

QUALITY OF GROUND WATER IN THE COASTAL PLAIN PHYSIOGRAPHIC
PROVINCE OF VIRGINIA

By Michael J. Focazio, Gary K. Speiran, and M. Eileen Rowan

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

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

Copies of this report can be
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ABSTRACT

Available water-quality data were used to describe spatial distributions of selected chemical-constituent concentrations and physical-property values in the Yorktown-Eastover, Chickahominy-Piney Point, Brightseat-upper Potomac, middle Potomac, and the lower Potomac aquifers in the Coastal Plain physiographic province of Virginia. Chemical-constituent concentrations and physical-property values used to describe water quality are spatially variable in these aquifers. Concentrations of chloride generally range from 1.3 to more than 17,000 mg/L (milligrams per liter), and of sodium, from 3.3 to 8,100 mg/L. Fluoride concentrations range from nondetectable to 6.3 mg/L. Dissolved solids, pH, hardness, alkalinity, sulfate, and silica also are spatially variable.

The spatial variability in chemical-constituent concentrations and physical-property values for the five aquifers is distributed in zones of different chemistry that are oriented north to south. These zones reflect the evolution of hydrochemical facies along west-to-east ground-water-flow paths. Hydrochemical facies evolve from a water with no dominant ions in the western zone, to a calcium bicarbonate-type water, to a sodium bicarbonate-type water, and finally to a sodium chloride-type water in the eastern zone.

Several chemical-constituent concentrations and physical-property values exceed U.S. Environmental Protection Agency Maximum Contaminant Levels (MCL's) and Secondary Maximum Contaminant Levels (SMCL's) and Virginia anti-degradation standards in parts of each aquifer. Chloride concentrations and dissolved-solids concentrations exceed the levels and standards in the eastern parts of each aquifer. Fluoride concentra-

tions exceed the MCL in parts of the Chickahominy-Piney Point and upper, middle, and lower Potomac aquifers. Sulfate concentrations exceed the SMCL in the extreme eastern parts of several aquifers. The pH values also exceed the SMCL locally in each aquifer.

INTRODUCTION

Ground-water quality in the Coastal Plain physiographic province of Virginia has been analyzed by several investigators, but complete maps of the water quality of individual aquifers within the region's geohydrologic system do not exist. However, planners at the State, county, and municipal levels need such regional-scale information about ground-water quality.

The hydrology and quality of ground water in the Virginia Coastal Plain was first described in detail by Cederstrom (1943; 1945a; 1946). Back (1966) described the evolution of the major hydrochemical facies in the northern part of the Atlantic Coastal Plain, including the part in Virginia. Powell and Hamilton (1986) completed an overview of the ground-water quality for the entire State of Virginia. That report summarized data for dissolved-solids, hardness, nitrate, iron, and fluoride concentrations, but spatial distributions were not included. The geohydrologic framework of the Coastal Plain was roughly approximated at that time, but the water quality of individual aquifers could not be evaluated.

In 1978, the U.S. Geological Survey (USGS) began the Regional Aquifer-System Analysis (RASA) Program, and designated the northern Atlantic Coastal Plain as a RASA study area. The RASA program in Virginia described a detailed geohydrologic framework for the Virginia Coastal

Plain physiographic province (Meng and Harsh, 1988). Harsh and Lacznia (1990) developed a conceptual model of the ground-water-flow system, which was refined for the southeastern Virginia area by Hamilton and Larson (1988). Regional¹ ground-water quality was assessed for James City County (Harsh, 1980), the York-James peninsula (Lacznia and Meng, 1988), and the Delmarva peninsula (Hamilton and others, 1989). Many local assessments of ground-water quality were made by the Virginia Water Control Board and local water authorities, primarily for regulation of water-supply-source quality. As part of the continuing analysis of the Coastal Plain ground-water system, Focazio (1990) incorporated the work of Harsh and Lacznia (1990), Hamilton and Larson (1988), and Lacznia and Meng (1988) into an updated geographic information system. The USGS, in cooperation with the Hampton Roads Planning District Commission and the Virginia Water Control Board, combined ground-water-quality data from selected previous studies with current (1992) knowledge of the ground-water-flow system as part of a continuing study to improve the understanding of the regional ground-water quality of the Virginia Coastal Plain.

Purpose and Scope

This report describes the regional spatial distribution, by aquifer, of the major chemical constituents and physical properties of ground water in the Virginia Coastal Plain. Only data from the USGS data base were used in the analysis. Sufficient data were available to contour regional spatial distributions of selected chemical-constituent concentrations and physical-property values for the Chickahominy-Piney Point, Brightseat-upper Potomac, middle Potomac, and lower Potomac aquifers. Data for the Yorktown-Eastover aquifer were also mapped but were not contoured. The Columbia, Aquia, and Virginia Beach aquifers were not analyzed because of insufficient spatial distribution of water-quality data. The physical properties mapped and described in this report are pH, dissolved solids, total hardness, and alkalinity. The chemical constituents mapped and

described are sodium, sulfate, chloride, fluoride, and silica. The major hydrochemical facies also are described. General patterns in water quality are characterized for each of the five aquifers and for the Virginia Coastal Plain. A brief discussion of possible major factors contributing to the observed water-quality patterns is also included.

Description of Study Area

The study area consists of the part of the Atlantic Coastal Plain that lies within the boundaries of the State of Virginia (fig. 1). This province encompasses an area of approximately 13,000 mi. The Coastal Plain physiographic province slopes gently seaward and is transected by a series of broad, seaward-facing, ocean-cut terraces that trend north to south. In the study area, several major rivers, including the Potomac, Rappahannock, York, and James Rivers, have incised valleys that drain into the Chesapeake Bay (fig. 2). The deposits that underlie the province form an eastward-thickening wedge of unconsolidated, interbedded gravel, sand, silt, and clay of early Cretaceous to Holocene age (fig. 3). These deposits are underlain by consolidated bedrock.

Regional water-quality patterns reflect the natural ground-water-flow system. Although water is heavily pumped from aquifers in some areas, pumping is low in other areas. This may cause local changes in water quality, but natural effects probably continue to dominate regional water-quality patterns. The most likely water-quality change caused by pumping is saltwater intrusion; however, regional intrusion of saltwater has not been documented in the confined aquifers in Virginia. Thus, interpretation in this report assumes natural water-quality patterns, the slow rate of ground-water flow, the probable large effects of regional patterns in sediment mineral composition on water quality even where the aquifer is pumped, and the large distances between centers of major pumping and sources of saltwater.

The natural ground-water-flow system for the Virginia Coastal Plain was described by Harsh and Lacznia (1990). A water-table aquifer and an underlying sequence of confined aquifers and intervening confining units compose the ground-water-flow system of the Virginia Coastal Plain

¹The term "regional" is used in this report to refer to a major geographical subdivision of the Virginia Coastal Plain.

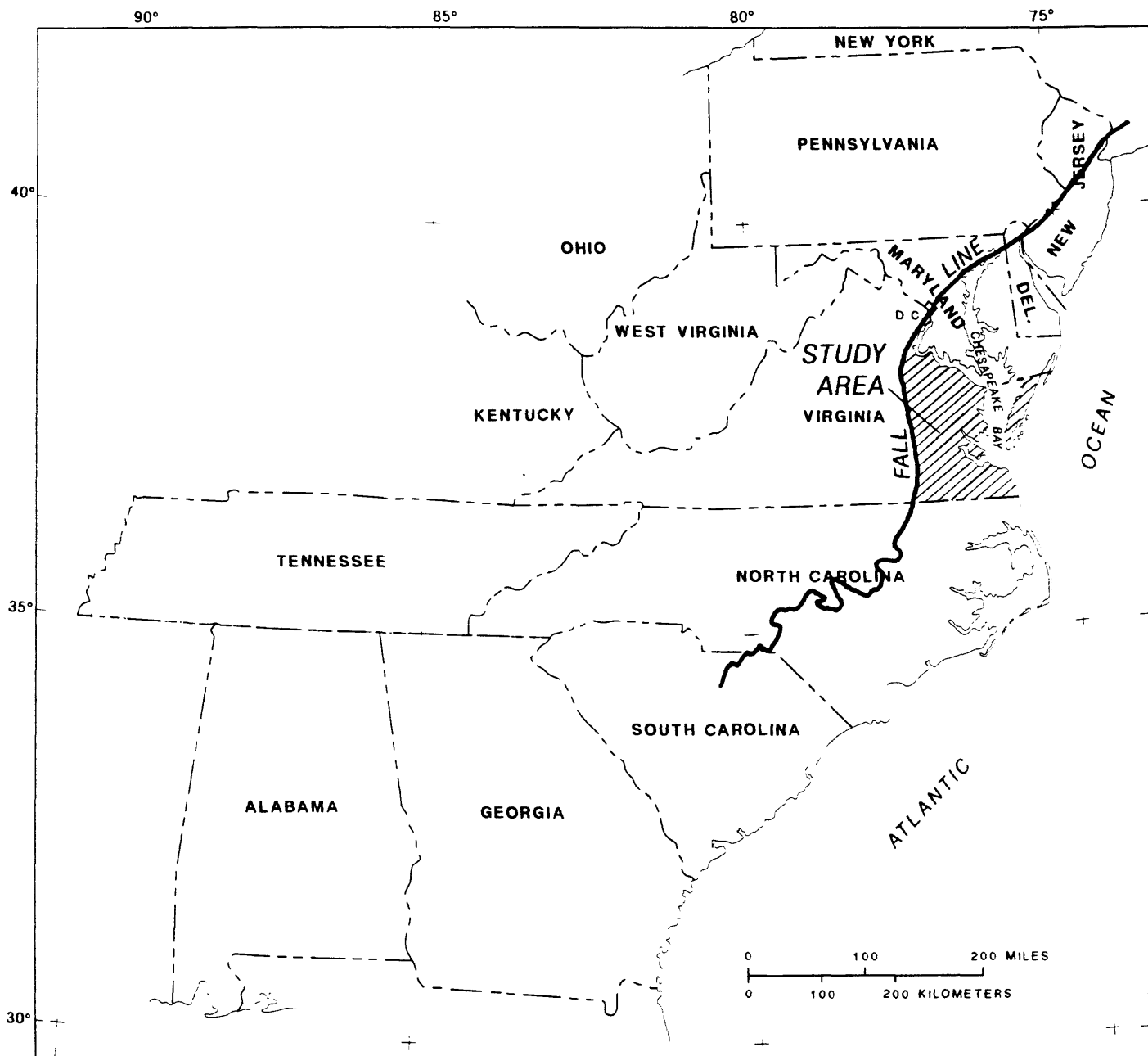


Figure 1.--Location of study area within the northern Atlantic Coastal Plain physiographic province.
(Modified from Meng and Harsh, 1988)

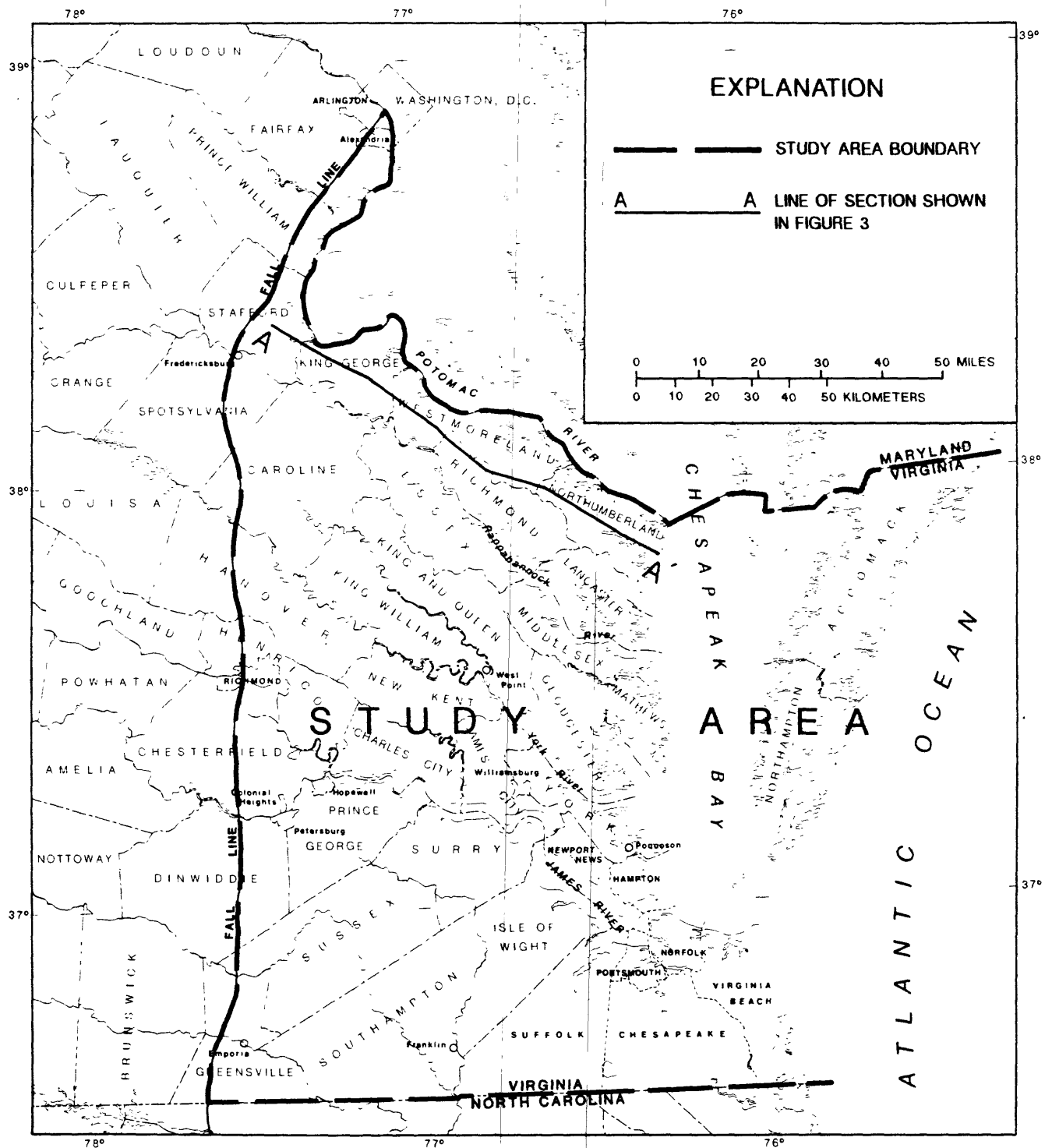


Figure 2.--Study area with location of geohydrologic section.
(Modified from Meng and Harsh, 1988)

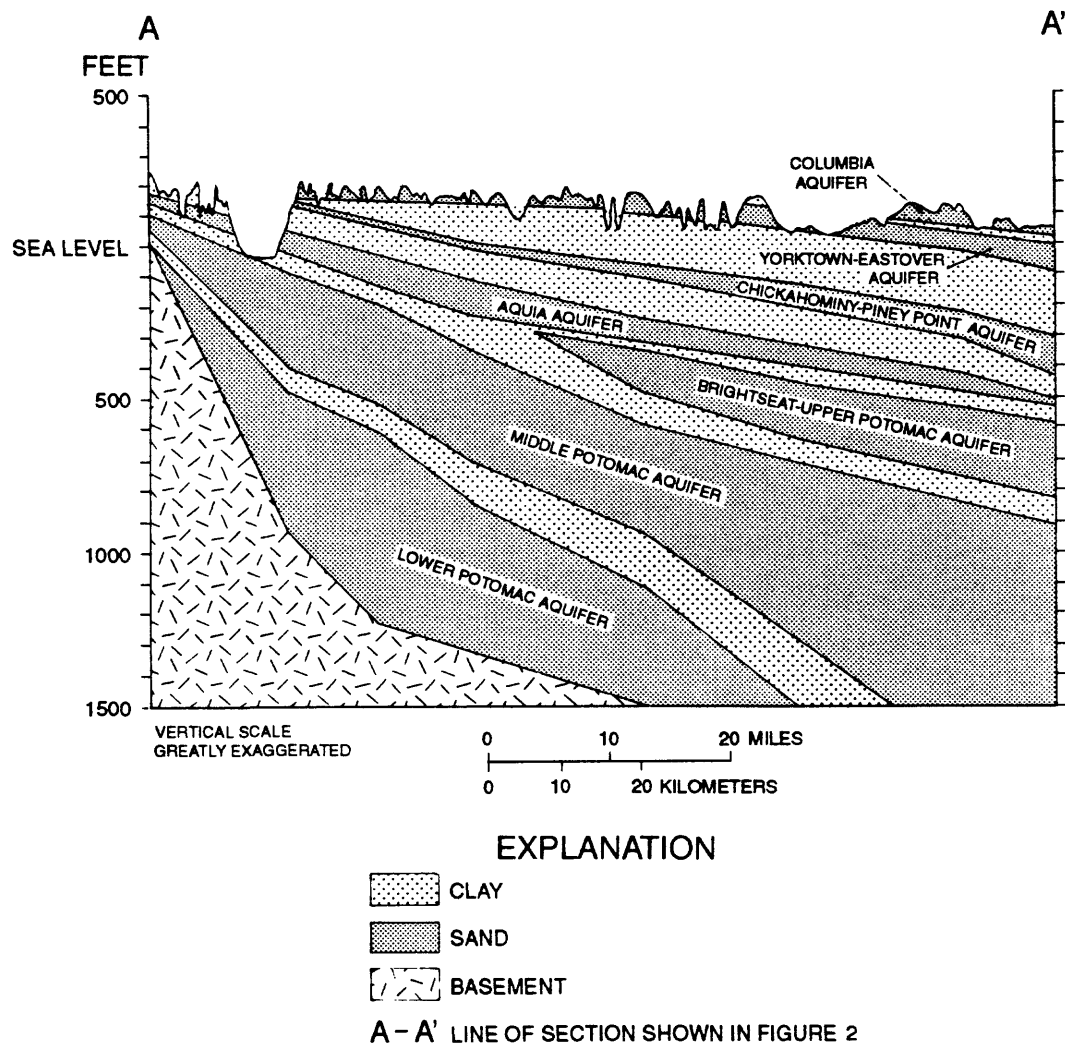


Figure 3.--Generalized geohydrologic section of eastward-thickening wedge of alternating sand and clay.
(Modified from Harsh and Lacznia, 1990)

(fig. 3). The aquifers consist primarily of permeable sand and shell deposits interbedded with silt and clay; the poorly permeable confining units consist primarily of silt and clay.

Infiltration from precipitation recharges the water-table aquifer throughout the Coastal Plain. In most of the Coastal Plain, the Columbia aquifer is the water-table aquifer; along the Fall Line, however, the water-table aquifer also can include outcrop areas of aquifers that are confined farther downgradient. Under natural conditions, ground water either leaks downward through confining units to recharge the confined aquifers, or flows from higher altitudes of the water-table aquifer to lower altitudes, where the water discharges to the surface as seepage to streams, wetlands, and coastal water. Water leaks primarily to the confined aquifers under areas of high land-surface elevation between major river valleys and along a narrow band that is almost parallel to the Fall Line. Natural horizontal flow of water in the confined aquifer system is from the Fall Line toward coastal areas and toward major river valleys. Water flows upward from the confined aquifers to the water-table aquifer in areas of low land-surface elevation beneath and adjacent to major streams, wetlands, and coastal waters.

Horizontal and vertical ground-water-flow directions have changed as a result of pumping during the last 100 years (Harsh and Lacznia, 1990). Changes in horizontal-flow directions have resulted in localized landward flow of brackish water in the confined aquifers. Reversals of vertical ground-water flow, induce flow from the water-table aquifer into the confined-flow system and reduce ground-water discharge to streams and coastal areas. Vertical-flow reversals also induce movement of water through confining units, which could result in mixing of waters with differing chemical compositions. Vertical flow across confining units, however, is a slower process than horizontal flow within an aquifer; vertical hydraulic conductivities of confining units in the study area are five to six orders of magnitude smaller than horizontal hydraulic conductivities of the aquifers (Harsh and Lacznia, 1990). The changes in ground-water-flow patterns because of pump-

ing could, therefore, affect the spatial distribution of water quality characteristics; however, this is primarily a localized phenomenon.

METHODS

Ground-water-quality data used in this report were retrieved from the National Water Information System (NWIS). The NWIS is the national repository of the USGS for hydrologic data collected by the USGS and its cooperators.

Maps of the geohydrologic framework of the Coastal Plain of Virginia (Hamilton and Larson, 1988; Lacznia and Meng, 1988; and Meng and Harsh, 1988) were spatially described and the data were recorded in a geographic-information system (GIS). The GIS is used to record and manipulate spatial and temporal information on the ground-water resources of the Virginia Coastal Plain (Focazio, 1990). Wells were selected as control points when water-quality data from the wells met certain criteria. The aquifer(s) in which each well is screened was determined by comparing well locations and screen depths recorded in NWIS with the information in the GIS, for each well with sufficient water-quality data. Water-quality data were not used if well data in NWIS were inadequate to determine the aquifer boundaries, or if the wells were screened in more than one aquifer, or in a confining unit. Because water quality can vary vertically within an aquifer, screen placement within the aquifer can affect the observed water quality. No attempt was made to account for this vertical variability. A single well was selected to represent a control point in an area where several other wells were locally screened in the same aquifer. Selection was based on the completeness of the water-quality data, date of sample, and distance of well screen(s) from adjacent confining units.

An ion balance was calculated to identify any major analytical errors in the water-quality data for the selected wells. If the difference between the sum of cations and the sum of anions exceeded 10 percent of the sum of the ions, the analysis was not used. Chloride-concentration data were available from a number of partial

analyses for which an ion balance could not be calculated; however, these data were used in the chloride-distribution maps.

The most recent analysis reported at any site that met the stated criteria was considered to be representative of the water quality at that site. The assumption in this method is that changes in water quality as a function of time are insignificant relative to regional geographical variation. This assumption was tested by analyzing the record of chloride concentrations over time in water from 98 wells. The periods of record for these wells are wide ranging; periods for 11 wells extend at least 20 years before 1970, and periods for 7 wells extend at least 10 years after 1970. Analysis of water-quality data from these wells does not indicate a persistent upward trend in chloride concentrations, which would significantly affect the interpretation of regional water-quality patterns.

After control points were selected for inclusion in this analysis, chemical-constituent concentrations and physical-property values were plotted on maps of each aquifer. Approximate lines of equal concentration were then drawn by visual interpolation among control points. Where data densities were sparse, locations of lines of equal concentration were visually extrapolated on the basis of geohydrologic information, and water-quality patterns in overlying and underlying aquifers. Extrapolation was possible because of similarities in geohydrologic characteristics, such as sediment depositional environments, sediment mineral content, and ground-water-flow paths of adjacent aquifers. Such similarities would produce similar water-quality patterns. The reasonableness of this approach was verified in areas where data from two adjoining aquifers was sufficient to contour. Where patterns in geohydrologic or water-quality characteristics of adjoining aquifers were not similar, contours were not extrapolated in this manner. Lines of equal concentration were then smoothed to provide a simple representation of regional patterns. In addition, smoothing reduced the bias that is associated with highly localized effects, variations in concentrations with time, and variations in concentrations caused by vertical location of well screen(s) in the aquifer.

Information from water-quality-distribution maps drawn by Lacznia and Meng (1988) for the York-James peninsula were used to define the configuration of certain regional patterns. Also, the position and configuration of the 10,000 mg/L chloride-concentration line for the lower, middle, and upper Potomac aquifers was obtained from Harsh and Lacznia (1990), Hamilton and Larson (1988), and Lacznia and Meng (1988).

If data from an individual well did not fit the regional pattern, further verification of its suitability as a control point was required. Corroboration was sought by checking with the original data base, by comparing samples from the well with earlier samples where possible, by comparing with patterns in overlying or underlying aquifers, or by evaluating samples from the well with respect to physical/chemical processes thought to operate in the area. In the absence of such corroboration, the data were not considered representative of ambient water-quality conditions and were deleted from the analysis.

DESCRIPTION OF SELECTED AQUIFERS

The Yorktown-Eastover aquifer consists of late Miocene and Pliocene sandy deposits of the Yorktown, Eastover, and Bacons Castle Formations (Meng and Harsh, 1988). The aquifer dips eastward from outcrops in upland areas of the western and north-central Coastal Plain physiographic province, thickening from 0 to 300 ft, and could be incised by estuaries of large rivers in the lower Coastal Plain. The Yorktown-Eastover aquifer is unconfined throughout its western extent, but is overlain by the Yorktown confining unit in the central and eastern Coastal Plain, except where exposed along stream valleys. The aquifer overlies the Calvert confining unit in the western and south-central Coastal Plain, and the St. Marys confining unit in the central and eastern Coastal Plain (Meng and Harsh, 1988). Sediments were deposited beneath seas on a shallow, embayed shelf. The aquifer consists of thick beds of fine- to medium-shelly sand that is separated by thinner clay layers; these clay layers are thin and discontinuous to the west and thick and extensive toward the east.

The Chickahominy-Piney Point aquifer consists primarily of middle to late Eocene sandy deposits of the Piney Point and Chickahominy Formations, and the Woodstock member of the Nanjemoy Formation (Meng and Harsh, 1988). The aquifer dips eastward from outcrops in most of the major stream valleys of the Coastal Plain from the James River northward and subcrops elsewhere. It thickens to at least 165 ft in the north-central and southeastern Coastal Plain, then pinches out near the Eastern Shore. The aquifer is overlain by the Calvert confining unit and overlies the Nanjemoy-Marlboro confining unit (Meng and Harsh, 1988). The aquifer consists of thick beds of fine- to coarse-glaucinitic quartz sand interbedded with thin glauconitic/illitic clay and calcareously cemented shell beds (Meng and Harsh, 1988). Deposition occurred during marine transgression on a shallow, inner-marine to middle-marine shelf (Hansen, 1972).

The Brightseat-upper Potomac aquifer consists of the Potomac Formation of Late Cretaceous age and the Brightseat Formation of Paleocene ages (Meng and Harsh, 1988). The aquifer dips eastward from subsurface pinchouts east of the Fall Line and thickens to more than 400 ft in the east. It is overlain by the Brightseat-upper Potomac confining unit and overlies most of the middle Potomac confining unit. Aquifer sediments consist of alternating beds of sand, silt, and clay. The fine- to medium-quartz sand and dark, silty clay contain micaceous, carbonaceous material, glauconite, wood, and shell fragments. Upper Potomac sediments were deposited during the area's first major marine transgression, when estuaries and intertidal basins were broadened (Meng and Harsh, 1988). Deposition of the Brightseat formation sediments was dominated by intertidal marine processes and probably represents a nearshore or lagoonal basin (Meng and Harsh, 1988).

The middle Potomac aquifer consists of Early Cretaceous deposits of the Potomac Formation (Meng and Harsh, 1988). It dips eastward from outcrops and subcrops near the Fall Line and thickens from 0 to more than 900 ft in the east. This aquifer is overlain by the middle Potomac confining unit and overlies the lower Potomac confining unit (Meng and Harsh, 1988). Aquifer

sediments consist of interlensed medium sand, silt, and clay (Meng and Harsh, 1988). The quartz sand contains micaceous material (Clark and Miller, 1912), abundant heavy minerals, and some plagioclase; clay minerals include illite, montmorillonite, and kaolinite (Reinhardt and others, 1980). Fluvial deposition processes formed a continental delta (Reinhardt and others, 1980). The aquifer that provides the largest amounts of water for withdrawals in the Virginia Coastal Plain is the middle Potomac aquifer (Harsh and Lacznik, 1990). Therefore, data are better distributed than in other aquifers and a more detailed discussion of water quality in the middle Potomac aquifer is possible than for the other aquifers.

The lower Potomac aquifer consists of Early Cretaceous deposits of the Potomac Formation (Meng and Harsh, 1988). The aquifer dips eastward from outcrops along the Fall Line and reaches a thickness greater than 3,000 ft in the east. The sediments include thick, interbedded sequences of coarse sand, clayey sand, and clay (Meng and Harsh, 1988). The quartz sand contains micaceous and lignitic material (Clark and Miller, 1912), abundant weathered potassium feldspar, and some plagioclase feldspar; the clay minerals include illite, montmorillonite, kaolinite and glauconite (Reinhardt and others, 1980). Deposition is thought to have occurred in a broad alluvial plain that was occasionally inundated by the sea, and by a developing continental delta (Reinhardt and others, 1980). The lower Potomac aquifer is overlain by the lower Potomac confining unit. The underlying bedrock consists of igneous and metamorphic rock of Precambrian to Lower Paleozoic age (Milici and others, 1963).

QUALITY OF GROUND WATER

This section (1) defines the data for the chemical-constituent concentrations and physical-property values that were used to create the maps, (2) describes the most likely source(s) within the Virginia Coastal Plain, and (3) provides pertinent regulatory or recommended drinking-water limits. Reported SMCL's² are set for aesthetics (such as taste or odor) or for limits on properties that affect

²U.S. Environmental Protection Agency (1990a) Maximum Contaminant Levels (not enforceable).

use of the water because of properties (such as chemical aggressiveness, or potential for the water to deposit solid chemicals). Reported MCL's³ are set for health concerns.

Physical Properties and Chemical Constituents

Physical Properties

The physical properties described in this report include pH, dissolved solids, hardness, and alkalinity. These properties are described in the following sections.

pH

pH is a measure of hydrogen-ion activity, which contributes to the chemical aggressiveness of water. Low pH values represent high hydrogen-ion activities. Hydrogen-ion activity in ground water is controlled by interrelated chemical reactions that produce or consume hydrogen ions (Hem, 1989). The pH value, therefore, is a useful index of the status of these reactions in the water. The greatest control on pH in ground water of the Virginia Coastal Plain is the carbonate-equilibrium reactions. In the carbonate reactions, dissolved carbon dioxide hydrolyzes to form carbonic acid. Carbonic acid dissociates to form hydrogen ions, bicarbonate ions, and carbonate ions. Other chemical reactions that affect pH include the dissolution of silica-bearing minerals and oxidation-reduction reactions involving iron, nitrogen, and sulfur species.

The U.S. Environmental Protection Agency (USEPA) established the SMCL for pH as the range from 6.5 to 8.5. The State of Virginia maintains an antidegradation standard⁴ for the Coastal Plain of 6.5 to 9.0 (Commonwealth of Virginia 1988).

³U.S. Environmental Protection Agency (1990a) Maximum Contaminant Levels (enforceable)--Maximum permissible level of a contaminant in water that is delivered to any user of a public-water system.

⁴Virginia's antidegradation policy for ground water is intended to regulate activities affecting ground water in order to maintain ambient water quality. The policy is stated as follows: "If the concentration of any constituent in groundwater is less than the limit set forth by groundwater standards, the natural quality for the constituent shall be maintained; natural quality shall also be maintained for all constituents, including temperature, not set forth in groundwater standards. If the concentration of any constituent in groundwater exceeds the limit in the standard for that constituent, no addition of that constituent to the naturally occurring concentration shall be made" (Commonwealth of Virginia, 1988).

Dissolved solids

The concentration of dissolved solids is a measure of the concentration of all dissolved material in water, and is determined either by direct measurement or by summation of individual dissolved constituents. Dissolved-solids concentrations can be used to classify water as follows:

Description	Dissolved-solids concentration (milligrams per liter)
Fresh	Less than 1,000
Slightly saline	1,000 - 3,000
Moderately saline	3,000 - 10,000
Very saline	10,000 - 35,000
Brine	More than 35,000

(From Robinove and others, 1958.)

The USEPA SMCL for dissolved solids is 500 mg/L (U.S. Environmental Protection Agency, 1990c). The State of Virginia's antidegradation standard for dissolved solids in ground water in the Coastal Plain is 1,000 mg/L (Commonwealth of Virginia, 1988). The American Water Works Association's (1981) potable water-quality goal is no greater than 200 mg/L.

Hardness

Total hardness is a measure of the concentration of polyvalent ions; calcium and magnesium are the primary components of hardness in the ground water of the Virginia Coastal Plain. A primary source of these two constituents is dissolution of carbonate material. Water can be classified by its hardness for water-supply planning as follows:

Description	Hardness (milligrams per liter, as calcium carbonate)
Soft	0 - 60
Moderately hard	61 - 120
Hard	21 - 180
Very hard	More than 180

(From Durfor and Becker, 1964.)

Although there are no Federal or State drinking-water regulations for hardness, the American Water Works Association (1981) recommends a potable water-quality goal for total hardness of 80 mg/L as calcium carbonate for aesthetic purposes. The State of Virginia maintains an antidegradation standard for ground water in the Coastal Plain of 120 mg/L (Commonwealth of Virginia, 1988).

Alkalinity

Alkalinity is a measure of water's capacity to neutralize acid, and in ground water, is usually attributed to the presence of bicarbonate and carbonate ions. These ions are produced by the dissolution of minerals, such as calcite or silicates by water that contains dissolved carbon dioxide. Carbon dioxide enters ground water from the atmosphere by infiltration of precipitation, and from microbial decomposition of organic matter and reduction of sulfate.

There are no federal drinking-water regulations for alkalinity. The State of Virginia maintains an antidegradation standard for ground water in the Coastal Plain of 30 to 500 mg/L as calcium carbonate (Commonwealth of Virginia, 1988).

Chemical Constituents

The chemical constituents described in this report include sodium, sulfate, chloride, fluoride, and silica. These constituents are described in the following sections.

Sodium

Several sources of sodium are present in the study area, including dissolution of aquifer material, connate seawater, ion exchange, and salt-water intrusion. Low concentrations of sodium in ground water can reflect mixing with rainwater, which, in Virginia, typically contains sodium concentrations less than 10 mg/L (Gambell and Fisher, 1966). Sodium in minerals is released by the dissolution of plagioclase feldspars and other minerals in the sediments and underlying bedrock. Sediments of the Virginia Coastal Plain also can contain sodium from connate seawater that was incorporated in a mineral. Sodium can enter solution when calcium ions in ground water exchange

with sodium on exchange sites on clay minerals. Ion exchange may be reversed where ground water already contains a high concentration of sodium, such as where seawater enters a freshwater aquifer. Sodium also can be present in connate seawater in pore water of the sediments. High concentrations of sodium (averaging 10,500 mg/L) can reflect mixing of fresh ground water with connate or intruding seawater, which has an average sodium concentration of 10,500 mg/L (Goldberg and others, 1971).

Although there is no current Federal drinking-water regulation for sodium, the State of Virginia maintains an antidegradation standard for sodium in ground water in the Coastal Plain of 100 mg/L (Commonwealth of Virginia, 1988). The State also advises that persons on sodium-restricted diets avoid drinking water with sodium concentrations greater than 20 mg/L, if the restriction is severe, and 270 mg/L, if moderate (Commonwealth of Virginia, 1982).

Sulfate

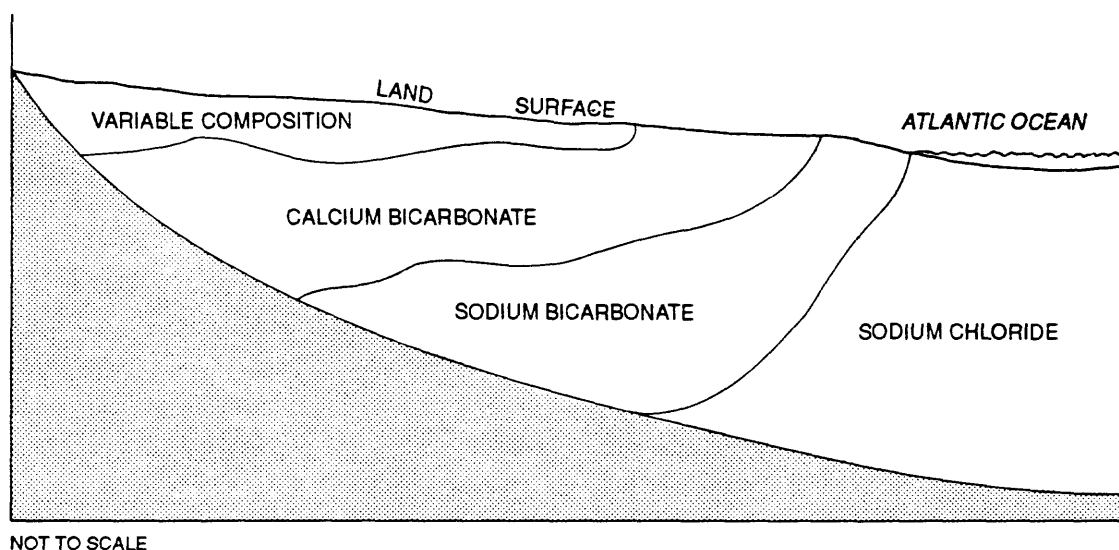
Sulfate in ground water generally originates from oxidation of sulfide minerals, such as pyrite, from dissolution of sulfate-bearing minerals, or from mixing of fresh ground water with seawater, which has an average sulfate concentration of 2,700 mg/L (Goldberg and others, 1971). Sulfate concentrations can be decreased by its reduction to sulfide under anaerobic conditions. The USEPA established an SMCL for sulfate of 250 mg/L (U.S. Environmental Protection Agency, 1990c). The State of Virginia maintains an antidegradation standard for sulfate in ground water in the Coastal Plain of 50 mg/L (Commonwealth of Virginia, 1988).

Chloride

Salty ground water underlies fresh water in much of the Virginia Coastal Plain (fig. 4) as a deepening wedge extending landward from coastal areas. As a result, chloride concentrations increase with depth and with proximity to the coast and major estuaries. The wedge is shallower and comes farther landward in the York-James peninsula than in other parts of the Virginia Coastal Plain. The salty water is a mixture of

WEST

EAST



EXPLANATION



BASEMENT ROCKS



LINE DELINEATING CHEMICAL FACIES

Figure 4.--Distribution of hydrochemical facies in the Coastal Plain physiographic province of Virginia.

sodium bicarbonate-type water and sodium calcium chloride brine (Meisler and others, 1988). The brine probably originated from leaching of evaporitic strata--deep beds of minerals, formed by evaporation of seawater, which lie beneath the Atlantic Continental Shelf and Slope. During major sea-level rises, this brine advanced landward and chloride diffused upward through the sediments overlying the evaporitic strata (Meisler and others, 1988). In shallow aquifers, high chloride concentrations are related to intrusion from the Atlantic Ocean, the Chesapeake Bay, and major estuaries of the Bay. The chloride concentration in seawater is approximately 19,000 mg/L (Hem, 1989).

The USEPA established a SMCL for chloride of 250 mg/L (U.S. Environmental Protection Agency, 1990c). The State of Virginia maintains

an antidegradation standard for chloride in ground water in the Coastal Plain of 50 mg/L (Commonwealth of Virginia, 1988).

Fluoride

In the Virginia Coastal Plain, fluoride sources can include fluorite and fluorapatite, which is found to be prevalent in fossil sharks' teeth in Coastal Plain aquifers of South Carolina (Zack, 1980). Although the USEPA established both an MCL of 4.0 mg/L and an SMCL of 2.0 mg/L for fluoride, the State of Virginia enforces a standard of 1.8 mg/L (Commonwealth of Virginia, 1982). Virginia also maintains an antidegradation standard of 1.4 mg/L for fluoride in ground water in the Coastal Plain, except in aquifers of Cretaceous age (the Potomac group) (Commonwealth of Virginia, 1988).

Silica

Silicon is an abundant element in most rocks and soils. Most silica, or silicon dioxide, enters ground water from mineral weathering processes and can be removed from solution by adsorption to sediments or by precipitation. There are no Federal or State drinking-water regulations or standards for silica.

Hydrochemical Facies

Ground water in the Atlantic Coastal Plain is characterized by four hydrochemical facies, or zones of water, with similar overall chemical character (fig. 4)--a zone of varied composition, a calcium bicarbonate facies, a sodium bicarbonate facies, and a sodium chloride facies (Cederstrom, 1946; Back, 1966; Lacznia and Meng, 1988; Meisler and others, 1988). As ground water flows, it reacts chemically with minerals that are present in the aquifer; thus evolving, along its flow path, into water with different chemical characteristics. The chemical character of the water is controlled by several factors, including the mineralogy of the aquifer material, the extent to which freshwater flushes out seawater marine transgressions, the extent to which fresh ground water mixes with deep offshore evaporitic brines, and the direction and velocity of ground-water flow. The transitions between hydrochemical facies represent locations where the chemical characterizations change because of the dominant processes that control the water chemistry.

Areal Distribution

Several hydrochemical facies are present throughout the Virginia Coastal Plain. These include calcium bicarbonate, sodium bicarbonate, or sodium chloride facies. Facies of variable composition are present where none of the other three facies are dominant.

Variable composition facies.--This is characterized by water that contains naturally low concentrations of dissolved solids and major ions in variable proportions. Such water is found along the Fall Line where ground water is recharged and

is in contact with the aquifer sediments for a short period of time. No cations or anions consistently dominate the chemistry of the ground water.

Calcium bicarbonate facies.--As ground water flows downgradient east of the Fall Line, concentrations of calcium, magnesium, bicarbonate, and silica increase because of contact and reaction with aquifer sediments. Calcium and bicarbonate dominate the water chemistry, thus forming a zone of calcium bicarbonate-type water.

Sodium bicarbonate facies.--Farther downgradient, concentrations of sodium increase in the ground water. In the predominately nonmarine Cretaceous deposits of the lower and middle Potomac aquifers, sodium is derived from saltwater that intruded into the aquifer by rises in sea level after deposition of the aquifer sediments. High sodium concentrations in the saltwater exchanged for other cations on aquifer sediments. As sea level receded, freshwater flushed saltwater from sediment-pore spaces. In some areas, saltwater was completely flushed from the sediments; in other areas, saltwater remains as dilute mixture with freshwater in the sediment-pore spaces. Even where saltwater was completely flushed from aquifer sediments, sodium can remain on sediment-exchange sites to exchange with calcium ions in the fresh ground water. In marine deposits of Tertiary or Quaternary age, ion exchange readily occurs in association with the presence of glauconite. This ion exchange softens water and forms a sodium bicarbonate zone, within which calcium concentrations decrease and sodium concentrations increase along the ground-water-flow path.

Areas where fluoride concentrations are high (greater than 1.0 mg/L) in the Coastal Plain are associated with sodium bicarbonate zones of the Potomac aquifers, and, to a lesser extent, with the shallow confined aquifers. In the ground water of these regions, calcium and magnesium concentrations are low and pH is high (7.5 to 8.0). Dissolved calcium can limit the solubility of fluoride (Hem, 1989); release of fluoride from minerals and soils occurs at pH higher than 8.0 because of ion exchange with hydroxide ions (Bower and Hatcher, 1967). Sodium bicarbonate-type water is, thus, a favorable environment for the release of fluoride into solution.

Sodium chloride facies.—Chloride replaces bicarbonate as the dominant anion in a sodium chloride facies that extends seaward from the east-central and southeastern Coastal Plain. The source of the chloride is attributed to submergence of sediments during previous marine transgressions and to deep offshore evaporitic brines.

Vertical Distribution

The vertical distribution of hydrochemical facies is controlled by the amount of time the water has been in contact with the aquifer. Contact time depends on several factors, including the distance that water has traveled through the system, hydraulic gradients, and vertical and horizontal hydraulic conductivities of the aquifers and confining units. In general, contact time increases with aquifer depth; consequently, deep water is more likely to have evolved through the sequence of hydrochemical facies than shallow water. Lacznia and Meng (1988) found that ground water in western James City County from the Yorktown-Eastover and Chickahominy-Piney Point aquifers was primarily of a calcium bicarbonate-type facies; from the underlying Aquia, Brightseat-upper Potomac, and middle Potomac aquifers, ground water was of a sodium bicarbonate-type facies; and from the lower Potomac (deepest aquifer), ground water was of a facies intermediate between sodium bicarbonate- and sodium chloride-type facies. This pattern of hydrochemical evolution with depth is found throughout the Virginia Coastal Plain.

Aquifers

The following sections describe the geohydrology and water quality of 5 of the 10 aquifers. Tables of summary statistics on water quality are included.

Yorktown-Eastover Aquifer

The spatial distributions of selected chemical-constituent concentrations and physical-property values in the Yorktown-Eastover aquifer are shown in plate 1. Water-quality data are not available for the western and northern Coastal Plain; only inferences about water quality in this region

are possible, based on data from samples collected elsewhere in the aquifer. Water of the Yorktown-Eastover aquifer is primarily a moderately hard, calcium bicarbonate-type, with a zone of soft sodium bicarbonate-type water located in the east-central part of the aquifer. Patterns in the distribution of chemical-constituent concentrations and physical-property values (pl. 1) could be affected by local-flow patterns caused by incision of the aquifer by streams in the southern Coastal Plain or by differing sediment mineralogy. Lines of equal concentration were not drawn for this aquifer because of the paucity of data and local effects.

At least one pH value was less than the USEPA SMCL. At least one chloride concentration and at least one dissolved-solids concentration was greater than the SMCL. A summary of chemical-constituent concentrations and properties in the Yorktown-Eastover aquifer is given in table 1.

Chickahominy-Piney Point Aquifer

The spatial distribution of selected chemical-constituent concentrations and physical-property values of the Chickahominy-Piney Point aquifer is shown in plate 2. Water-quality data are not available for the western part of the aquifer. Most of the data are from samples collected in the York-James peninsula.

Ground water in the Chickahominy-Piney Point aquifer is primarily of the sodium bicarbonate type but evolves to a sodium chloride type in the extreme eastern part of the aquifer. Water from the aquifer in the central part of the Coastal Plain physiographic province is slightly basic, fresh, and soft, and concentrations of sodium, dissolved solids, and fluoride decrease to the west. Toward the east, water becomes slightly acidic, moderately hard to very hard, and slightly saline to moderately saline. Concentrations of sodium, chloride, alkalinity, and sulfate increase toward the east. Dissolved-solids concentrations exceed 500 mg/L in most of the eastern part of the aquifer. Sodium concentrations exceed 20 mg/L throughout most of the aquifer. Concentrations of chloride in the eastern part of the aquifer are higher in places than in the underlying Brightseat-upper Potomac aquifer; however, this contradicts the previously reported concept that chloride con-

**Table 1.--Concentrations of chemical constituents and values of physical properties
in the Yorktown-Eastover aquifer**

[all analyses are for the dissolved constituent unless otherwise noted; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; $\mu\text{g}/\text{L}$, micrograms per liter; $^{\circ}\text{C}$, degrees Celsius; <, less than]

Chemical-constituent concentrations and physical-property values	Number of samples	Concentration or value		
		Minimum	Maximum	Median
Specific conductance, $\mu\text{S}/\text{cm}$	23	250	4,380	500
pH	22	5.6	8.1	7.3
Hardness, total, mg/L as CaCO_3	25	62	812	170
Calcium, mg/L	26	8.9	260	58
Magnesium, mg/L	26	.8	39	6.2
Sodium, mg/L	25	4.7	561	28
Potassium, mg/L	25	.2	21	6.2
Alkalinity, total, mg/L as CaCO_3	26	76	630	230
Sulfate, mg/L	26	2.0	130	10
Chloride, mg/L	28	3.0	1,200	18
Fluoride, mg/L	24	<.1	1.0	<.1
Silica, mg/L	19	7.	40	20
Solids, residue at 180 $^{\circ}\text{C}$, mg/L	24	108	1,120	279
Solids, sum of constituents, mg/L	19	154	2,233	306
Nitrogen, nitrite + nitrate, mg/L	16	<.10	.26	<.10
Iron, $\mu\text{g}/\text{L}$	20	4	5,500	140

**Table 2.--Concentrations of chemical constituents and values of physical properties
in the Chickahominy-Piney Point aquifer**

[all analyses are for the dissolved constituent unless otherwise noted; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; $\mu\text{g}/\text{L}$, micrograms per liter; $^{\circ}\text{C}$, degrees Celsius; <, less than]

Chemical-constituent concentrations and physical-property values	Number of samples	Concentration or value		
		Minimum	Maximum	Median
Specific conductance, $\mu\text{S}/\text{cm}$	24	250	8,000	348
pH	23	5.6	9.4	8.1
Hardness, total, mg/L as CaCO_3	27	14	700	53
Calcium, mg/L	27	1.1	100	13
Magnesium, mg/L	27	.8	110	3.6
Sodium, mg/L	27	3.3	2,900	61
Potassium, mg/L	24	.9	79	8
Alkalinity, total, mg/L as CaCO_3	27	76	770	160
Sulfate, mg/L	27	4.8	350	7.4
Chloride, mg/L	34	1.3	4,800	6.0
Fluoride, mg/L	25	<.1	2.5	.6
Silica, mg/L	26	20	59	34
Solids, residue at 180 $^{\circ}\text{C}$, mg/L	27	116	8,590	224
Solids, sum of constituents, mg/L	24	154	5,210	229
Nitrogen, nitrite + nitrate, mg/L	18	<.10	.35	<.10
Iron, $\mu\text{g}/\text{L}$	20	<10	3,200	50

centrations increase with depth (described in Hydrochemical Facies section). The reason for this is not certain, but is most likely because flushing of connate seawater from the Chickahominy-Piney Point aquifer is less complete than it is from the underlying Brightseat-upper Potomac aquifer because of lower horizontal hydraulic conductivities and younger age of the sediments in the Chickahominy-Piney Point aquifer compared to those in the Brightseat-upper Potomac aquifer. Fluoride concentrations exceed 2 mg/L in the south-central part of the aquifer. At least one pH value was lower than the USEPA SMCL. Concentrations of sulfate, chloride, and dissolved solids exceed the SMCL in the eastern part of the aquifer (pl. 2). Ranges in chemical-constituent concentrations and physical-property values in the Chickahominy-Piney Point aquifer are given in table 2.

Brightseat-Upper Potomac Aquifer

The spatial distribution of selected chemical-constituent concentrations and physical-property values of the Brightseat-upper Potomac aquifer is shown in plate 3. Water samples from wells in the Brightseat-upper Potomac aquifer were mostly collected from the eastern Coastal Plain; thus, less is known about the water quality in the western part of the aquifer than is known about the water quality in the eastern part. Interpretations for areas where data were not collected were based on flow patterns in the Brightseat-upper Potomac aquifer and on water-quality distributions in the underlying middle Potomac aquifer. It is possible that this lack of chemical-constituent-concentration data has caused the central east-west band, prominent on water-quality maps of the middle Potomac aquifer, to be less prominent in the Brightseat-upper Potomac aquifer.

Mineralization of the ground water increases as it flows from west to east in the Brightseat-upper Potomac aquifer. Transitions in chemical facies are evident from calcium carbonate in the west to sodium bicarbonate in the central part, and then to sodium chloride in the east. The water is slightly basic (pH greater than 7.0) throughout this aquifer. Dissolved-solids concentrations exceed the 500 mg/L USEPA SMCL in the eastern part of the aquifer. Sodium concentrations

exceed 20 mg/L, except near the western most limit of the aquifer. Fluoride concentrations exceed the 4 mg/L USEPA MCL in the south-central part of the aquifer and exceed the 2 mg/L USEPA SMCL throughout much of the rest of the aquifer. Concentrations of chloride exceed the 250 mg/L USEPA SMCL in the eastern part of the aquifer. Hardness decreases from west to east and becomes moderately hard to very hard in the southeast. The pH is greater than the USEPA SMCL in several areas. Concentrations exceed the USEPA SMCL for sulfate, chloride, fluoride, and dissolved solids at least once. A summary of chemical-constituent concentrations and physical-property values in the Brightseat-upper Potomac aquifer is given in table 3.

Middle Potomac Aquifer

The spatial distributions of selected chemical-constituent concentrations and physical-property values of the middle Potomac aquifer are shown in plate 4. Available chemical data were sparse in the northern Coastal Plain and were unavailable for the Eastern Shore for the middle Potomac aquifer. Much of these data (especially sodium and chloride) are similar to chemical-constituent-concentration data that geographically correspond to the overlying Brightseat-upper Potomac aquifer, indicating similar controls on water-quality distribution. The dense distribution of data in the northeastern Coastal Plain for the Brightseat-upper Potomac aquifer was, therefore, used to draw inferences about water-quality patterns in the northeastern middle Potomac aquifer. Similarities in chemical-constituent concentrations and physical-property values at locations where data had been collected in the Brightseat-upper Potomac and middle Potomac aquifers were identified and used to aid interpretation in areas where data points for the middle Potomac aquifer are sparse.

The distributions of chemical-constituent concentrations in the middle Potomac aquifer reflect the progression of ground water along the flow path, interaction with sediment minerals, and mixing with saltwater. The high concentrations of sodium, chloride, sulfate, and dissolved solids in the eastern zone have been attributed to ancient seawater intrusion, and subsequent incomplete

Table 3.--Concentrations of chemical constituents and values of physical properties in the Brightseat-upper Potomac aquifer

[all analyses are for the dissolved constituent unless otherwise noted; $\mu\text{S/cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; $\mu\text{g/L}$, micrograms per liter; $^{\circ}\text{C}$, degrees Celsius; <, less than]

Chemical-constituent concentrations and physical-property values	Number of samples	Concentration or value		
		Minimum	Maximum	Median
Specific conductance, $\mu\text{S/cm}$	60	171	10,200	862
pH	52	6.7	8.7	8.2
Hardness, total, mg/L as CaCO_3	62	2	450	12
Calcium, mg/L	62	<.1	1,100	2.8
Magnesium, mg/L	62	<.1	59	1.2
Sodium, mg/L	62	4.8	3,000	210
Potassium, mg/L	62	2	60	10
Alkalinity, total, mg/L as CaCO_3	62	89	850	360
Sulfate, mg/L	62	.6	407	16
Chloride, mg/L	73	.8	4,400	20
Fluoride, mg/L	59	<.1	6.3	2.4
Silica, mg/L	59	1.1	54	16
Solids, residue at 180°C , mg/L	58	106	5,230	499
Solids, sum of constituents, mg/L	60	98	7,960	541
Nitrogen, nitrite + nitrate, mg/L	29	<.10	.60	<.10
Iron, $\mu\text{g/L}$	32	<10	8,200	30

flushing of this seawater, and to diffusion from deep offshore evaporitic brines (Meisler and others, 1988).

A prominent feature in the distribution of the sodium, chloride, dissolved solids, and alkalinity is an east-west band of high concentrations that extends westward from water of a similar type in the east. This east-west band typically appears as a protrusion from the York-James peninsula toward the confluence of the James and Appomattox Rivers. Silica concentrations in the western and central parts of this east-west band (20 to 40 mg/L) are similar to water in the western zone, where the water is a hard calcium carbonate type. Hardness concentrations are lower in the east-west band than in areas to the north and south, where the water is moderately hard to very hard.

The data are not adequate to determine whether the high concentrations of sodium, chloride, dissolved solids, and alkalinity in the east-west band result from effects of the river valley, from an interfluvial ridge, from some other structural feature either north or south of the river, or from localized features of the ground-water chem-

istry. Cederstrom (1946) first described a wedge-shaped region of high chloride concentrations with an apex near Toano in western James City County and attributed its origin to incomplete flushing of ancient seawater because of a structural trough along the James River. Cederstrom (1946) hypothesized that the hydrochemical-facies change continued westward, but data were not available to demonstrate this at that time. Data available for this study indicate an association between water of high chloride concentrations and the James River valley, but additional data and analysis would be required to attribute this association to a specific process or feature, such as a structural trough. Back (1966) attributed the westward incursion of saline water in the Cretaceous aquifers to the presence of deeply transected stream valleys of central Virginia. These valleys are areas of local ground-water discharge, which lowers freshwater heads and subsequently controls the location of the saltwater-freshwater transition zone. Rogers and Spencer (1971) believed that a more important factor could be the fault zone that was first proposed by Cederstrom (1945b).

Concentrations of dissolved solids exceed the 500 mg/L USEPA SMCL in approximately the eastern third of the aquifer. Sodium concentrations exceed 20 mg/L throughout most of the aquifer. Fluoride concentrations exceed the 4.0 mg/L USEPA MCL in a large part of the southern Coastal Plain and exceed the 2.0 mg/L USEPA SMCL throughout much of the central and eastern parts of the aquifer. Chloride concentrations exceed the 250 mg/L USEPA SMCL in the eastern part of the aquifer. Hardness values exhibit no distinct pattern. Ranges in chemical-constituent concentrations and physical-property values in the middle Potomac aquifer are given in table 4.

Lower Potomac Aquifer

The spatial distribution of selected chemical-constituent concentrations and physical-property values of the lower Potomac aquifer is shown in plate 5. The large depths and water quality of the lower Potomac aquifer have limited its use, and consequently, fewer water-quality data are available for water-quality mapping. The aquifer is still used for large water withdrawals, however, and, therefore, is included in this analysis. Available data for the lower Potomac aquifer indicate that water-quality patterns are generally similar to regional patterns for the middle Potomac, with key differences most likely resulting from the greater age, increased distances along groundwater-flow paths, less completely flushed connate seawater, and proximity to underlying bedrock of the lower Potomac aquifer and saltwater compared to the middle Potomac aquifer. Calcium carbonate-type water is not common in the lower Potomac aquifer. Chemical-facies transitions from sodium bicarbonate- to sodium chloride-type waters are found farther west in the lower Potomac aquifer than they are in the overlying middle Potomac aquifer. Comparisons of water quality in the lower Potomac aquifer with that in the overlying middle Potomac aquifer, combined with information about the differences noted before among the aquifers, were used to help estimate water quality of the lower Potomac aquifer.

Dissolved-solids concentrations exceed the 500 mg/L USEPA SMCL in about the eastern third of the aquifer. Sodium concentrations exceed 20 mg/L throughout most of the aquifer.

Fluoride concentrations exceed the 2.0 mg/L USEPA SMCL in water from one well in the central Coastal Plain. Chloride concentrations exceed the 250 mg/L USEPA SMCL in about the eastern half of the aquifer. The water is soft throughout the western half of the aquifer, increasing to very hard in the east. A summary of values for chemical-constituent concentrations and physical-property values in the lower Potomac aquifer are given in table 5.

SUMMARY

Sufficient water-quality data for 5 of the 10 aquifers in the Coastal Plain physiographic province were available to describe spatial distributions. The five aquifers described are the Yorktown-Eastover, Chickahominy-Piney Point, Brightseat-upper Potomac, middle Potomac, and the lower Potomac. Distributions of chemical-constituent concentrations and physical-property values are spatially variable in these aquifers. Concentrations of chloride range from 1.3 to 17,000 mg/L, and sodium concentrations range from 3.3 to more than 8,100 mg/L. Fluoride concentrations range from nondetectable to 6.3 mg/L. Dissolved solids, pH, hardness, alkalinity, sulfate, and silica are also spatially variable.

The spatial differences among chemical-constituent concentrations and physical-property values for the five aquifers are distributed in zones of similar chemistry that are oriented north to south. These zones reflect the evolution of hydrochemical facies along the west-to-east paths of groundwater flow. The differences in hydrochemical facies result from the chemical reaction of ground water with minerals in aquifer materials, from the extent of previous intrusion and subsequent incomplete flushing of seawater, from the mixing of fresh ground water with deep offshore evaporitic brines, and from patterns of regional groundwater flow. Hydrochemical facies evolve from a water with no dominant ions in the western part of the study area, to a calcium bicarbonate water, to a sodium bicarbonate-type water, and finally to a sodium chloride-type water in the east.

Several chemical-constituent concentrations and physical-property values exceed Federal and State regulations and standards in parts of each

**Table 4.--Concentrations of chemical constituents and values of physical properties
in the middle Potomac aquifer**

[all analyses are for the dissolved constituent unless otherwise noted; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; $\mu\text{g}/\text{L}$, micrograms per liter; $^{\circ}\text{C}$, degrees Celsius; <, less than]

Chemical-constituent concentrations and physical-property values	Number of samples	Concentration or value		
		Minimum	Maximum	Median
Specific conductance, $\mu\text{S}/\text{cm}$	69	104	9,000	400
pH	56	6.4	8.9	7.8
Hardness, total, mg/L as CaCO_3	71	<1	570	10
Calcium, mg/L	71	.2	120	2.5
Magnesium, mg/L	71	<.1	65	.9
Sodium, mg/L	71	4.4	3,000	94
Potassium, mg/L	70	2	43	7
Alkalinity, total, mg/L as CaCO_3	71	24	676	190
Sulfate, mg/L	71	2.3	280	13
Chloride, mg/L	83	.8	5,000	3.4
Fluoride, mg/L	67	<.1	6.3	1.1
Silica, mg/L	68	13	53	26
Solids, residue at 180 $^{\circ}\text{C}$, mg/L	69	96	8,900	258
Solids, sum of constituents, mg/L	69	95	8,682	261
Nitrogen, nitrite + nitrate, mg/L	28	<.10	.37	<.10
Iron, $\mu\text{g}/\text{L}$	33	<10	3,800	160

**Table 5.--Concentrations of chemical constituents and values of physical properties
in the lower Potomac aquifer**

[all analyses are for the dissolved constituent unless otherwise noted; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; CaCO_3 , calcium carbonate; $\mu\text{g}/\text{L}$, micrograms per liter; $^{\circ}\text{C}$, degrees Celsius; <, less than]

Chemical-constituent concentrations and physical-property values	Number of samples	Concentration or value		
		Minimum	Maximum	Median
Specific conductance, $\mu\text{S}/\text{cm}$	13	165	8,000	419
pH	12	6.8	8.4	7.7
Hardness, total, mg/L as CaCO_3	13	2	3,345	31
Calcium, mg/L	13	.4	960	9.0
Magnesium, mg/L	13	.2	230	2
Sodium, mg/L	13	13	8,100	73
Potassium, mg/L	13	2	94	10
Alkalinity, total, mg/L as CaCO_3	13	42	557	160
Sulfate, mg/L	13	.6	580	14
Chloride, mg/L	13	2.1	17,000	12
Fluoride, mg/L	13	<.1	3.8	.3
Silica, mg/L	13	12	40	19
Solids, residue at 180 $^{\circ}\text{C}$, mg/L	13	122	28,600	246
Solids, sum of constituents, mg/L	12	123	27,100	284
Nitrogen, nitrite + nitrate, mg/L	7	<.10	<.10	<.10
Iron, $\mu\text{g}/\text{L}$	8	40	16,000	370

aquifer. Chloride and dissolved solids generally exceed State standards in eastern parts of each aquifer. Fluoride concentrations exceed the U.S. Environmental Protection Agency (USEPA) MCL in parts of the Chickahominy-Piney Point and Potomac aquifers. Sulfate concentration exceeds the USEPA SMCL in extreme eastern parts of several aquifers. The pH also exceeds the USEPA SMCL locally in each aquifer. Although ground-water quality in the aquifers analyzed for this study exceeds different Federal and State regulations and standards in some areas throughout the Virginia Coastal Plain, ground water at most locations in these aquifers is of a quality suitable for human consumption and most other uses.

SELECTED REFERENCES

- American Water Works Association**, 1981, 1981-82 officers and committee directory, including policy statements and official documents: Denver, Colo., 114 p.
- Back, William**, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498-A, 42 p.
- Bower, C.A., and Hatcher, J.T.**, 1967, Adsorption of fluoride by soils and minerals: *Soil Science*, v. 103, no. 3, p. 151-154.
- Cederstrom, D.J.**, 1943, Chloride in ground water in the Coastal Plain of Virginia: *Virginia Geological Survey Bulletin* 58, 384 p.
- _____, 1945a, Geology and ground-water resources of the Coastal Plain in southeastern Virginia: *Virginia Geological Survey Bulletin* 63, 384 p.
- _____, 1945b, Structural geology of southeastern Virginia: *American Association of Petroleum Geologists Bulletin*, v. 29, no. 1, p. 71-95.
- _____, 1946, Chemical character of ground water in the Coastal Plain of Virginia: *Virginia Geological Survey Bulletin* 68, 62 p.
- Clark, W.B., and Miller, R.L.**, 1912, The physiography and geology of the Coastal Plain province of Virginia: *Virginia Geological Survey Bulletin* 4, p. 13-322.
- Commonwealth of Virginia**, 1982, Drinking water standards--chemical and physical quality: Commonwealth of Virginia Administrative Code Section 4.06, February 1, 1982, 10 p.
- Commonwealth of Virginia**, 1988, Water quality standards--antidegradation policy: State Water Control Board Regulations VR680-21-04.2, July 1, 1988, 10 p.
- Durfor, C.N., and Becker, Edith**, 1964, Public water supplies of the 100 largest cities in the United States, 1962: U.S. Geological Survey Water-Supply Paper 1812, 364 p.
- Focazio, M.J.**, 1990, Application of a geographic-information system to the analysis of ground-water resources in the Coastal Plain of Virginia, in *International conference on application of geographic information systems, simulation models, and knowledge-based systems for landuse management*: Blacksburg, Virginia, 1990, Proceedings, p. 351-359.
- Gambell, A.W., and Fisher, D.W.**, 1966, Chemical composition of rainfall, eastern North Carolina and southeastern Virginia: U.S. Geological Survey Water-Supply Paper 1535-K, 41 p.
- Goldberg, E.D., Broecker, W.S., Gross, M.G., and Turekian, K.K.**, 1971, Marine chemistry, in *Radioactivity in the marine environment*: Washington, D.C., National Academy of Sciences, p. 137-146.
- 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.
- Hamilton, P.A., Shedlock, R.J., and Phillips, P.J.**, 1989, Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia--analysis of available ground-water-quality data through 1987: U.S. Geological Survey Water-Supply Paper 2355-B, 65 p.
- Hansen, H.J.**, 1972, A user's guide for the artesian aquifers of the Maryland Coastal Plain, Part 2--Aquifer characteristics: Maryland Geological Survey, 123 p.

- Harsh, J.F.**, 1980, Ground-water hydrology of James City County, Virginia: U.S. Geological Survey Open-File Report 80-961, 73 p.
- Harsh, J.F., and Lacznia, R.J.**, 1990, Conceptualization and analysis of ground-water flow system in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina: 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, 264 p.
- Lacznia, 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.
- Meisler, Harold**, 1981, Preliminary delineation of salty ground water in the northern Atlantic Coastal Plain: U.S. Geological Survey Open-File Report 81-71, 34 p.
- Meisler, Harold, Miller, J.A., Knobel, L.L., and Waite, R.L.**, 1988, Region 22, Atlantic and eastern Gulf Coastal Plain, in Back, William, Rosenshein, J.S., and Seaber, P.R., eds., *Hydrogeology*: Boulder, Colo., Geological Society of America, *The Geology of North America*, v. O-2. 35 p.
- Meng, A.A., III, and Harsh, J.F.**, 1988, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1404-C, 82 p.
- Milici, R.C., Spiker, C.T., Wilson, J.M., comps.**, 1963, Geologic map of Virginia: Charlottesville, Virginia Division of Mineral Resources, scale 1:500,000.
- Powell, J.D., and Hamilton, P.A.**, 1986, State summaries of ground-water quality (Virginia), in *National Water Summary 1986--hydrologic events and ground-water quality*: U.S. Geological Survey Water-Supply Paper 2325.
- Reinhardt, Juergen, Christopher, R.A., and Owens, J.P.**, 1980, Lower Cretaceous stratigraphy of the core, in *Geology of the Oak Grove Core*: Virginia Division of Mineral Resources Publication 20, part 3, p. 31-52.
- Robinove, C.J., Langford, R.H., and Brookhart, J.W.**, 1958, Saline-water resources of North Dakota: U.S. Geological Survey Water-Supply Paper 1428, 72 p.
- Rogers, W.S., and Spencer, R.S.**, 1971, Ground-water quality and structural control in southeastern Virginia: *Geological Society of America Bulletin* 82, p. 2313-2318.
- U.S. Environmental Protection Agency**, 1990a, Maximum contaminant levels (subpart B of part 141, National primary drinking water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1990, p. 559-563.
- _____, 1990b, Maximum contaminant level goals (subpart F of part 141, National primary drinking water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1990, p. 620-621.
- _____, 1990c, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1990, p. 674.
- Zack, A.L.**, 1980, Geochemistry of fluoride in the Black Creek aquifer system of Horry and Georgetown Counties, South Carolina--and its physiological implications: U.S. Geological Survey Water-Supply Paper 2067, 40 p.

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

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
foot (ft)	0.3048	meter
square mile (mi ²)	2.590	square kilometer
mile (mi)	1.609	kilometer

Water temperature is expressed in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

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

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

Abbreviated water-quality units used in report: Chemical concentration and specific electrical conductance in this report are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or in micrograms per liter (µg/L). Specific electrical conductance of water is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm).