion and(or) upconing of saltwater and to isolate by simulation the local effect of pumping within a regional flow field.

Model Grid Design, Model Boundaries, and Fluid Properties

Saltwater movement in the Potomac aquifers and the factors that affect the distributions of saltwater in the aquifers were evaluated with the aid of a two-dimensional, density-dependent, solute-transport model. The USGS solute-transport model SUTRA, Version V-0690-2D (U.S. Geological Survey, 1991) was used. The solute-transport method used in this study is a variation of the seawater intrusion problem described by Voss (1984 p. 196-202) in the original SUTRA documentation. SUTRA-PLOT (Souza, 1987), a graphical display program, was used to plot mass fraction as dissolved-solids concentrations and velocity vectors as ground-water flow directions.

The model was designed to represent a simplified vertical section of the Potomac aquifers and associated confining units near Lee Hall, Va. The Lee Hall section encompasses the Upper, Middle, and Lower Potomac aquifers and associated confining units immediately above those aquifers; all units were assumed to be horizontal within the section. The section trends east-northeast from an industrial center near the James River in James City County through a cluster of USGS observation wells at Newport News Park across the buried outer rim of the peak-ring crater in York County (fig. 3). The section line was oriented to approximate the pre-pumping directions of ground-water flow and the opposite, reversed direction of ground-water flow caused by pumping in order to minimize errors inherent in using the two-dimensional approach.

The section is 9,000 m long by 400 m deep by 1 m wide (fig. 8.) Each of the 1,200 elements in the model is 300 m long, 10 m deep, and 1 m wide. The top of the section is 130 m below sea level and the bottom is 530 m below sea level. Aquifer and confining-unit depths were averaged from those determined for the area by the hydrogeologic framework study of the Virginia Coastal Plain (Meng and Harsh, 1988, Appendix).

The top nodes of the section, which represent the top of the confining unit above the Upper Potomac aquifer, were designated as constant-pressure nodes with a mass-fraction inflow equal to a dissolved-solids concentration of 1,000 mg/L. The inflow concentration was taken from field measurements in the aquifers immediately above the Upper Potomac.

The pressure designated for the top row of nodes generally represented sea level; however, several different ranges in pressure were tested before arriving at this generalization. Pressure gradients equivalent to 12 m (40 ft) and 9 m (30 ft) above sea level gradually declining toward the east down to the pressure of sea level were tested. These heads were derived from simulated and measured water levels in the aquifers above the Upper Potomac aquifer, before and after pumping, as indicated by Laczniak and Meng (1988, p. 80, 81, and 92).

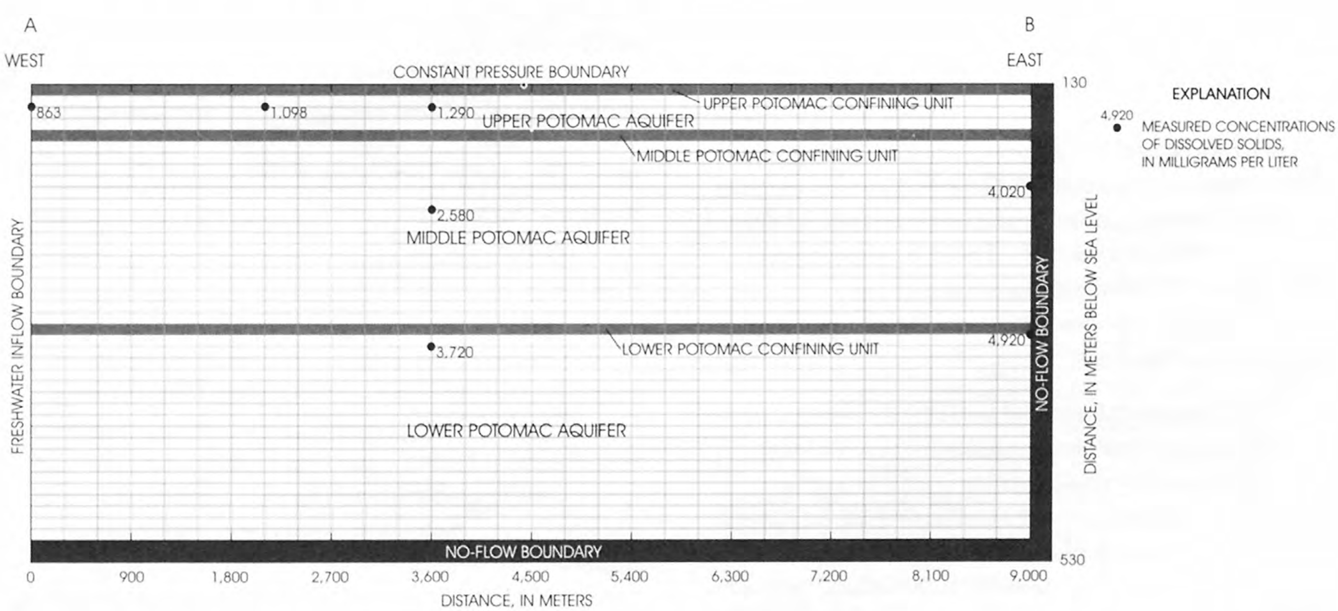

Figure 8. Finite-element mesh and boundaries of the Lee Hall Section.

Table 2. Fluid properties assumed for solute-transport simulations

Fluid property	Value
Fluid compressibility	4.47 x 10^{-10} meter-second-squared/kilogram
Fluid base concentration	0.0 milligrams/liter
Dissolved-solids base concentration as a mass fraction	0.0 kilograms/ kilograms of seawater
Dissolved-solid base concentration of seawater as a mass fraction	0.0357 kilograms /kilogram of seawater
Density of freshwater	1,000 kilograms/ cubic meter
Density of seawater	1,025 kilograms/cubic meter
Fluid viscosity	0.001 kilograms/meter second
Fluid diffusivity	1.00 x 10^{-9} square meters/ second
Density change with solute concentration	700 square kilometers (seawater) per kilogram dissolved solids-cubic meter

For the initial sweep of freshwater into saltwater, the western vertical boundary nodes were designated as freshwater inflows with inflow concentrations (mass fractions) of 1,000 mg/L, as indicated by measured concentrations of dissolved solids in the Upper Potomac aquifer (fig. 8). Concentrations of dissolved solids in the aquifers and confining units throughout the section were initially assumed to be 5,000 mg/L, on the basis of measured concentrations of dissolved solids in waters of the Middle and Lower Potomac aquifers, which were sampled during stem tests of the hole drilled at the remote well within the outer rim of the crater in York County.

The eastern vertical boundary was designated a no-flow boundary to represent the low permeability of the poorly sorted breccia and finer ejecta deposits of the Exmore tsunami deposits associated with the peak-ring crater. The bottom of the section also was designated a no-flow boundary to represent the low permeability of the bedrock formations compared to the Potomac aquifers.

Fluid properties assumed for the simulations (table 2) were those described by Voss in the original SUTRA documentation, with corrections of a later revision (1990, p. 196-202). These fluid properties were used in all of the simulations.

Freshwater Sweep

To approximate initial conditions, the pre-pumping simulations were begun with dissolved-solids concentrations (equivalent mass fractions) of 5,000 mg/L throughout the aquifer system. Freshwater with a concentration of inflow of 1,000 mg/L was applied along the western vertical boundary until the simulated concentrations of dissolved solids (as mass fractions) swept far enough eastward to approximate the measured dissolved-solid concentrations unchanged in modern times (fig 8). The dissolved-solids inflow concentrations from the west were estimated from field measurements in the Upper Potomac at the western end of the section, and the initial dissolved-solids concentration in the aquifer system were from dissolved-solids measurements at the remote-well site in the east.

Rates of freshwater inflow were determined by trial and error. A constant rate was applied equally along the vertical boundary nodes (half that rate at the edge nodes), and the pressures that resulted in the Upper Potomac aquifer were compared to those simulated and measured for pre-pumping conditions in the Lee Hall area by Laczniak and Meng (1988, p. 81 and 82). A number of freshwater sweeps were simulated in which the freshwater inflow rates and the vertical dispersivity of the units were changed through reasonable ranges; these parameters were tested first because they were known with the lowest degree of confidence. Each sweep was simulated through 1,000 years or more; some required more than 2,000 years before the simulated concentrations of dissolved solids (as mass fractions) swept far enough eastward to approximate the measured dissolved-solid concentrations. One-year time steps were used.

The absolute differences between simulated and measured dissolved-solids concentrations (nodes to equivalent well points) was calculated for different time periods. The smallest sum of absolute differences was used to determine the approximate time (usually within 100 years) when the closest approximation of simulated to measured dissolved solids had been reached. The sum of absolute differences for that time was recorded to compare results with the other simulations. Thus, a reasonable approximation for the two unknowns (freshwater inflow and vertical dispersivity) was reached on the basis of pre-pumping pressures and concentrations of dissolved solids that had not changed over time.

After the series of freshwater sweeps were simulated and the closest approximations to pre-pumping pressures and measured dissolved-solids concentrations were determined, those conditions were used as initial starting points for subsequent simulations representing pumping. Pumping was simulated as a reversal in the direction of ground-water flow by specifying negative flow rates at the eastern vertical boundary of the section. Different flow rates were tested by trial and error by comparing simulated pressures to equivalent pressures of the measured water levels in 1995 in the Lee Hall area (fig. 9).

The vertical permeabilities of the confining units were tested by changing the values through reasonable ranges in conjunction with the changes in the reversed-flow rates so that the pressures equivalent to the measured water levels across the section could be approximated.

These tests indicated that the simulated pressures were always higher than those equivalent to the measured water levels for the reversed-flow (pumping) conditions because too much water was leaking through the confining unit at the top of the section. A change in the geologic framework of the deposits comprising the confining unit above the Potomac Formation in the Lee Hall area was suggested by the work of D.S. Powars of the USGS and by T.S. Bruce of the VADEQ (written commun., 1997). The confining unit that was previously believed to consist primarily of sediments deposited either in a marginal outer-delta or a near-shore marine environment was also in large part an Eocene deposit of disturbed beds, coarse breccia, and tsunami deposits overlain by finer ejecta material.

Such a change in the concept of the hydrogeologic framework could indicate a lower permeability for the confining unit above the Upper Potomac aquifer. The initial vertical (and horizontal) permeability of the confining unit was reduced through a range of reasonable values, and the previous simulations were re-run. The series of re-runs indicated that

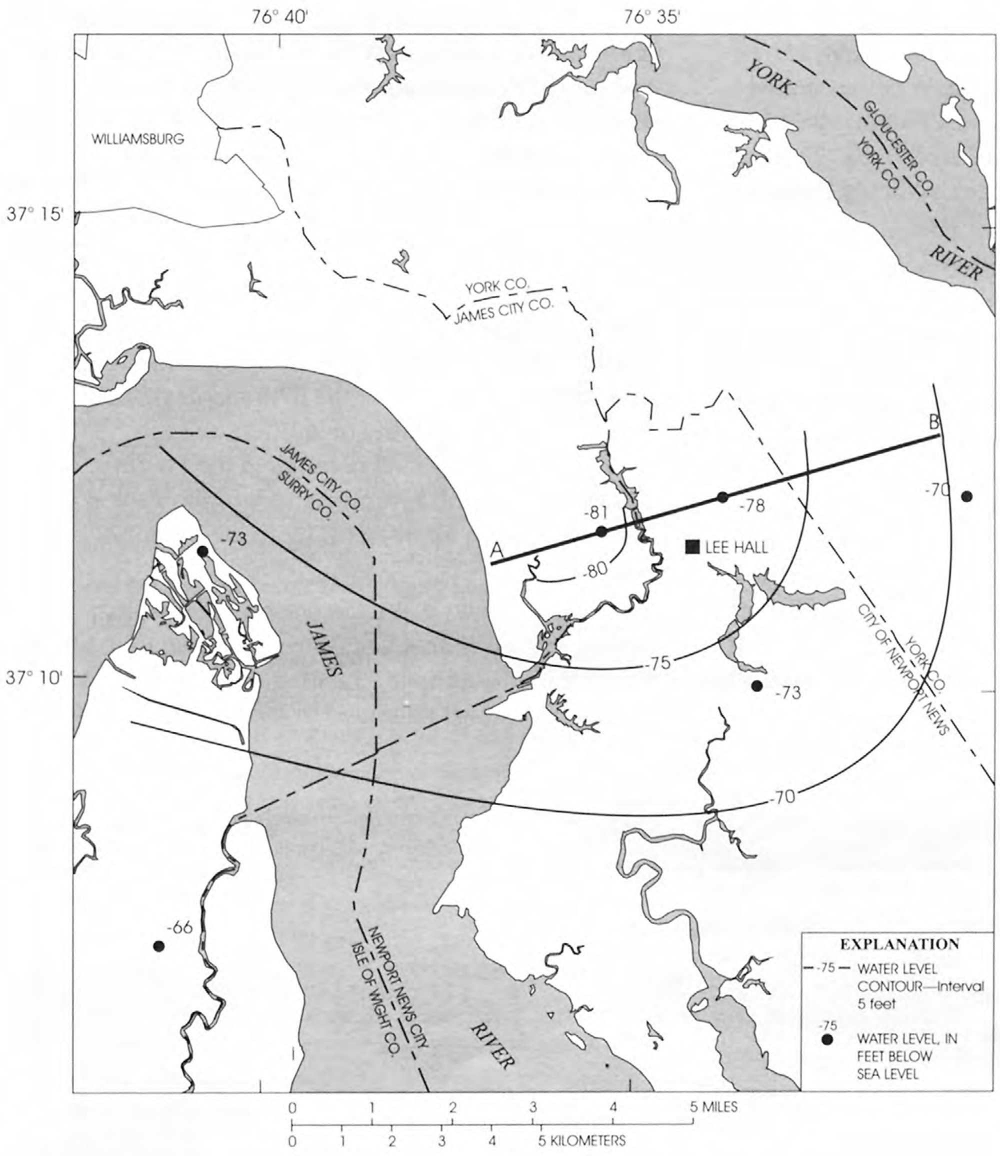

Figure 9. Water levels measured in the Middle Potomac aquifer, summer 1995.

a permeability equivalent to a vertical hydraulic conductivity of 0.0003 m/d (0.001 ft/d) for the Upper Potomac confining unit could best approximate the drawdowns measured during pumping. This value was then used for the Upper Potomac confining unit and, following further simulations, for the Lower Potomac confining unit as well. The same values were used in all subsequent simulations of freshwater sweeps and reverse-flow simulations to ensure an integrated approximation of pressures and concentrations for pre-pumping as well as pumping periods.

The hydrogeologic framework of the system was evaluated further by removing the Middle Potomac confining unit and re-running the simulations beginning with the freshwater sweep. By this method, it was determined that if the Middle Potomac confining unit was removed, a closer approximation of measured dissolved-solids concentrations would result. Measured water levels in the Upper and Middle Potomac aquifers, which had remained close and had fluctuated in tandem throughout the period of record (fig. 7), also were better approximated without a Middle Potomac confining unit.

With one continuous confining unit above the Lower Potomac aquifer and another above the Upper Potomac aquifer, the closest simulated approach to measured dissolved-solids concentrations was reached after about 1,200 years with an inflow of 0.0185 kg/s and a vertical dispersivity of 1 m (fig. 10). The pressures for the Upper Potomac aquifer were equivalent to water levels of 6.9 m (23 ft) above sea level in the west, grading to 4.7 m (15 ft) in the east. These are lower water levels but steeper gradients than those of the equivalent area of the section on the pre-pumping map of Laczniak and Meng (1988, p. 81), which were estimated at about 11 m (36 ft) in the west to 10 m (33 ft) in the east.

In the solute-transport simulation, freshwater displaced saltwater in the Upper Potomac aquifer over a distance of 2,700 m (from the western edge of the model to the dissolved-solids concentration of 1,000 mg/L) in 1,200 years, which is a rate of about 2 m/yr. A velocity vector plot of the pre-pumping simulation, vertically exaggerated 10 times, shows directions of ground-water flow from west to east in the aquifers with the highest velocities of about 8 m/yr toward the west in the Upper Potomac aquifer (fig. 11). Flows in the confining units were upward as water entered from the east but discharged upward through the confining unit above the Upper Potomac aquifer. The lowest velocity was 0.04 m/yr in the confining unit above the Lower Potomac aquifer.

After 1,200 years, the freshwater sweep had moved farther in the Upper Potomac aquifer where the permeability was highest but not as far in the Middle and Lower Potomac aquifers, respectively, in accordance with the lower permeability of each aquifer. The freshwater sweep eastward was particularly restricted by the confining unit above the Lower Potomac aquifer near the middle depths of the section. The contours of dissolved-solids concentrations lagged along the length of confining unit, because it had a low horizontal as well as vertical permeability. The solute-transport simulations indicate that the direction of ground-water flow and the properties of the hydrogeologic units, particularly the permeability of aquifers and the distribution of confining deposits in the Potomac Formation, control the hydrodynamics of the system and thus, the movement of saltwater in the Potomac aquifers.

Simulations using the previously established hydrogeologic framework (three confining units) had resulted in poorer approximation of the dissolved-solids concentrations measured in the Potomac aquifers

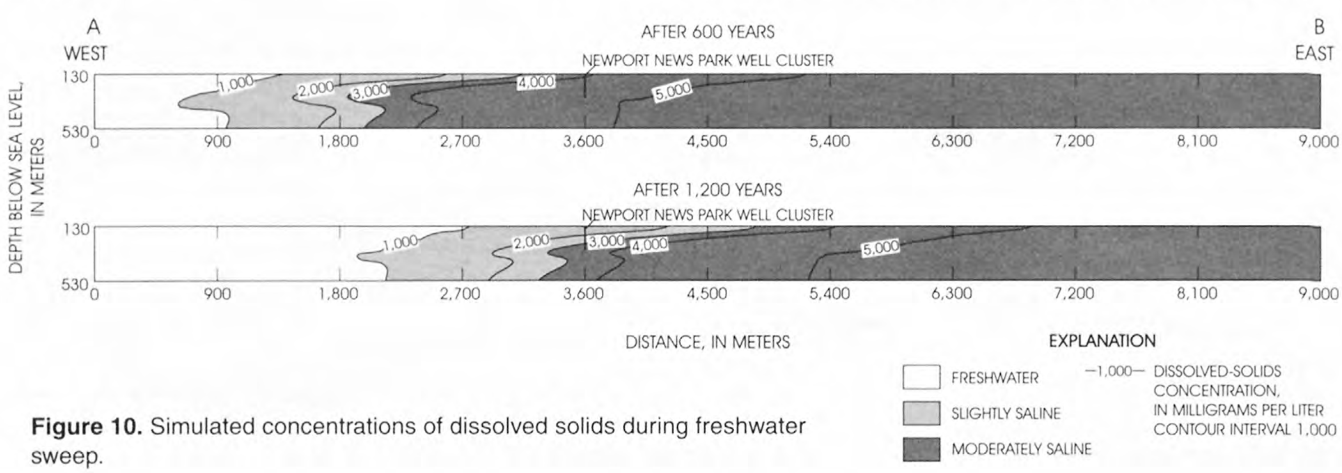

Figure 10. Simulated concentrations of dissolved solids during freshwater sweep.

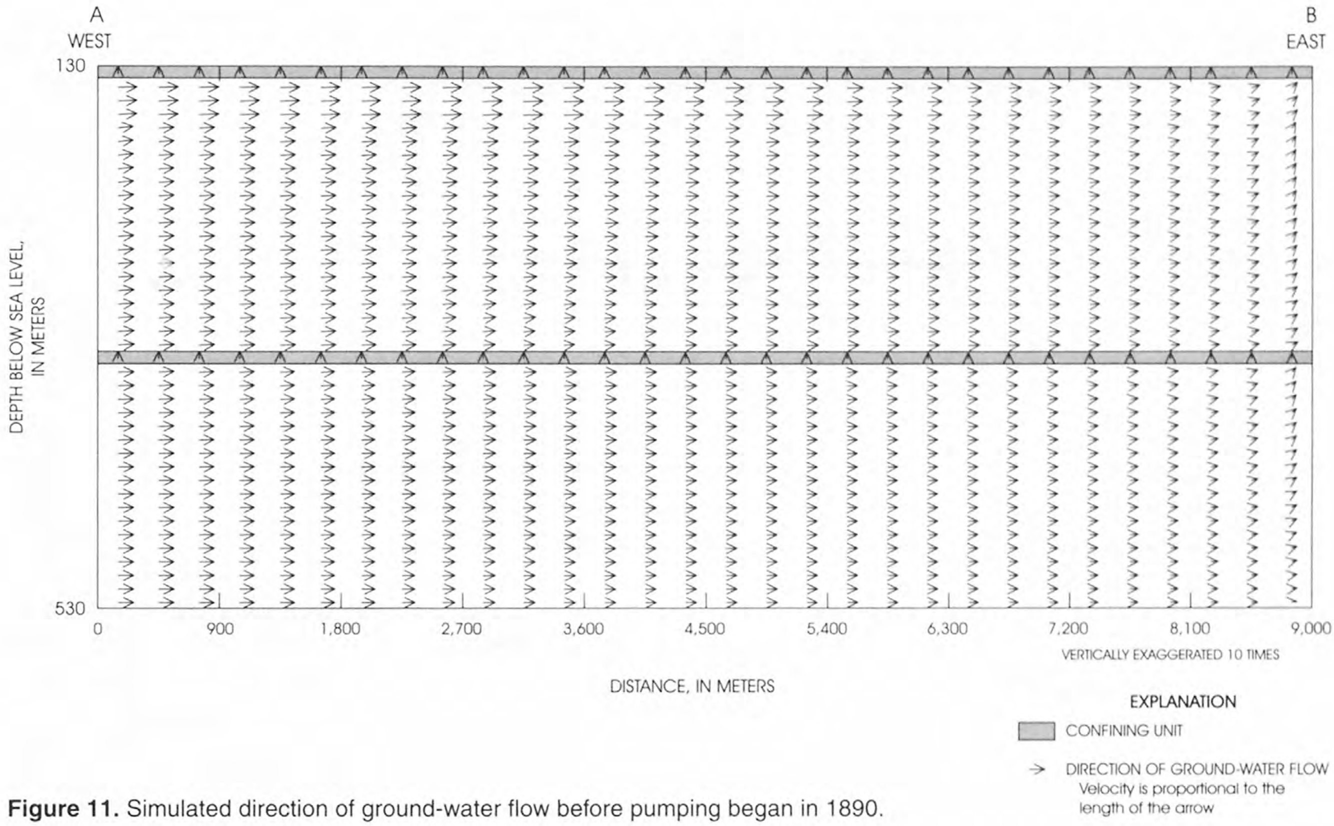

Figure 11. Simulated direction of ground-water flow before pumping began in 1890.

than those using just two confining units. The established hydrogeologic framework (Meng and Harsh, 1988, p. C33) delineates continuous confining units above all three of the Potomac aquifers, which is probably an oversimplification for this and many other areas of the Virginia Coastal Plain. The Potomac sediments, particularly the earlier Potomac sediments, were deposited by low-gradient rivers and meandering streams and would not generally have formed continuous units over very large distances.

The simulated concentration gradients of dissolved solids were not as evenly distributed in the vertical direction as the measured gradients, a persistent problem that has not been completely solved. The eastward sweeps of freshwater and the opposite, saltwater migrations westward may have occurred many times in the past as ancient seas advanced and retreated through the millennia. The pressure changes back and forth would have mixed freshwater and saltwater, causing a more uniform, vertically dispersed concentration than that simulated by only one eastward sweep of freshwater. The diffusion of ions during the millennia also could have contributed to the spreading of concentration gradients.

Pumping and Reversed Flow

Continuing with one confining unit above the Upper Potomac aquifer and another above the Lower Potomac aquifer, a series of reversed-flow simulations was run to approximate the movement of saltwater from 1890, when pumping began, to the end of 1997. The objective was to simulate dissolved-solids concentrations in the Upper, Middle, and Lower Potomac aquifers, as measured in June 1984 through July 1997 at the well cluster in Newport News Park.

An outflow of -0.0185 kg/s, equal to but opposite the pre-pumping flow, was withdrawn from the nodes of the eastern vertical boundary of the section for a period of 50 years to represent the first withdrawals from the aquifers from 1890 to the end of 1940. Reversing the flow had the expected result of changing the simulated-flow directions in the aquifers and in the confining units. Where freshwater had previously flowed eastward in the aquifer, saltwater began to slowly displace freshwater from east to west, and in the confining units where flow had been upward prior to pumping, simulated directions of flow were downward for the pumping period (fig. 12).

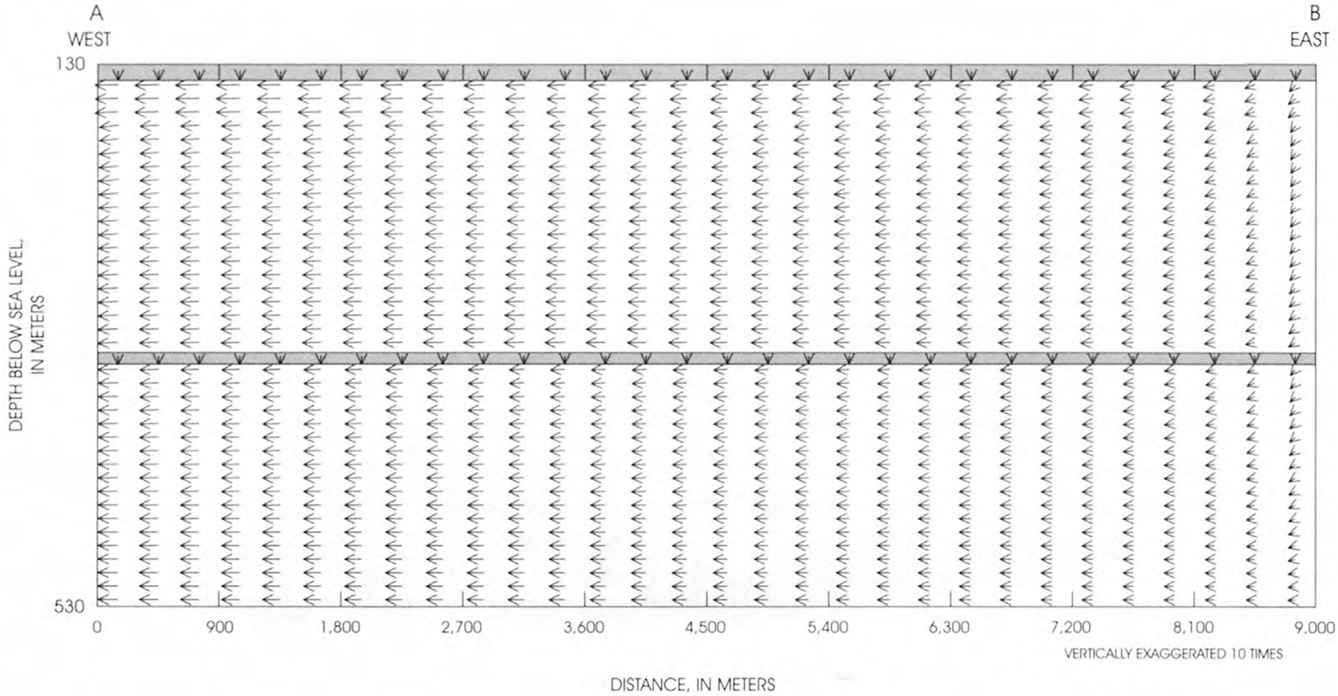

Figure 12. Simulated direction of ground-water flow in 1940.

Saltwater moved slightly westward from 1890 to 1940 because of the reversal in flow directions (fig. 13). The simulated 4,000 mg/L contour of dissolved solids moved about 100 m westward in the Lower Potomac aquifer in those 50 years, a rate of about 2 m/yr, and the 1,000 mg/L contour moved about 300 m westward at the bottom of the Middle Potomac aquifer in 50 years, a rate of about 6 m/yr. The velocities were greater in the west—as high as 8 m/yr—in the Upper Potomac aquifer where the permeability was highest as indicated by velocity vectors of the simulation.

Pressures simulated for the Upper Potomac aquifer in the west were equivalent to water levels of 6.6 m (22 ft) below sea level. Pressures representing the Upper Potomac site at Newport News Park near the center of the section were equivalent to 5.7 m (19 ft) below sea level, and pressures in the east were equivalent to 5.6 m (18 ft) below sea level. Pressures representing the Lower Potomac site at Newport News Park were equivalent to 8.8 m (29 ft) below sea level.

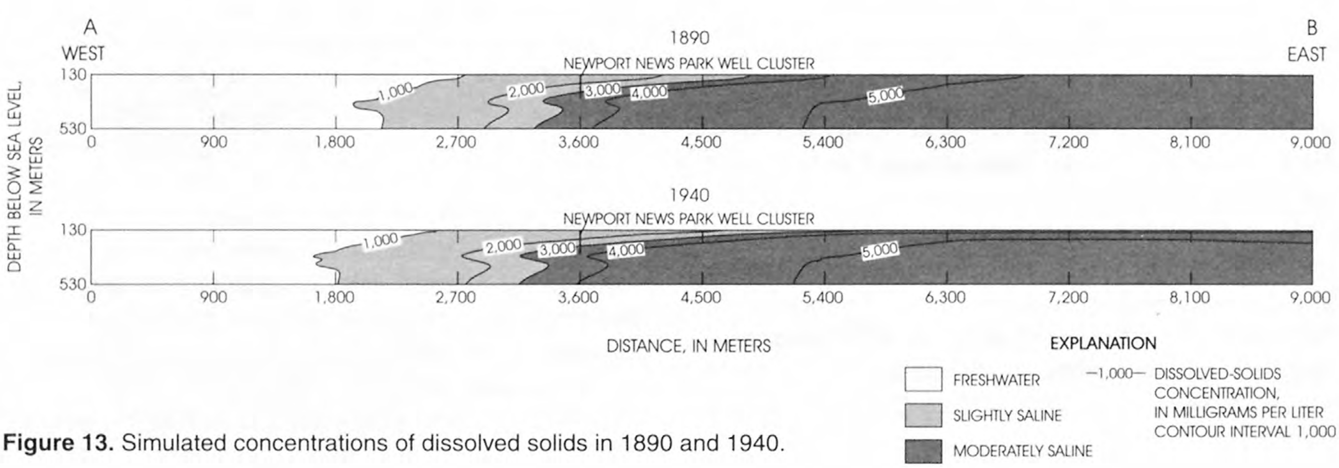

Figure 13. Simulated concentrations of dissolved solids in 1890 and 1940.

For the next time step, the withdrawals were doubled to -0.037 kg/s. The additional withdrawals were taken from the lower half of the vertical section at the westward vertical boundary (from depths of 320 to 530 m below sea level) to represent pumping from the Middle and Lower Potomac aquifers.The withdrawals were taken from the Middle and Lower Potomac aquifers because initial simulations of the additional withdrawals when distributed evenly from all of the aquifers resulted in substantial saltwater movement in the Upper and Middle Potomac aquifers but not in the Lower Potomac aquifer, which was the opposite of what the measured dissolved-solids concentrations had indicated. The simulation was continued for 20 years to represent the increase in pumping from 1940 to the end of 1960.

Simulating reversed flows in the lower half of the section from 1940 to the end of 1960 resulted in saltwater movement in the Lower Potomac aquifer but not much movement in the Upper Potomac aquifer (fig. 14). Saltwater did not move appreciably in the Upper Potomac aquifer because downward migration of water through the confining unit at the top of the section, which was specified with an inflow dissolved-solids concentration of 1,000 mg/L, contributed freshwater from above to the Upper Potomac aquifer.

Some saltwater also moved in the bottom of the Middle Potomac aquifer, but there was not much movement where the Middle Potomac well point was represented. Simulated saltwater movement was greater in the Lower Potomac aquifer, particularly in the west because of higher flow rates there. The highest velocities were in the Upper Potomac aquifer, 35 m/yr at the westward boundary as calculated by the velocity vectors. Simulated displacement of water near the well cluster was, however, much slower. The 4,000 mg/L contour of dissolved solids had moved about 100 m westward in the Middle and in the Lower Potomac aquifers from 1940 to the end of 1960, a rate of about 5 m/yr.

For the next time step, the withdrawals were doubled again to -0.074 kg/s and the added withdrawals were again from the lower half of the section (the Middle and Lower Potomac aquifers). The simulation was continued for another 20 years to represent the largest increases in pumping from the end of 1960 to the end of 1980. Then pumping was reduced slightly to -0.070 kg/s, and the simulation was continued for 17 more years to represent the period from the end of 1980 to the end of 1997.

Saltwater continued to move in the lower half of the section from 1960 to 1997, as indicated by results of the simulation (fig. 15). Simulated concentrations of dissolved solids moved westward farther and faster than in previous years because of the increase in pumping. At the bottom of the Lower Potomac aquifer, the 4,000 mg/L contour of dissolved solids moved about 400 m in 37 years, a rate of about 11 m/yr. Very little movement of saltwater was simulated in the Upper Potomac aquifer, however, where inflows of freshwater from above inhibited saltwater intrusion. Although the simulations indicate that saltwater could have moved in the Lower Potomac aquifer west of Newport News Park, no data from observation wells were available there to indicate a change in concentrations of dissolved solids or chlorides.

Measured concentrations of dissolved solids in the Lower Potomac aquifer at Newport News Park increased from 3,860 mg/L in 1984 to 4,580 mg/L in 1997, an increase of about 19 percent. The simulated concentration for the node representing that well point increased about 3 percent, from 4,243 mg/L at the end of 1984 to 4,353 mg/L at the end of 1997 (fig. 6). Although not precise, the simulated concentration for

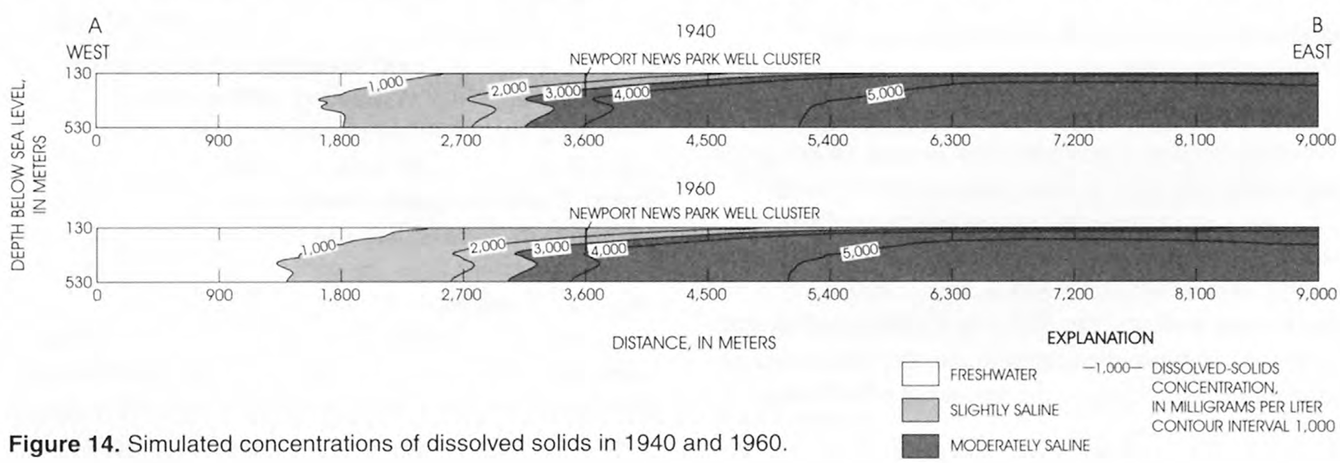

Figure 14. Simulated concentrations of dissolved solids in 1940 and 1960.

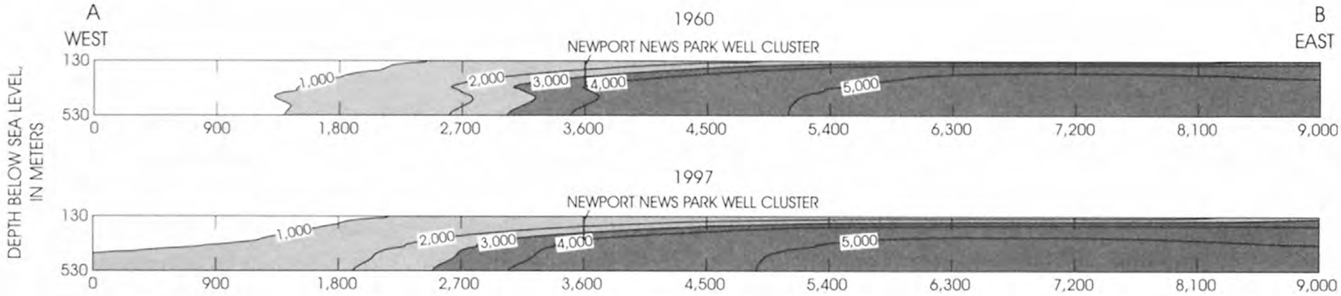

Figure 15. Simulated concentrations of dissolved solids in 1960 and 1997.

the nodes representing the well points for the Upper, Middle, and Lower Potomac aquifers were reasonable approximations of the measured dissolved-solids concentrations, considering that a total period of 1,307 years was simulated from the initial freshwater sweep through the reversals in flow and increases in pumping from 1890 through 1997.

Simulated pressures in the Upper and Middle Potomac aquifers in 1997 were equivalent to water levels of 73 ft below sea level at the well cluster in Newport News Park, which is a reasonable approximation of the average levels recorded from 1993 through 1997 (fig. 7); however, simulated pressures in the Lower Potomac aquifer were equivalent to 131 ft below sea level, which is somewhat lower than those recorded for the same period. Thus, the model did not simulate an upward vertical gradient from the Lower Potomac to the Middle Potomac aquifer as the data had indicated. A more accurate simulation of ground-water flow and saltwater movement in the Lower Potomac aquifer would probably require a three-dimensional solute-transport approach.

Upward Migration of Saltwater Toward a Production Well

Upconing is the vertical upward movement of saltwater beneath a pumping well or well field. Upconing is typically a local phenomenon and becomes evident as an increase in concentrations of dissolved solids or chloride within a few months or years following the initial start-up of production. A typical production well was simulated in the Middle Potomac aquifer to indicate the approximate area that could be immediately affected by the upconing of saltwater.

According to the Theis solution (Freeze and Cherry, 1979, p. 317), pumping a well at 3 Mgal/d would cause a drawdown of about 12 m (40 ft) in an observation well 1,800 m (5,906 ft) away as it approached equilibrium, assuming a transmissivity of 590 m^2/d (6,400 ft^2/d) and a storage coefficient of 0.0006. By trial and error, such a drawdown was found to be equivalent to withdrawing 0.035 kg/s from a single model node in the Middle Potomac aquifer. Withdrawing an additional 0.035 kg/s from the Middle Potomac aquifer resulted in changes in the directions of flow immediately adjacent to the production well (fig. 16). The area of immediate influence was at most about 30 m (100 ft) below the withdrawal point. The area of influence was relatively small compared to the larger velocity field, which is controlled by regional flows directed toward a few large-production well fields. The immediate effect of upconing also would probably be small, because the concentrations of dissolved solids grade moderately with depth in the Potomac aquifers. The simulated concentrations of dissolved solids in the production well increased 5 percent (from 1,011 to 1,061 mg/L) after 10 years and 22 percent (from 1,011 to 1,236 mg/L) after 37 years.

The typical production well would, however, contribute an added component of flow to the regional flow field that would affect the migration of saltwater beyond the immediate area. Transport velocities in the Upper Potomac aquifer would increase if additional withdrawals were added, and saltwater would move farther westward from the well in the horizons above (fig. 17). In the Middle Potomac aquifer, concentrations of dissolved solids would not change along the same horizon westward of the production well because flow there was eastward. Saltwater movement in the Lower Potomac aquifer, however, would have an

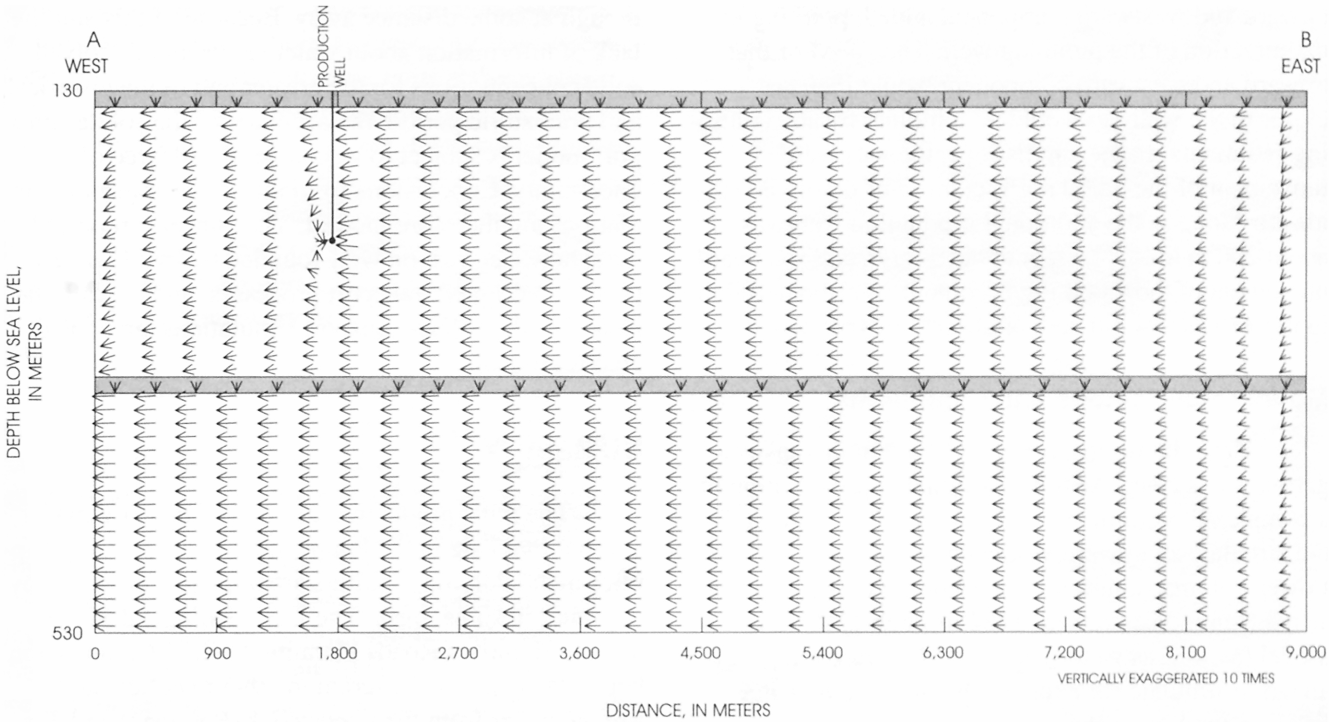

Figure 16. Simulated direction of ground-water flow near a typical production well.

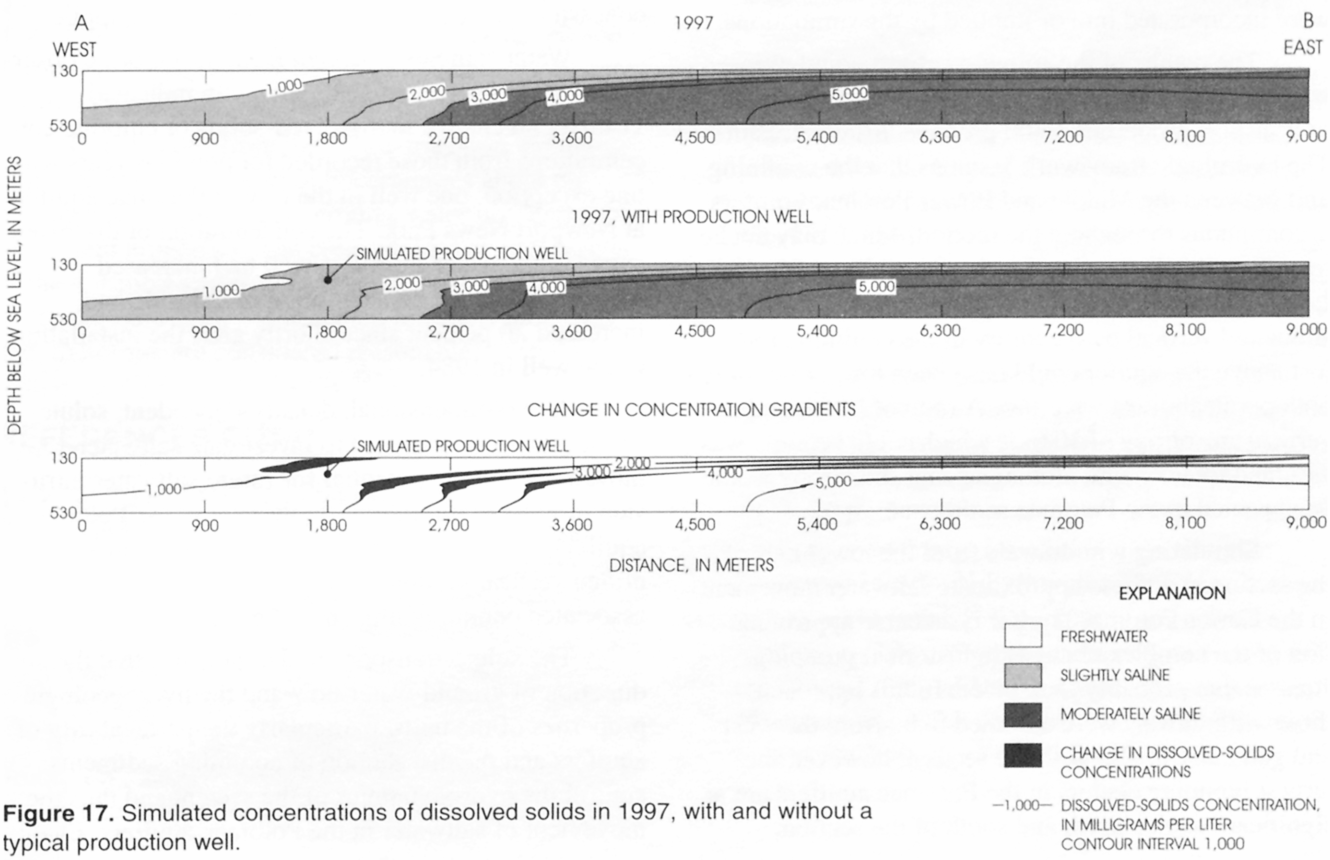

Figure 17. Simulated concentrations of dissolved solids in 1997, with and without a typical production well.

upward and westward component added, pointing in the direction of the pumping well. The speed of that upward and westward component would increase closer to the well but would be inhibited by any confining sediments. In the simulations, the westward movement of the 2,000 mg/L contour of dissolved solids attributed to the additional production well was about 200 m in 37 years, or about 5 m/yr, and westward movement of the 4,000 mg/L contour was about 100 m in the 37 years simulated, or about 3 m/yr.

Model Uncertainties and Limitations

The solute-transport model used in this investigation was a coarse two-dimensional approximation of a complex three-dimensional system. The model did not simulate an upward vertical gradient from the Lower Potomac aquifer to the Middle Potomac aquifer as the data indicated from 1984 through 1997. The model (as well as water-use data) also were too generalized to simulate (or explain) the increase in water levels in the Lower Potomac aquifer at Newport News Park from 1993 to 1996. Such differences between the simulated pressures and measured water levels in the Lower Potomac aquifer are indications of the uncertainties in the hydrogeologic framework, permeabilities, and ground-water withdrawal rates that were incorporated into or implied by the simulations.

The results of the solute-transport simulations were not unique solutions, and variations in hydraulic or transport properties could produce different results. The hydrologic framework assumes that the confining unit between the Middle and Lower Potomac aquifers is continuous throughout the section, which may not be true. As a result, the simulated permeability of the Lower Potomac aquifer could have been too low, the simulated vertical permeability in the confining unit just above the aquifer could have been low, or possibly both permeabilities were low. A ratio of horizontal to vertical anisotropy of 10 to 1, which could be high, was assumed for each unit although some anisotropy would be expected in the Potomac sediments.

Simulating withdrawals from the lower half of the section in order to approximate saltwater movement in the Lower Potomac aquifer is a coarse approximation of the complex changes in historical pumping stresses that probably took place. In this approach, those withdrawals were assumed to be from the west and generally in line with the section; however, the largest pumping centers in the Potomac aquifers are at significant angles north and south of the section, though at some distance away. Because of this and the lack of information about water levels and dissolved-solid concentrations for the greater part of the historical and prehistoric period, the accuracy of the solute-transport model is subject to a considerable degree of uncertainty. Conclusions from the solute-transport simulations are therefore modest. The concepts reported here, however, rest on well-founded hydraulic principles and accepted transport processes, and overall, the results of the solute-transport simulations are considered reasonable.

SUMMARY

The most productive aquifers of the Virginia Coastal Plain are in the Potomac Formation. Water supplies in the Potomac aquifers are impaired, however, by saltwater in some areas. The U.S. Geological Survey and the Hampton Roads Planning District Commission began the Chloride Program in 1995 to collect and sample water from the Cretaceous (Potomac) and Tertiary (Chickahominy-Piney Point) aquifers at selected sites in the Coastal Plain in order to determine the spatial and temporal distribution of chloride as related to saltwater in the aquifers and to determine which aspects of saltwater intrusion, if any, could be of concern to present and future ground-water supplies.

Water samples collected from the chloride observation-well network in 1995 and 1996 indicated virtually no change in dissolved-solids or chloride concentrations from those recorded for previous years with one exception, one well in the Lower Potomac aquifer at Newport News Park. The concentration of dissolved solids in the water from this well had increased 15 percent and the concentration of chloride had increased 20 percent since shortly after the installation of the well in 1984.

A two-dimensional, density-dependent, solute-transport model was used to investigate saltwater movement and the potential for future saltwater intrusion or upward migration of saltwater in the Potomac aquifers. The model was designed to represent a simplified vertical section of the Potomac aquifers and associated confining units near Lee Hall, Va.

The solute-transport model indicates that the direction of ground-water flow and the hydrogeologic properties of the units, particularly the permeability of aquifers and the distribution of confining sediments, control the hydrodynamics of the system and thus the movement of saltwater in the Potomac aquifers. Evaluation of the established hydrogeologic framework by solute-transport simulations suggests that the current concept of continuous confining units above all three Potomac aquifers is probably an oversimplification for the Lee Hall area and possibly for many other areas of the Virginia Coastal Plain. Knowledge of the hydrodynamics of the ground-water-flow system, the effects of pumping wells on aquifer water levels, and saltwater movements in the aquifers could be improved if the hydrogeologic framework of the Coastal Plain was refined.

Although the accuracy of the solute-transport model is subject to a considerable degree of uncertainty, the transport simulations indicated that lateral intrusion was probably the mechanism for saltwater movement in the Lower Potomac aquifer near Lee Hall, Va. The transport model also indicated that a typical production well in the Middle Potomac aquifer could induce upconing of saltwater but only within the immediate vicinity of about 30 m (100 ft) beneath the well. Slow upward and lateral migration of saltwater from the Middle and Lower Potomac aquifers some distance seaward of the production well was, however, also indicated. Overall, the transport simulations indicate a slow but steady movement of saltwater toward pumping wells. Such slow but persistent saltwater intrusion in an aquifer system as large and complex as that of the Virginia Coastal Plain can be observed and accurately measured only through a long-term, quality-assured monitoring network.

Conclusions from the solute-transport simulations are modest because of uncertainties about the hydrogeologic framework, ground-water use, and aquifer-system properties. The concepts and overall results of the transport simulations rest on well-founded hydraulic principles and accepted transport processes and, therefore, are considered reasonable.

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