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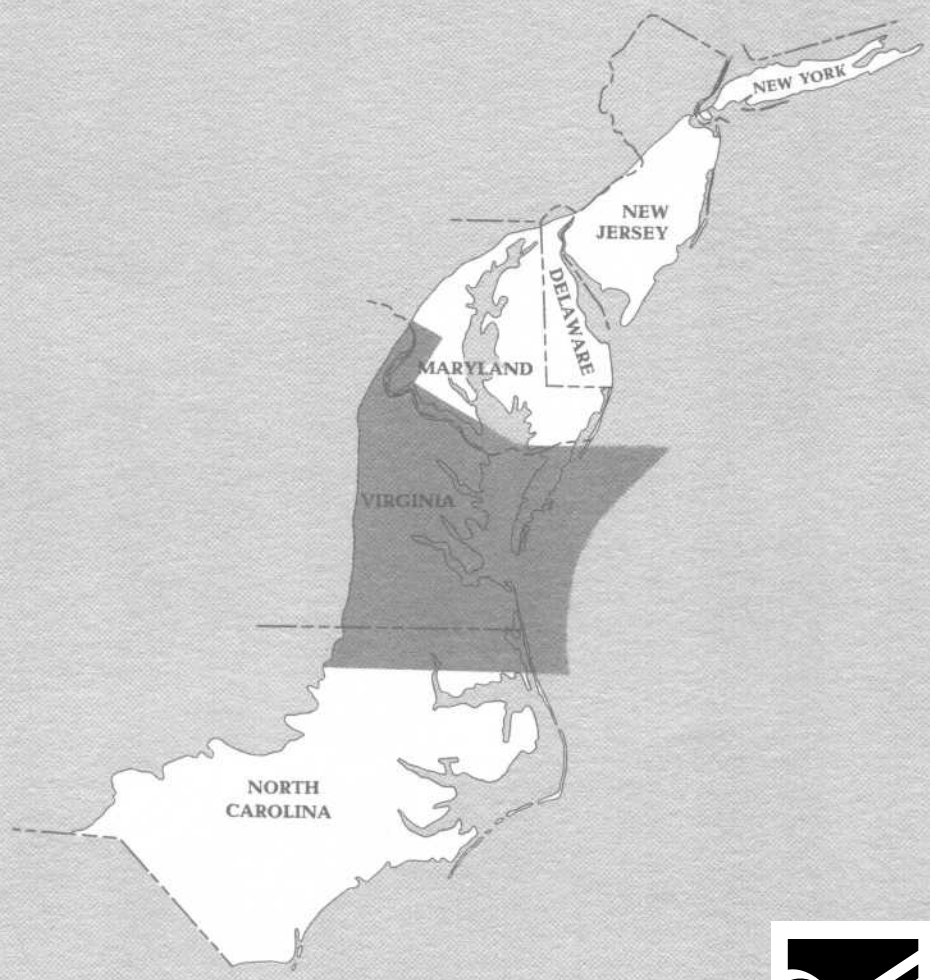
CONCEPTUALIZATION AND ANALYSIS OF GROUND-WATER FLOW SYSTEM IN THE COASTAL PLAIN OF VIRGINIA AND ADJACENT PARTS OF MARYLAND AND NORTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1404—F

YORKTOWN-EASTOVER AQUIFER AND YORKTOWN CONFINING UNIT

The Yorktown-Eastover aquifer, designated aquifer 9, includes sediments of the Pliocene Yorktown Formation and the upper part of the Miocene Eastover Formation, which were deposited in a shallow marine to deltaic or estuarine environment (Rasmussen and Slaughter, 1955, p. 43; Ward and Blackwelder, 1980). The aquifer is both confined and unconfined, depending on location, and is made up of eastward-thickening, interfingering, fine to coarse sand interbedded with clay, shell, and sandy clay. The aquifer is unconfined in a broad belt almost parallel to the Fall Line. Thickness ranges from about 6 ft near its western limit to about 100 ft in the southeastern part of the Virginia Coastal Plain. The aquifer has been incised by streams in areas along the middle and upper reaches of major river valleys and tributaries, particularly north of the James River. It is an important source of water in the southeastern and northeastern parts of the study area. Where the aquifer is unconfined, it is a major source of recharge to the confined flow system.

Transmissivity of the Yorktown-Eastover aquifer, compiled from Geraghty and Miller (1979b), Converse and others (1981), and Siudyla and others (1981), ranges from 200 to 3,000 ft^2/d in the southeastern part of the Virginia Coastal Plain. Storage coefficients from these sources range from 6.0×10^{-3} to 7.7×10^{-4}. Reported yields from residential, commercial, and light industrial wells in these areas range from 20 to 250 gallons per minute (gal/min) (Siudyla and others, 1981; Fennema and Newton, 1982).

The Yorktown confining unit, designated confining unit 9, overlies the Yorktown-Eastover aquifer, except near the Fall Line, where the aquifer is unconfined or is in direct contact with the Columbia aquifer. The confining unit is a blue-gray to green-gray clay interbedded with massive silty clay, fine sand, and calcareous shell fragments. Thickness of the confining unit ranges from about 10 ft near its western limit to about 80 ft along the Atlantic Coast. The confining unit is incised by streams along the major river valleys and tributaries, particularly north of the James River.

Vertical hydraulic conductivity of the Yorktown confining unit, determined from laboratory tests, ranges from 5.9×10^{-4} to 3.9×10^{-3} feet per day (ft/d) (table 4). Siudyla and others (1981) estimated that leakance (the ratio of vertical hydraulic conductivity to thickness of the confining unit) of the Yorktown confining unit from aquifer tests using the Hantush-Jacob method of analysis (Hantush and Jacob, 1955) ranges from 1.3×10^{-4} to 1.8×10^{-3} per day.

ST. MARYS-CHOPTANK AQUIFER AND ST. MARYS CONFINING UNIT

The St. Marys-Choptank aquifer includes sediments of the Miocene Choptank Formation and the lower part of the Miocene St. Marys Formation and is designated aquifer 8. These sediments are light-yellow to greenish-gray, very fine to fine quartzose sand interbedded with shell and silty clay. The sediments were deposited in a shoaling, midshelf setting, possibly during a climatic change (Hansen, 1981, p. 128). The aquifer is not a primary source of water because adequate supplies are more easily obtained from overlying aquifers.

The aquifer is confined and consists of sand units separated by noncontinuous clay layers. It attains a maximum thickness of about 160 ft in the northeastern part of the study area. Values of transmissivity and storage coefficient have not been determined in Virginia, but are estimated from aquifer tests for the same aquifer in southern Maryland (Cushing and others, 1973). Transmissivity ranges from 200 to 4,000 ft^2/d, and storage coefficient ranges from 1.0×10^{-4} to 6.0×10^{-3}.

The St. Marys confining unit, designated confining unit 8, overlies the St. Marys-Choptank aquifer. The confining unit includes sediments of the upper part of the St. Marys Formation and the lower part of the Eastover Formation. The unit forms an eastward-thickening wedge of light-gray, shelly to laminated clay interbedded with very fine sand; it attains a maximum thickness of about 300 ft in the northeastern part of the study area and 150 ft in the southeastern part. Vertical hydraulic conductivity determined from laboratory tests ranges from 2.8×10^{-6} to 2.0×10^{-5} ft/d (table 4).

CHICKAHOMINY-PINEY POINT AQUIFER AND CALVERT CONFINING UNIT

The Chickahominy-Piney Point aquifer includes sediments of the Miocene and Oligocene Old Church Formation and the Eocene Chickahominy and Piney Point Formations, and is designated aquifer 7. The aquifer is a fine to medium, well-sorted, glauconitic sand interbedded with dark-green micaceous clay and calcareous shell fragments. The sediments were deposited in a shallow neritic environment (Hansen, 1971, p. 139). The aquifer is an important source of water for residential, agricultural, and light industrial users in the Northern Neck, Middle, and York-James Peninsulas of Virginia. Figure 3 shows the location of these general geographic areas.

The confined aquifer contains two continuous sand bodies separated by clayey material; these sediments function as a single aquifer north of the James River. The aquifer consists of a single lenticular body interbedded

with clay and shell fragments south of the James River. The aquifer averages about 90 ft thick in the northern part of the study area and 85 ft thick in the southern part. Composition of the aquifer changes from predominantly sand west of Chesapeake Bay to silt and clay beneath the bay. The aquifer is unconfined where it crops out near the Fall Line.

Interpretation of reported specific capacities from the Middle Peninsula of Virginia (fig. 3) indicates that the transmissivity of the aquifer ranges from 150 to 2,000 ft^2/d (Siudyla and others, 1977). No transmissivity data on the aquifer are available for other parts of this study area. Data on storage coefficients in Virginia are lacking; however, Hansen (1972) reports values for the same aquifer in southern Maryland ranging from 3.0×10^{-4} to 4.0×10^{-4}. Reported well yields range from 20 to 250 gal/min (Siudyla and others, 1977; Newton and Siudyla, 1979).

The Calvert confining unit, designated confining unit 7, overlies the Chickahominy-Piney Point aquifer, except where the aquifer crops out near the Fall Line. The confining unit includes sediments of the Miocene Calvert Formation and forms an eastward-thickening wedge of dark-green clay interbedded with fossiliferous sandy clay, marl, and diatomite. The unit attains a maximum thickness of about 300 ft in the northern part of the study area. Laboratory analysis of a core from a test hole in Isle of Wight County, Va., indicates that vertical hydraulic conductivity is 9.2×10^{-6} (table 4).

AQUIA AQUIFER AND NANJEMOY-MARLBORO CONFINING UNIT

The Aquia aquifer consists primarily of sediments of the Paleocene Aquia Formation and is designated aquifer 6. The sediments are marine in origin and typically are well-sorted, fine to medium, dark-green, glauconitic sand interbedded with marl and shell fragments. These marine sediments were deposited in a shallow, nearshore environment, perhaps below wave base. The aquifer is an important source of water for residential and light industrial users north of the James River.

The sand thickness of the confined aquifer averages about 75 ft in the northern part of the study area and 95 ft in the southern part. The aquifer contains sand layers that are elongate and lenticular in shape and thin slightly to the west and considerably to the east. Composition of the aquifer changes from predominantly sand west of Chesapeake Bay to silt and clay beneath and east of the bay. The aquifer is unconfined where it crops out near the Fall Line.

Results from single-well aquifer tests and specific capacity tests indicate that transmissivity ranges from 125 to 1,000 ft^2/d in the Middle and Northern Neck Peninsulas of Virginia (Siudyla and others, 1977; Newton and Siudyla, 1979). As expected, transmissivities are high where the sand is thickest, as in the southern part of the study area. No data on storage coefficient for the Aquia aquifer in Virginia are available; however, Hansen (1972) reports storage coefficients of the Aquia aquifer in southern Maryland of 1.0×10^{-4} to 4.0×10^{-4}. Reported well yields range from 20 to 110 gal/min (Siudyla and others, 1977; Newton and Siudyla, 1979).

The Nanjemoy-Marlboro confining unit, designated confining unit 6, overlies the Aquia aquifer, except where the aquifer crops out in the northwestern part of the study area. The confining unit, in its lower part, is a red to gray, kaolinite-illite clay of the Paleocene and Eocene Marlboro Clay, and, in its upper part, a thick-bedded, argillaceous and calcareous green sand of the Eocene Nanjemoy Formation. The unit varies in thickness from about 15 ft to about 300 ft. The confining unit crops out in a narrow belt along the upper reaches of major rivers and tributaries from the James to Potomac Rivers. Results of laboratory tests to determine the vertical hydraulic conductivity are listed in table 4.

AQUIFER 5 AND CONFINING UNIT 5

Aquifer 5 includes sediments of the Upper Cretaceous Peedee Formation in North Carolina and the Severn Formation in Maryland. It is designated aquifer 5. The sediments are marine in origin and consist of fine to medium, gray to green sand, with varying amounts of glauconite and shell material interbedded with gray to black silt and clay. Thin beds of consolidated calcareous sandstone and impure limestone are present locally. The aquifer is confined and consists of interfingering sand and clay that function as a single aquifer. The aquifer ranges in thickness from a featheredge at its western limit to about 300 ft along the Atlantic Coast (M.D. Winner, U.S. Geological Survey, written commun., 1984). The estimated transmissivity of the aquifer ranges from about 300 to about 1,240 ft^2/d in the study area.

Confining unit 5 overlies aquifer 5. The sediments of the confining unit are composed of clay, silty clay, and sandy clay; they thicken to the east, where they attain a maximum thickness of about 60 ft along the Atlantic Coast (M.D. Winner, U.S. Geological Survey, written commun., 1984). A typical vertical hydraulic conductivity of the confining unit is estimated to be 8.64×10^{-6} ft/d (G.L. Giese, U.S. Geological Survey, written commun., 1984).

AQUIFER 4 AND CONFINING UNIT 4

Aquifer 4 includes sediments of the Black Creek and Middendorf Formations and is present only in North Carolina and the extreme southeastern part of the Virginia Coastal Plain. The sediments typically are gray to

tan in color and consist of fine to coarse sand with thin to laminated clay. Lignitized wood, shell material, and glauconite are common in the sample cuttings. Tan and red to white kaolinitic clay balls or fragments are scattered throughout the sand. The aquifer is confined and consists of fluvial-marine deposits that thicken seaward and function as a single water-bearing unit. These deposits are characterized by well-defined beds of sand and clay or lens-shaped bodies of sand. The aquifer attains a maximum thickness of 300 to 400 ft at the Atlantic Coast (M.D. Winner, U.S. Geological Survey, written commun., 1984). The estimated transmissivity of the aquifer ranges from about 210 to about 3,320 ft^2/d in the study area.

Confining unit 4 completely covers aquifer 4; the unit consists of a series of clay, silty clay, and sandy clay beds ranging in thickness from less than 10 ft near its updip limit to more than 150 ft along the Atlantic Coast (M.D. Winner, U.S. Geological Survey, written commun., 1984). A typical vertical hydraulic conductivity of this confining unit is estimated to be 3.2×10^{-5} ft/d (G.L. Giese, U.S. Geological Survey, written commun., 1984).

BRIGHTSEAT-UPPER POTOMAC AQUIFER AND CONFINING UNIT

The Brightseat-upper Potomac aquifer includes sediments of the upper part of the Cretaceous Potomac Formation and the Paleocene Brightseat Formation and is designated aquifer 3. Typically, the sediments of the aquifer are white to gray, medium to very fine, quartzose sand interbedded with dark-colored micaceous clay, varying amounts of shell material, lignite, and glauconite. The sediments are marine in origin and represent either a marginal outer-delta or nearshore intertidal environment. The aquifer is confined and consists of sand layers separated by thin clay beds. The layers are either interbedded sheet-form sand and silty clay or lens-shaped bodies of sand. The aquifer is a principal source of ground water for municipal, industrial, and agricultural use in the York-James, Middle, and Northern Neck Peninsulas of Virginia.

The sands form an eastward-thickening wedge that attains a maximum thickness of 425 ft in the northeastern part of the study area. The lens-shaped sand is more than 150 ft thick beneath Chesapeake Bay. Transmissivity decreases toward the Atlantic Coast, where the sand thins and silt and clay predominate. Transmissivities determined from aquifer test data are listed in table 3. Average transmissivities range from 1,500 to 13,000 ft^2/d in southeastern Virginia. Locations of aquifer test sites are shown in figure 3. Other estimated values of transmissivities contained in ground-water data reports by Siudyla and others (1977) and Newton and Siudyla (1979) range from less than 150 ft^2/d in northern Westmoreland County, Va., to 2,000 ft^2/d near West Point, Va. Reported yields from wells completed in the Brightseat-upper Potomac aquifer range from 25 to 350 gal/min (Cederstrom, 1957; Siudyla and others, 1977; Newton and Siudyla, 1979).

The Brightseat-upper Potomac confining unit, designated confining unit 3, overlies the Brightseat-upper Potomac aquifer. The sediments are dark-green to black, highly micaceous silty clay with oxidized red to yellow, thin clay. Hydraulic properties of this confining unit in Virginia are not available. Hansen (1977) reports a vertical hydraulic conductivity of 8.64×10^{-4} ft/d and a specific storage of 7.4×10^{-5} ft^{-1} (specific storage is defined as storage coefficient per unit thickness of confining unit sediment) for the same confining unit in southern Maryland. These values were determined from laboratory analyses of a core.

MIDDLE POTOMAC AQUIFER AND CONFINING UNIT

The middle Potomac aquifer includes sediments of the middle part of the Cretaceous Potomac Formation and is designated aquifer 2. These sediments are continental in origin and were deposited in fluvial-deltaic environments. The aquifer typically consists of interfingering lenses of medium sand, silt, and clay of differing thickness. A small part of the aquifer is unconfined where it crops out near the Fall Line. The aquifer is a principal source of ground water for large users throughout the Coastal Plain of Virginia.

The aquifer thickens to the east and attains a maximum thickness of more than 1,000 ft in the northeastern part of the Eastern Shore Peninsula of Virginia. Transmissivity of the aquifer decreases seaward because of increased amounts of silt and clay. A summary of transmissivities is given in table 3. Average transmissivities range from 2,000 ft^2/d in Westmoreland County, Va., to 19,000 ft^2/d in the southeastern part of Virginia. Other values of transmissivity based on aquifer and specific capacity test data, reported by drillers, are summarized in ground-water data reports by the Virginia State Water Control Board (1973, 1974), Siudyla and others (1977), Newton and Siudyla (1979), and Siudyla and others (1981). Storage coefficients for this aquifer from these references range from 2.0×10^{-4} to 1.5×10^{-3}. Well yields from this aquifer in southeastern Virginia are reported to exceed 750 gal/min (Brown and Cosner, 1974).

The middle Potomac confining unit, designated confining unit 2, overlies the middle Potomac aquifer, except where the aquifer crops out in a narrow belt along the Potomac River south of Washington, D.C. The confining unit consists predominantly of montmorillonitic red clay and is typically massive and thick bedded, but it is finely

laminated in some places. The confining unit thickens from the Fall Line and attains a maximum thickness of more than 200 ft in the northeastern part of the study area. The confining unit also thickens to the south along the Virginia-North Carolina border. The vertical hydraulic conductivity of the confining unit, determined from laboratory analysis of a core from a test hole at Sewells Point in Norfolk, Va., is 3.4×10^{-6} ft/d (table 4).

LOWER POTOMAC AQUIFER AND CONFINING UNIT

The lower Potomac aquifer is the lowermost confined aquifer in the Coastal Plain and lies unconformably on basement; it is designated aquifer 1. The sediments are the lower part of the Cretaceous Potomac Formation and typically consist of coarse, arkosic quartz sand with intervening clay. Individual sand bodies within the aquifer suggest a continental origin and deposition by low-gradient meandering streams in a broad alluvial plain. These sand bodies tend to be thick, interbedded sequences of angular to subangular coarse sand, clayey sand, and clay. The aquifer is a principal source of ground water for large users throughout the western and central parts of the Virginia Coastal Plain.

The aquifer thickens to the east and reaches a maximum thickness of more than 3,000 ft in the northeastern part of the study area. Even though the average thickness of the aquifer increases seaward, transmissivity decreases because of a facies change to finer grained marine sediments having lower permeability. The aquifer begins to thin to the south at the Virginia-North Carolina border. The aquifer contains saltwater along the coast in North Carolina and in an adjoining area of the Virginia mainland. Average transmissivity ranges from 12,000 to 19,000 ft^2/d. A summary of transmissivities is given in table 3. Other transmissivity values interpreted from aquifer and specific capacity test data from production wells, reported by drillers, can be found in ground-water data reports by the Virginia State Water Control Board (1973, 1974), Siudyla and others (1977), Newton and Siudyla (1979), and Siudyla and others (1981). Average storage coefficients range from 5.0×10^{-4} to 1.5×10^{-3} (table 3). Well yields from this aquifer are reported to be as much as 700 gal/min (Brown and Cosner, 1974).

The lower Potomac confining unit, designated confining unit 1, overlies the lower Potomac aquifer. The confining unit is composed of thick sequences of finely laminated, usually brown, gray, or dark-green carbonaceous clay interbedded with thin, sandy clay. The unit thickens from the Fall Line and attains a maximum thickness of more than 175 ft in the northeastern part of the study area. Vertical hydraulic conductivity, determined from laboratory analysis of a core from a test hole near Pughville in the City of Suffolk, is 1.9×10^{-6} ft/d (table 4).

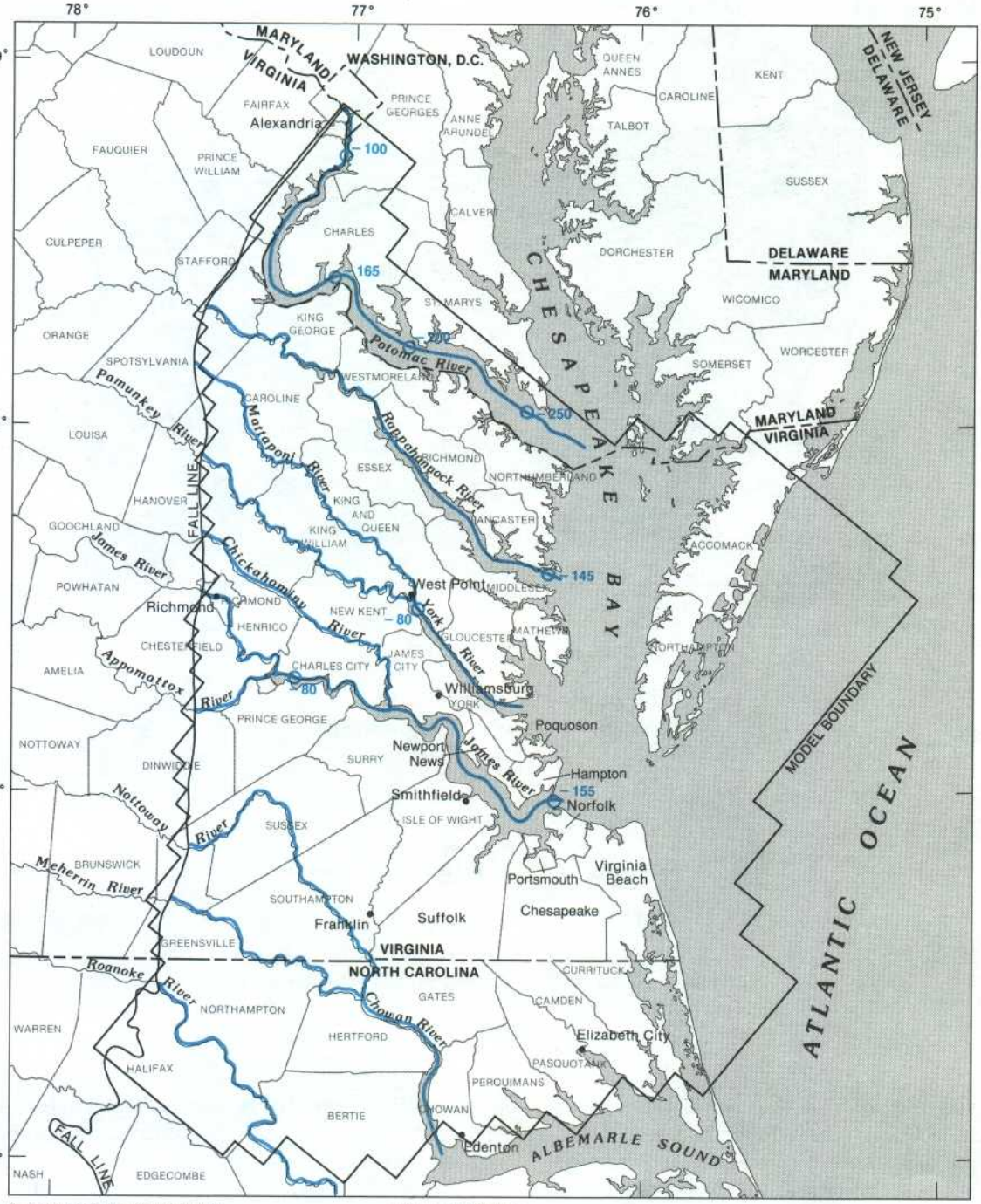
HYDROGEOLOGIC EFFECTS OF PLEISTOCENE EROSION

Considerable erosion by river channels occurred in the study area during the Pleistocene when Chesapeake Bay estuary—a drowned river system—approached equilibrium with a sea level 300 to 400 ft below present sea level (Hack, 1957). Chapelle and Drummond (1982, 1983) identified areas in southern Maryland where rivers eroded through a sequence of interbedded sand and clay corresponding to aquifers and confining units 9 through 6. Hack (1957) constructed geologic sections at six bridge sites in Virginia from examination of borehole data gathered during construction. These sections showed that the Pleistocene channels closely coincided with the present-day channels of the major rivers. The data were used to estimate the longitudinal profiles of selected Pleistocene channels and major tributaries. Figure 4 shows the approximate locations and estimated depths of these channels based on data from Hack (1957).

As a result of Pleistocene channel incision, aquifers and confining units were partially or completely eroded and replaced by material more permeable than the confining units but less permeable than the aquifers. This condition increased the hydraulic connection between surface water in the major river channels and ground water in the underlying aquifers. Because of the increased connection, the lowering of the water level in an aquifer below river stage results in more rapid movement of river water into the aquifer until the water level in the aquifer again approaches that of the river. Chapelle and Kean (1985) described the occurrence and movement of salty river water into the Patuxent (lower Potomac) aquifer near Baltimore, Md.

GROUND-WATER MOVEMENT

Prior to ground-water development, an approximate state of hydraulic equilibrium prevailed in the multiaquifer system (fig. 5). Precipitation infiltrated downward to recharge the water-table aquifer. Once in the water-table aquifer, water either moved laterally in the direction of decreasing hydraulic head (water level) and was ultimately discharged to the surface as seepage to streams, swamps, and coastal water or moved downward through confining units to recharge the confined flow system. Most downward movement of water into the confined aquifers occurred along a narrow band almost parallel to the Fall Line and under interfluves (areas of high elevation between the major river valleys). Some



Base from U.S. Geological Survey
State base maps, 1:1,000,000

SCALE 1:2,000,000

0 10 20 30 40 50 MILES

0 10 20 30 40 50 KILOMETERS

EXPLANATION

INFERRED LOCATION OF PLEISTOCENE CHANNEL

○ −80 DATA POINT—Number is estimated depth of Pleistocene channel in feet below sea level. Based on longitudinal profiles of Hack (1957)

FIGURE 4.—Approximate locations and depths of Pleistocene channels.

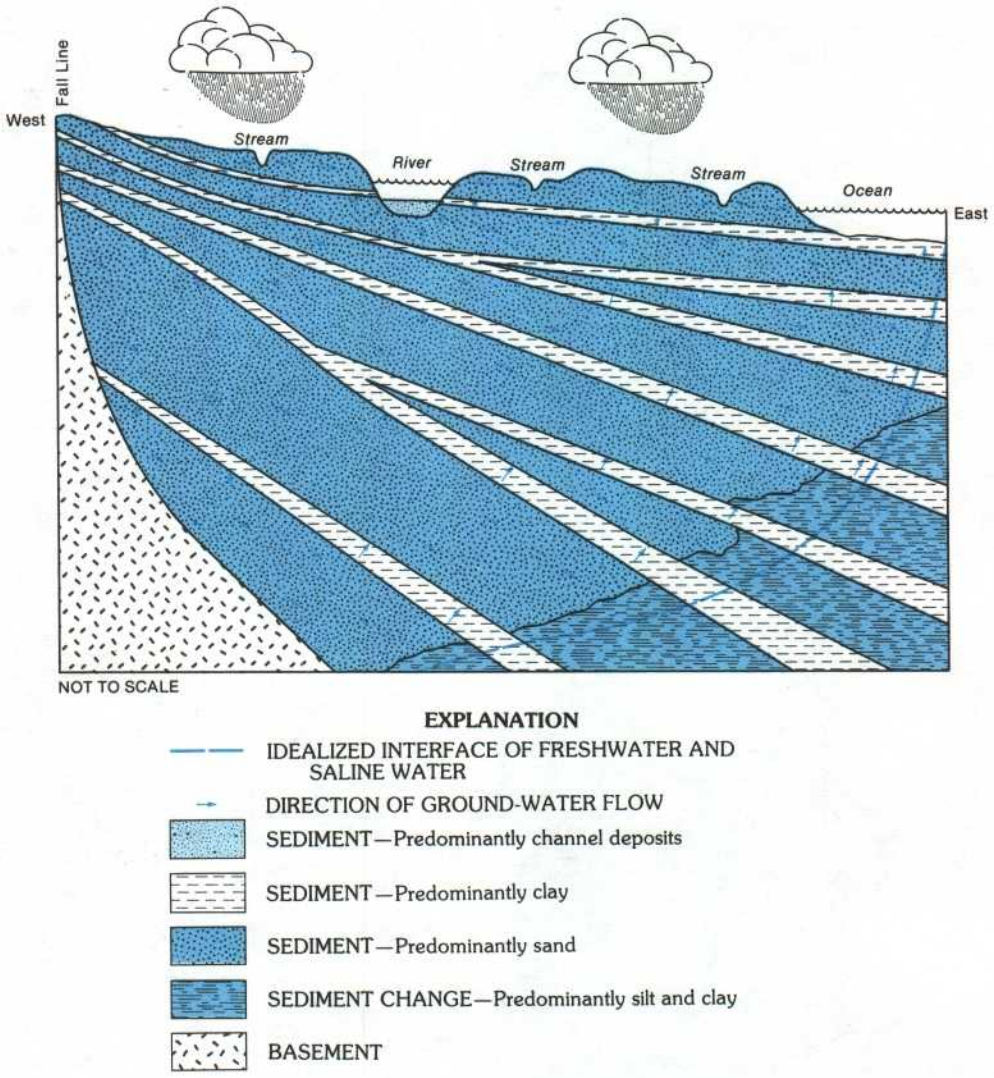


FIGURE 5.—Generalized prepumping ground-water flow system.

water moved upward from the confined flow system and recharged the water-table aquifer in areas of low elevation beneath and adjacent to major river channels.

Movement of ground water in the confined flow system was predominantly lateral in the direction of decreasing hydraulic head. The general direction of flow, defined by the hydraulic gradient, was from the Fall Line toward coastal areas and from interfluves toward major river valleys. Flow through the intervening confining units was predominantly vertical—downward between major river valleys and along the Fall Line and upward toward major river valleys and coastal water. Rates of flow through the confining units were small compared with rates of flow within the aquifers. However, the total volume of water moving across confining units was a significant component in the ground-water budget of the aquifers, because the confining units extend over very large areas.

The withdrawal of large amounts of ground water from the confined aquifers lowered water levels and resulted in the formation of regional cones of depression around major pumping centers. These withdrawals disturbed the natural balance between recharge and discharge and captured a large part of the water previously discharged from the ground-water flow system to surface water during prepumping conditions. The lowering of water levels changed the directions of ground-water flow toward the major pumping centers. Withdrawals increased vertical leakage through confining units, reduced the volume of water stored in the ground-water

flow system, increased flow from the water-table aquifer into the confined flow system, and decreased local ground-water discharge to streams and regional discharge to coastal water.

GROUND-WATER USE

Use of ground water from confined aquifers in the Virginia Coastal Plain began in the late 1800's. Sanford (1913) and Cederstrom (1945) reported the presence of many flowing wells along major rivers and tributaries throughout the study area. Estimates of discharge from these individual flowing wells range from a few gallons per minute to about 50 gal/min. The estimated aggregate annual discharge from these wells ranges from 4 to 10 million gallons per day (Mgal/d) for the period 1891 through 1945. Flowing wells continued to be the major source of ground water until about 1935; after that time, water levels in the deeper confined aquifers declined below land surface. As demand for water increased, users had to depend on pumped wells for adequate water supplies. Water levels continued to decline, with an accompanying decrease in the number of flowing wells. A few wells open to shallow confined aquifers located near coastal areas still flow today, though most contain salty water.

Data on ground-water use were compiled to provide the history of ground-water development in the study area. Withdrawal data for industrial, commercial, and public-supply wells were obtained from individual users and the Virginia State Water Control Board, and for commercial and public-supply systems from the Virginia State Health Department. Complete records on domestic use are not available. Per capita domestic use has been estimated to be between 50 and 80 gallons per day (gal/d), but because most ground water withdrawn for self-supplied domestic use is returned through septic tank discharge and because overall domestic use represents only a small percentage of total ground-water use from the confined flow system, domestic withdrawals were not included as part of the estimated history of development. Most industrial, commercial, and public-supply users maintained complete and consistent records; however, significant gaps of as much as 25 years (yr) in the historical record have occurred between the beginning of ground-water development and the date that withdrawal records were first reported. Withdrawal values were estimated for these data-gap periods from pump capacities and from a few reported withdrawals. Withdrawal rates were reported as metered or estimated averages or totals by month or year. Reports describing water use in areas of the Virginia Coastal Plain by Sanford (1913), Cederstrom (1945), Sinnott (1967), Cederstrom (1968), and Cosner (1975) were used

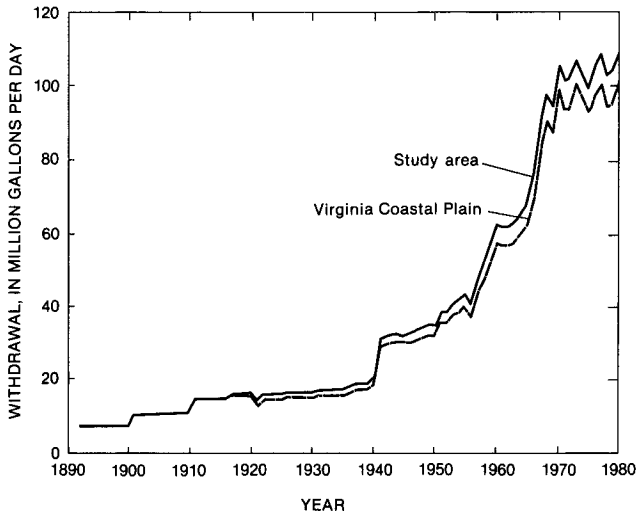


FIGURE 6.—Estimated annual ground-water withdrawal from Coastal Plain aquifers, 1891–1980.

to supplement the withdrawal data compiled during this study. Withdrawal rates were interpolated for time intervals for which data were not available. Withdrawals from wells in Maryland and North Carolina were provided by W.B. Fleck and G.L. Giese, respectively (U.S. Geological Survey, written commun., 1983).

Data on ground-water use include the user name, latitude and longitude, annual withdrawal rate, aquifers from which water is withdrawn, and percentage of water withdrawn from each aquifer. These data are stored on a computer file at the U.S. Geological Survey in Richmond, Va., and are available to the public upon request. Maps of aquifer tops and confining unit thicknesses (Meng and Harsh, 1988) were compared with the water-intake depth interval for each screen or open-end well to identify the source aquifer. For most multiaquifer wells, detailed transmissivity data were not available to determine the rates of flow from individual aquifers; therefore, withdrawal was apportioned to aquifers by the percentage of the total screen present within each aquifer.

Estimated annual ground-water withdrawal (including withdrawal for industrial, commercial, and public-supply uses) from the study area for the period 1891 through 1980 is shown in figure 6. Withdrawal in 1980 is estimated to have been about 110 Mgal/d. The figure also shows estimated annual withdrawal from wells in only the Virginia Coastal Plain. Withdrawal from the Virginia Coastal Plain in 1980 is estimated to have been about 100 Mgal/d. Estimated withdrawal includes discharge from both pumped and flowing wells.

Major ground-water-pumping centers in the Virginia Coastal Plain are located near the cities of Franklin, Williamsburg, Suffolk, and Alexandria and the towns of

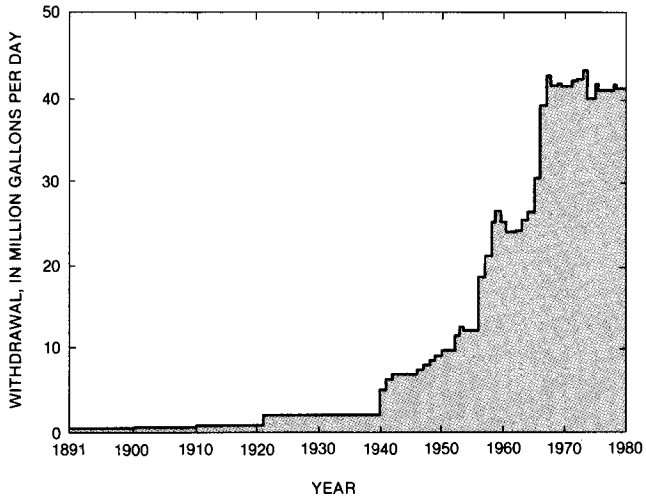


FIGURE 7.—Average annual withdrawal from the lower, middle, and upper Potomac aquifers in the Franklin area, Virginia, 1891–1980.

West Point and Smithfield. Estimated withdrawal from these centers in 1980 totaled about 65 Mgal/d. The largest center is near Franklin, where withdrawals from the lower, middle, and upper Potomac aquifers have increased to more than 40 Mgal/d (fig. 7).

The principal sources of ground water in the Virginia Coastal Plain are the lower and middle Potomac, Brightseat-upper Potomac, Aquia, Chickahominy-Piney Point, and Yorktown-Eastover aquifers. These aquifers supply more than 90 percent of the ground water withdrawn, and three aquifers, the lower and middle Potomac and the Brightseat-upper Potomac, provide approximately 90 percent of this withdrawal. Table 5 gives ground-water withdrawals for the major users in the study area in 1980. Locations of the major users are shown in figure 8.

ANALYSIS OF THE GROUND-WATER FLOW SYSTEM

The ground-water flow system in the Virginia Coastal Plain was analyzed using a digital flow model. Digital flow models are used to test a conceptualization of the ground-water flow system, to improve or verify estimates of the flow components in the ground-water budget, and to estimate regional aquifer properties and water levels in areas where data are sparse. Once calibrated, the model can analyze the response of an aquifer system to past and present ground-water withdrawals, estimate the effects of future ground-water development, and test effects of alternative water-development plans on a regional scale.

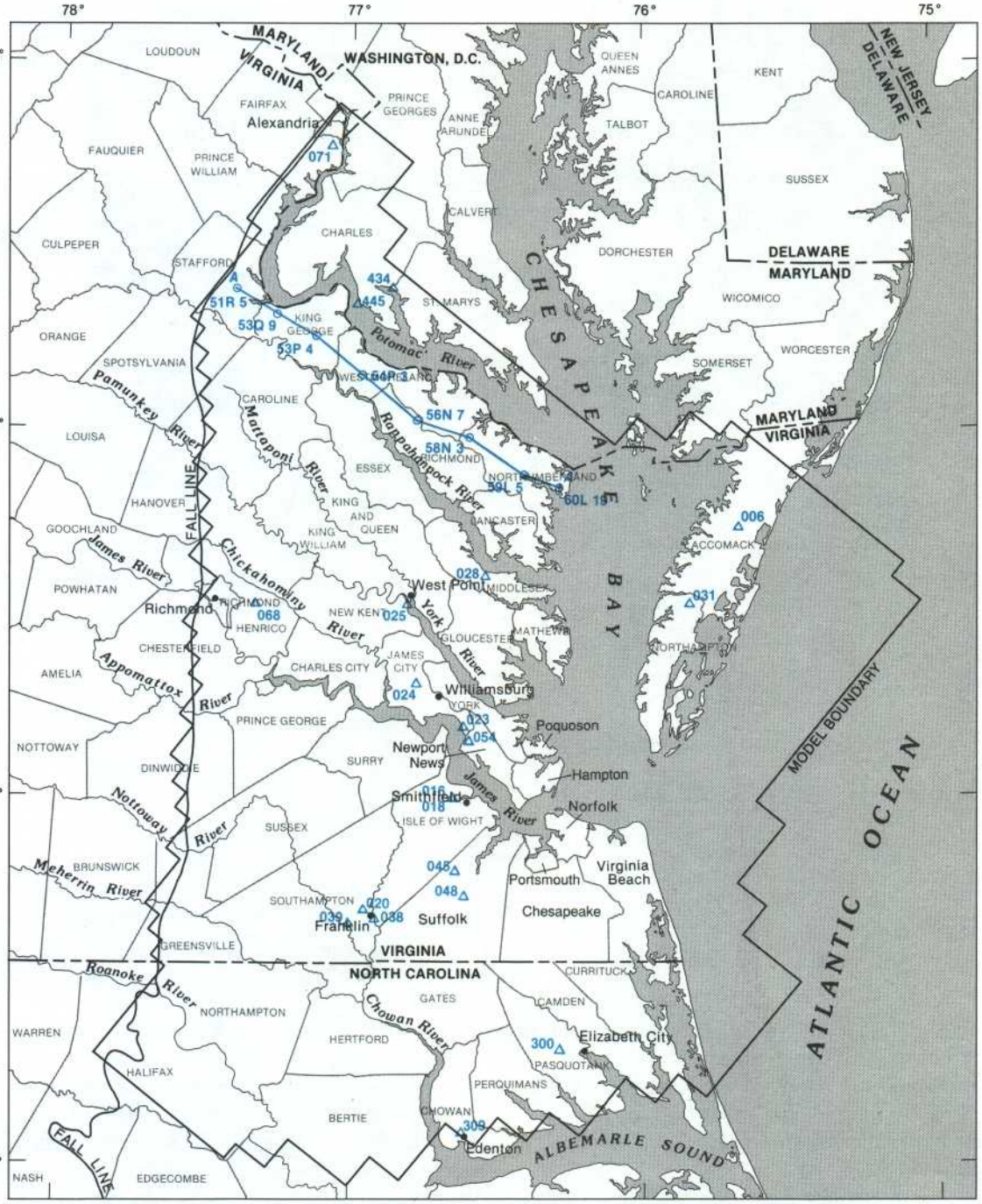
MODEL DESCRIPTION

The ground-water flow system was simulated using the quasi-three-dimensional approach described by Bredehoeft and Pinder (1970). The computer code used was a version of the three-dimensional finite-difference model of Trescott (1975) as modified and documented by Leahy (1982). This approach uses a layered sequence of two-dimensional aquifers coupled to simulate vertical flow through intervening confining units without considering the release of water from storage within the confining unit (fig. 9, table 2). This assumption of two-dimensional flow within the aquifer is valid if the horizontal hydraulic conductivities of the aquifers are more than two orders of magnitude greater than those of the intervening confining units (Neuman and Witherspoon, 1969). The error due to neglecting storage in the confining unit is minimal if simulated pumping periods are long enough to establish a constant hydraulic gradient between the individual aquifers. The shortest simulated pumping period was 3 yr, which was considered long enough to avoid any errors resulting from this assumption. In this approach, confining units are not represented as individual layers but as vertical conductors of flow between adjacent aquifers and are defined by leakance values (fig. 10). Horizontal flow in the confining units is assumed to be negligible because of the low hydraulic conductivity of the sediments.

BOUNDARIES

Model boundaries were selected and located to approximate the natural hydrologic boundaries of the ground-water flow system. The westernmost boundary of the model coincides with the Fall Line and is considered impermeable to flow. This assumption is supported by the large difference in hydraulic conductivity between the rocks of the Piedmont physiographic province and the unconsolidated sediments of the Coastal Plain physiographic province.

The easternmost boundary approximates the seaward limit of the freshwater system and is defined by the location of 10,000 milligrams per liter (mg/L) chloride concentration delineated by Meisler (1981). Movement across this boundary is assumed to be negligible because of density effects. This condition is considered stable over time. The spatial stability of this boundary throughout the history of ground-water development has been suggested by Larson (1981) and by recent research of P.P. Leahy (U.S. Geological Survey, oral commun., 1985). Significant lateral movement of this boundary could occur as a result of greatly increased pumping and would thus require modification of the model conceptualization to incorporate boundary movement.



Base from U.S. Geological Survey
State base maps, 1:1,000,000

SCALE 1:2,000,000

0 10 20 30 40 50 MILES

0 10 20 30 40 50 KILOMETERS

EXPLANATION

△028 LOCATION AND IDENTIFICATION NUMBER OF WATER USER SHOWN IN TABLE 5

A——A' LINE OF SECTION SHOWN IN FIGURE 2

○54P 3 WELL AND LOCAL WELL NUMBER SHOWN IN FIGURE 2

FIGURE 8.—Locations of major ground-water users.

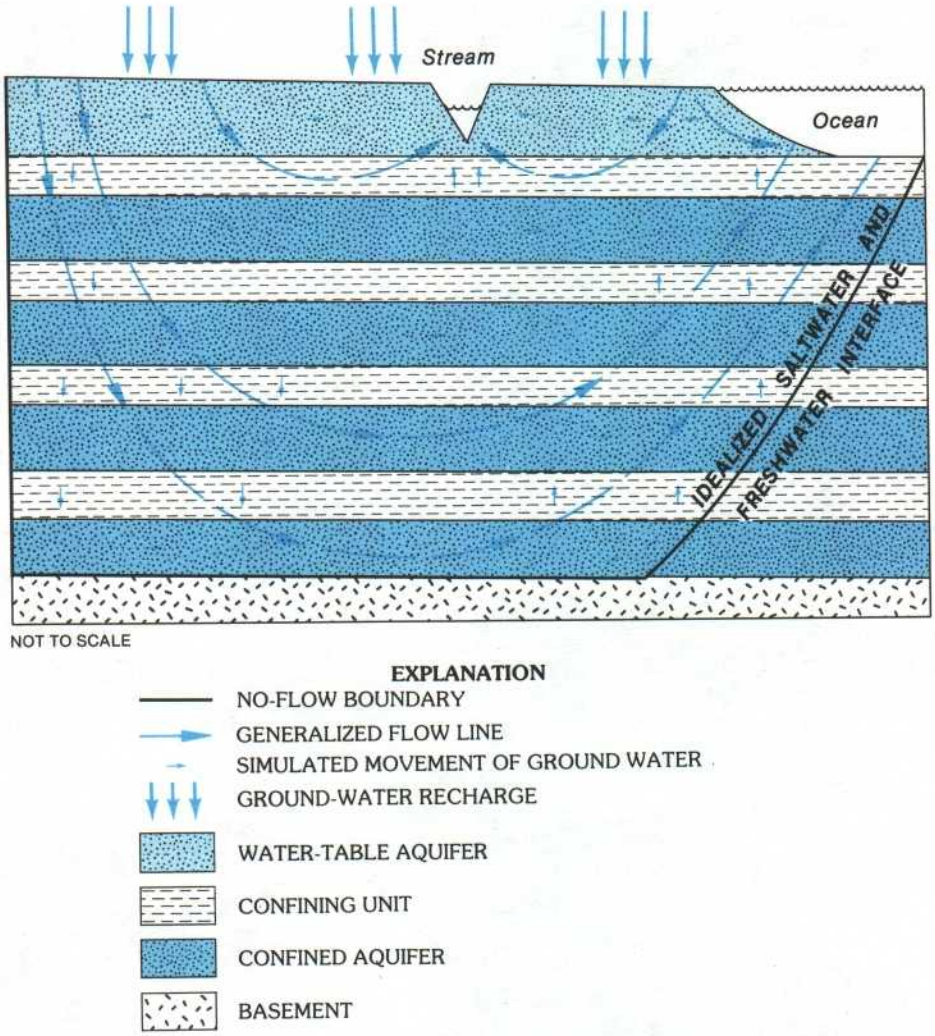


FIGURE 9.—Model conceptualization of prepumping ground-water system.

The lowermost boundary coincides with the contact between the lower Potomac aquifer and the underlying basement rocks. The contact is considered a no-flow boundary. This assumption is supported by the large difference in hydraulic conductivities between the two rock types.

The uppermost boundary simulates surface water and is approximated as the average stage in surface-water bodies. The boundary is simulated as a constant-head boundary and allows for vertical flow between it and the underlying water-table aquifer. The relative consistency of water levels within surface-water bodies over the time and scale of simulation supports the use of this boundary condition (Cederstrom, 1945; Johnston, 1977).

Aquifers continue beyond the northern and southern limits of the study area. Continuity of the aquifers across these lateral model boundaries is simulated using lateral boundary fluxes that were calculated by the regional flow model of the entire northern Atlantic Coastal Plain. Lateral boundaries are located to include, within the modeled limits, those areas outside the Virginia Coastal Plain that are affected by withdrawals from within the Coastal Plain of Virginia. The northern flux boundary is north of the Potomac River and extends across southern Maryland. The southern flux boundary coincides with Albemarle Sound and extends westward to the Fall Line across North Carolina. The locations of lateral flow boundaries are shown in figure 11. The method of estimating lateral boundary fluxes is discussed later in the section "Lateral Boundary Flow."

GRID DESIGN

A three-dimensional grid of blocks is superimposed on a map of the study area in the finite-difference method of solving the ground-water flow equation. The discretiza-

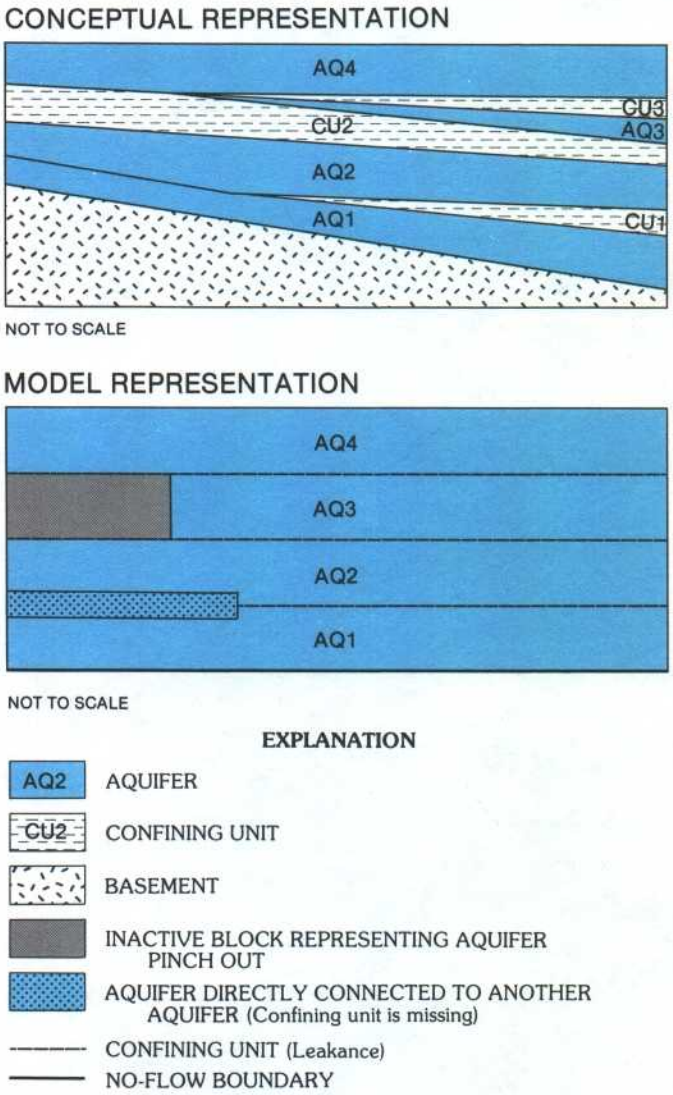


FIGURE 10.—Conceptual and model representations of aquifers and confining units.

tion defines the geographic limits and spatial variation of hydraulic properties of each of the 10 aquifers.

The grid consists of 68 rows and 50 columns for a total of 3,400 blocks per layer (fig. 11). Each aquifer is represented by a layer of blocks (fig. 12). Each block is assigned values representative of the average aquifer characteristics within the block. The block size of 12.25 square miles (mi^2) and the grid orientation are the same as for models of adjoining States, allowing for transfer of input parameters and continuity of aquifers across model boundaries. The grid orientation is compatible with the regional model of the northern Atlantic Coastal Plain.

HYDRAULIC CHARACTERISTICS AND STRESSES

The hydraulic characteristics and hydrologic stresses that influence the flow of ground water in the digital flow model are aquifer transmissivity and storage coefficient, vertical leakance of confining units, streambed leakance, lateral boundary flow rates, and ground-water recharge and withdrawal. Maps presented in the following sections describe the spatial variation in the hydraulic characteristics. Values of hydraulic characteristics and hydrologic stresses used for the simulations are stored on computer files at the U.S. Geological Survey, Richmond, Va., and are available to the public upon request.

TRANSMISSIVITY

Movement of water within the multiaquifer system is characterized by values of transmissivity. The value of transmissivity for each block was calculated by multiplying an estimated sand thickness for each block by the lateral hydraulic conductivity of the sand. Average hydraulic conductivities initially (table 6) were estimated using lithologic logs and aquifer test data and were assumed constant for each aquifer. Transmissivity was assumed isotropic, and values were adjusted during model calibration. In areas where aquifer material was eroded and replaced by less permeable deposits, lower values of hydraulic conductivity were used. The range of transmissivity for each aquifer is given in table 7.

Figures 13 through 21 show the estimated transmissivity of the major aquifers. Aquifer 5 and confining unit 5 are not present in the Coastal Plain of Virginia; therefore, illustrations for these units are not included in this report. In general, transmissivity of the Brightseat-upper Potomac, middle Potomac, and lower Potomac aquifers (figs. 19, 20, 21) increases eastward from the Fall Line. Values begin to decrease near the 10,000 mg/L chloride concentration. This decrease is attributed to a facies change from continental to marine deposits (Meng and Harsh, 1988) and a thinning of the aquifer thicknesses caused by the presence of saltwater (greater than 10,000 mg/L chloride concentrations) in the lower part of the aquifers. Areas of high transmissivity are present south and west of Chesapeake Bay.

Transmissivity maps for the Chickahominy-Piney Point and Aquia aquifers and aquifer 4 (figs. 16, 17, 18) show zones of higher transmissivity landward of coastal water bodies. In general, values increase in a southeastwardly direction into North Carolina, where these aquifers are a major source of water for industrial and municipal users in North Carolina.

Transmissivity maps for the Columbia and Yorktown-Eastover aquifers (figs. 13, 14) show an increase in an eastwardly direction. Lower values are present where

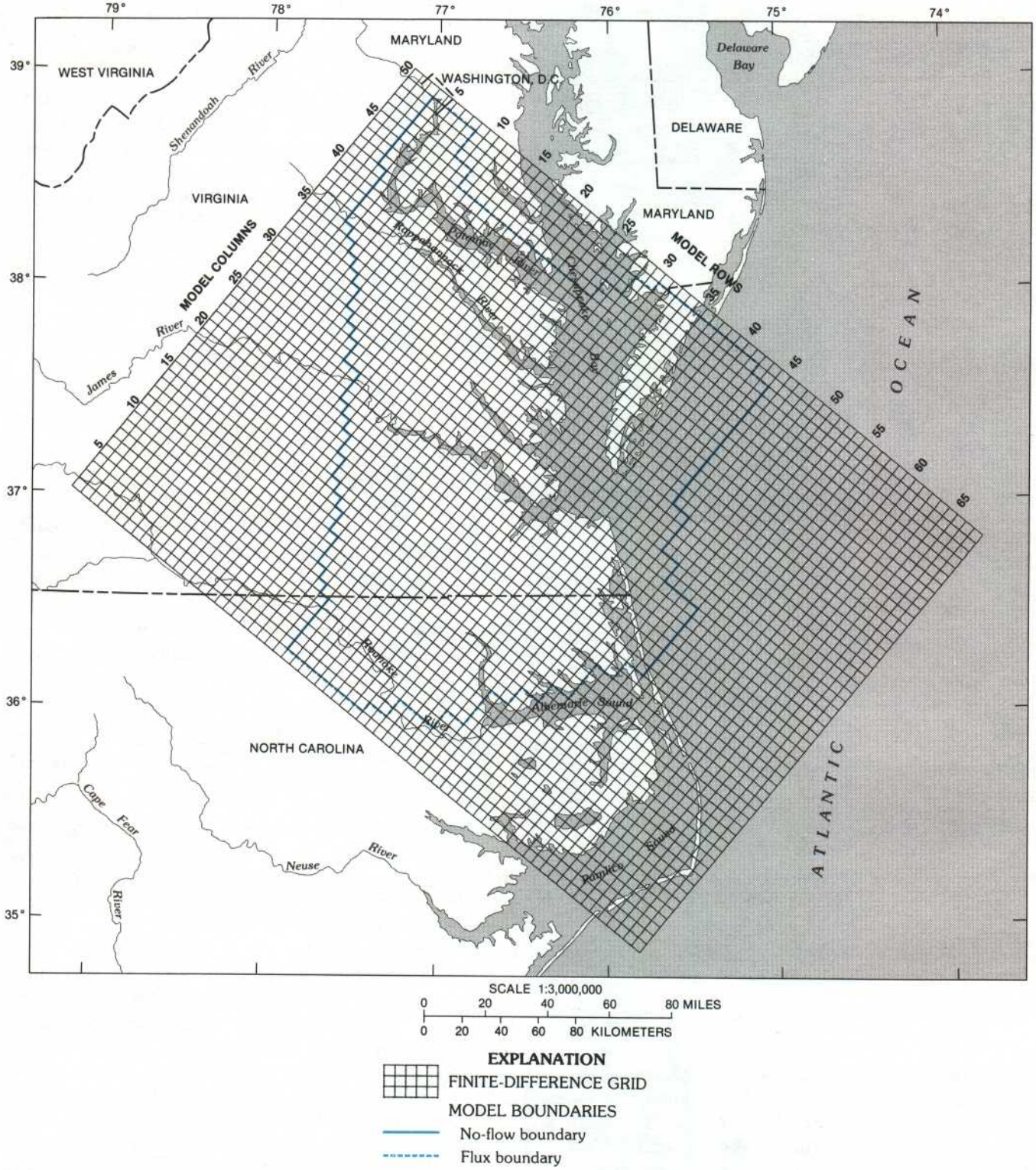


FIGURE 11.—Finite-difference grid and model boundaries.

these aquifers were incised by ancient river systems which eroded the original aquifer sediment and replaced it with less permeable material.

STORAGE COEFFICIENT

The storage coefficient defines the ability of an aquifer to store water. A value of 1.0×10^{-4} was used in the model

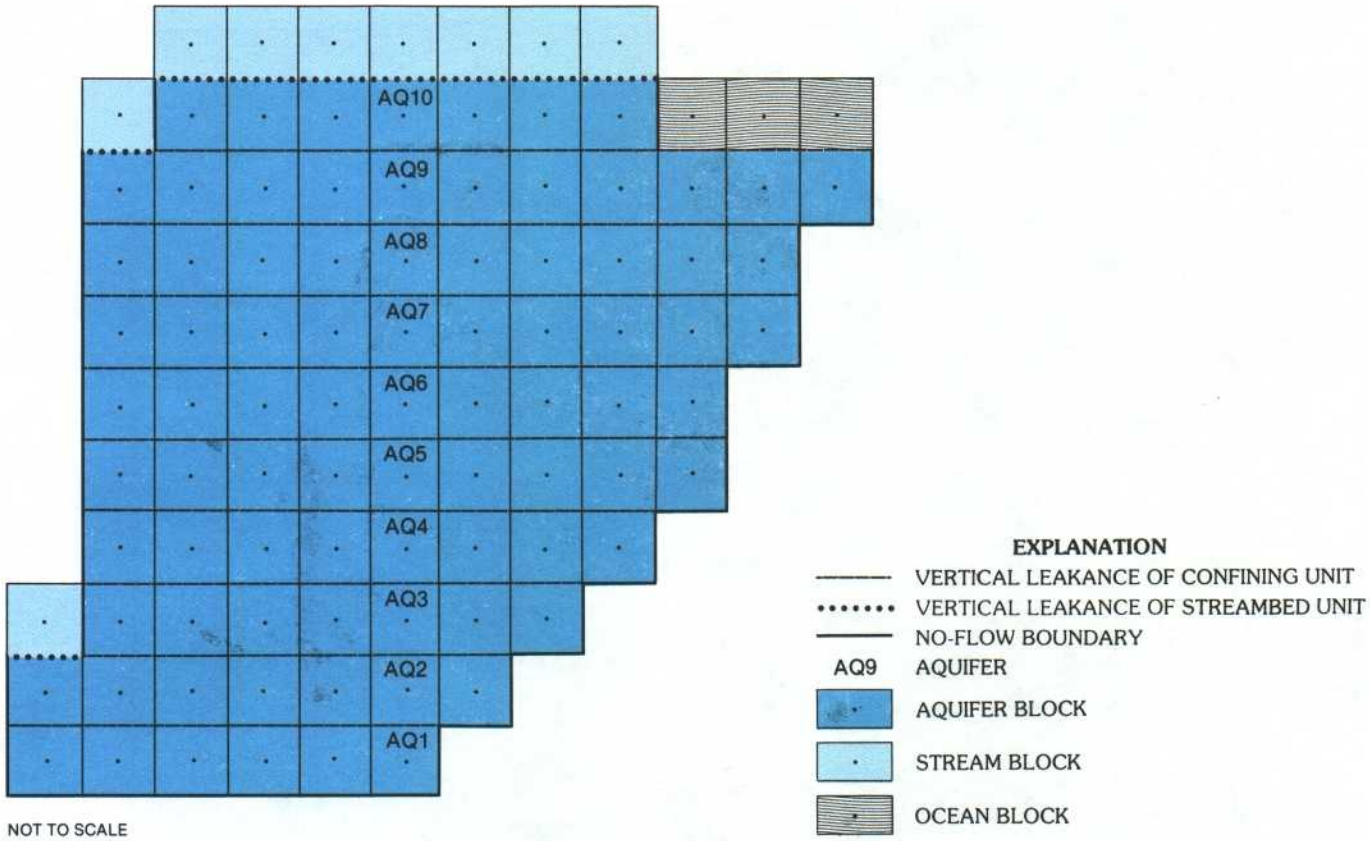


FIGURE 12.—Cross section of finite-difference grid and boundary conditions.

for all confined aquifers. This value is slightly lower than those given in table 3, but it is assumed reasonable because most values in table 3 were determined from standard nonleaky methods. This value is in close agreement with that estimated by Hopkins (U.S. Geological Survey, written commun., 1984) from compaction-recorder data and determined by model calibration (Cosner, 1975; Chapelle and Drummond, 1983). A value of 0.15 was used to simulate storage for the unconfined (water-table) parts of aquifers.

VERTICAL LEAKANCE

Vertical leakance controls the vertical flow of ground water through confining units. It defines the degree of hydraulic connection between aquifers and is dependent on the physical properties of the sediment that makes up the confining unit. Vertical leakance is defined as the average vertical hydraulic conductivity of the confining unit sediment divided by its thickness.

In the model, vertical leakance controls the degree of hydraulic connection between two vertically adjacent, or sequential, aquifer blocks and represents the intervening confining unit (fig. 22*A*). Confining unit thicknesses for blocks were estimated from confining unit thickness maps reported by Meng and Harsh (1988). Vertical hydraulic conductivities of confining units, estimated from laboratory cores, are given in table 6. The range of vertical leakance for each confining unit is given in table 7.

Aquifers and confining units are not continuous over the entire study area (Meng and Harsh, 1988). In some areas, the confining unit between two sequential aquifers pinches out or is not present (fig. 22*B*). In the model, high vertical leakance values were used to represent the hydraulic connection between two sequential aquifers not separated by a confining unit. Vertical leakance between two such blocks was assumed to be four orders of magnitude greater than the vertical hydraulic conductivity of the missing confining unit. A value of this magnitude is considered more representative of the vertical leakance of aquifer material.

In some areas, two nonsequential aquifers are connected hydraulically through a single confining unit, because the overlying sequential hydrologic units are missing (fig. 22*C*); blocks representing the missing aquifers are eliminated from the ground-water flow system