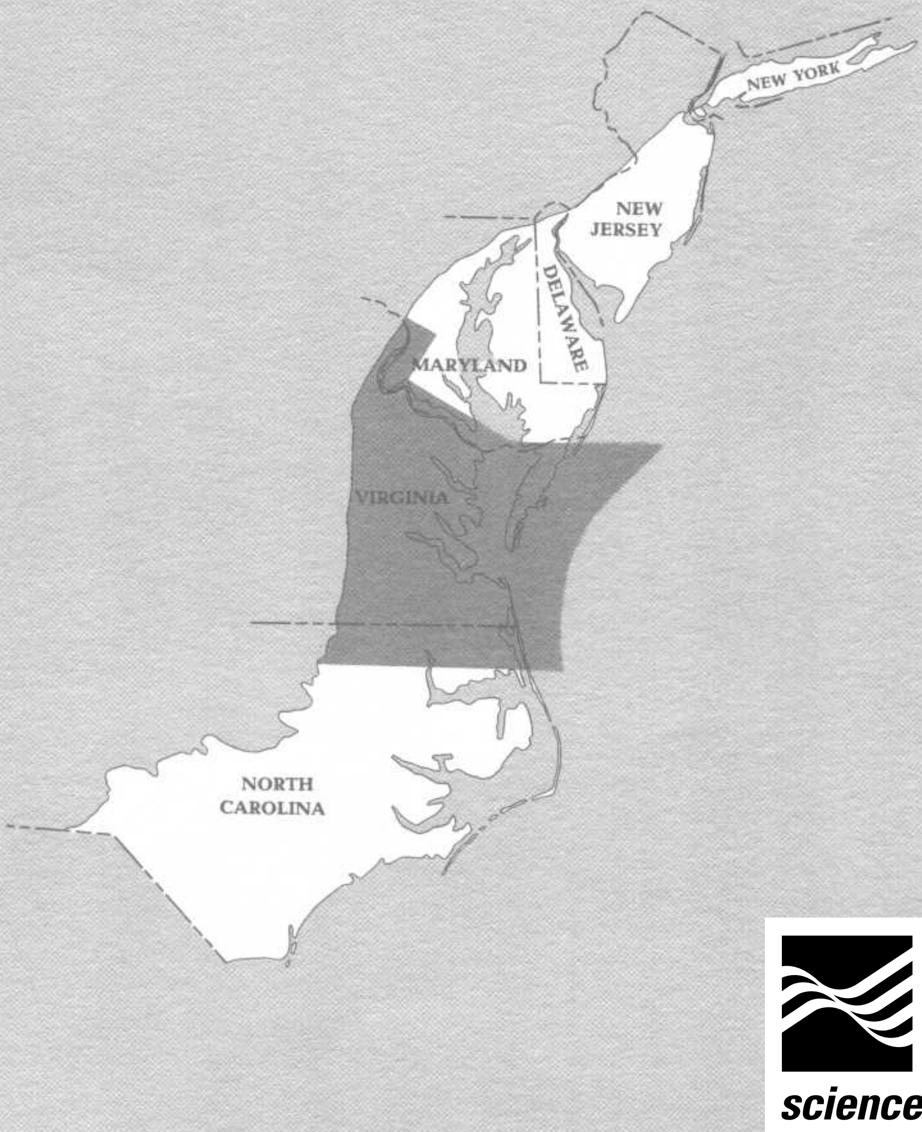
CONCEPTUALIZATION AND ANALYSIS OF GROUND-WATER FLOW SYSTEM IN THE COASTAL PLAIN OF VIRGINIA AND ADJACENT PARTS OF MARYLAND AND NORTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS



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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

By JOHN F. HARSH *and* RANDELL J. LACZNIAK

REGIONAL AQUIFER-SYSTEM ANALYSIS—
NORTHERN ATLANTIC COASTAL PLAIN

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1404-F

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	3.78540	liter per day (L/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

ALTITUDE DATUM

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

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

By JOHN F. HARSH and RANDELL J. LACZNIAK

ABSTRACT

This report presents the results of a study of the ground-water flow system in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina. The ground-water flow system consists of a water-table aquifer and an underlying sequence of confined aquifers and intervening confining units composed of unconsolidated sand and clay. Water levels have declined steadily, and cones of depression have expanded and coalesced around major ground-water withdrawal centers. A digital flow model was developed to enhance knowledge of the behavior of the ground-water flow system in response to its development. Transmissivity and vertical leakance maps were developed for each aquifer and confining unit. The model was calibrated to simulate ground-water flow within the system under both prepumping and pumping conditions. Simulated prepumping potentiometric-surface maps indicate that regional movement of ground water was from the Fall Line toward coastal areas and that local movement of ground water was from interfluves toward major river valleys. Maps of simulated prepumping flow across confining units show that most recharge occurred in narrow bands approximately parallel to the Fall Line and under interfluves and that discharge was toward major river valleys and coastal water. Simulated prepumping rates of recharge into the confined aquifer system from the water-table aquifer varied up to 3.2 inches per year (in/yr), and rates of discharge out of the confined system varied up to 2.8 in/yr.

Ten pumping periods covering 90 years (yr) of withdrawal simulated the history of ground-water development. Simulated potentiometric-surface maps for 1980 show lowered water levels and the development of coalescing cones of depression around the cities of Franklin, Suffolk, and Williamsburg and the town of West Point, all in Virginia. The largest simulated decline in water level, about 210 feet (ft), was near Franklin. Water budgets indicate that over the period of simulation (1891–1980) (1) pumpage from the model area increased by about 105 million gallons per day (Mgal/d), (2) lateral boundary outflow increased by about 5 Mgal/d, (3) ground-water flow to streams and coastal water decreased by about 107.5 Mgal/d, (4) lateral boundary inflow increased by about 0.7 Mgal/d, and (5) water released from aquifer storage increased by about 1.6 Mgal/d. The difference between total inflow and total outflow is the numerical truncation error of the digital simulation. Analysis of water budgets for individual confined aquifers shows that the major source of water supplied to wells was vertical leakage induced through confining units by pumping. Simulated rates of recharge into the confined aquifer system at the end of the final pumping period (1980) varied up to 3.8 in/yr, and simulated rates of discharge out of the confined system varied up to 2.2 in/yr. Results of simulations show an increase of about 110 Mgal/d into the confined system from the unconfined system over the period of simulation. This increase in flow into the confined system affected local discharge of ground water to streams and regional discharge to coastal water. Withdrawal of ground water from the confined aquifers also induced brackish water from Chesapeake Bay into the confined system.

Results of sensitivity analyses indicate that simulated water levels are more sensitive to decreases in aquifer transmissivity and confining unit vertical hydraulic conductivity than to increases in these properties. Lowering the storage coefficient of an aquifer had minimal effect on simulated water levels, whereas increasing the storage coefficient had a much more significant effect. The effect of confining unit storage is shown to be insignificant if it is assumed that the water released from confining unit storage is attributable to the compressibility of water only.

INTRODUCTION

Ground water is an important source of industrial, municipal, domestic, and agricultural water supplies in the northern Atlantic Coastal Plain. The continued withdrawal of ground water has caused a steady decline of water levels and the expansion and coalescence of cones of depression centered at major pumping centers. This decline concerns ground-water users and those responsible for the study and management of the resource. More hydrologic information is needed to better understand ground-water flow in the aquifers of the northern Atlantic Coastal Plain.

In 1978, the U.S. Geological Survey began a comprehensive program of regional investigations, known as the

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Regional Aquifer-System Analysis (RASA), to describe the hydrogeology of major aquifers in the United States. The study of the northern Atlantic Coastal Plain aquifer system began in 1979. The northern Atlantic Coastal Plain was divided into five subregional projects extending from Long Island, N.Y., through North Carolina (Meisler, 1980). One of the five subregional projects defines the hydrogeologic framework and analyzes ground-water flow in the multiaquifer system of the Virginia Coastal Plain. Two reports have resulted from the subregional project: a report by Meng and Harsh (1988) that describes the hydrogeologic framework, and this report, which provides the results of an analysis of ground-water flow in the multiaquifer system of the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina.

PURPOSE AND SCOPE

The purposes of this report are to describe the ground-water flow system in the Coastal Plain of Virginia and to provide an analysis of the response of the ground-water flow system to past and present ground-water withdrawals through the use of a digital flow model. Specifically, the report describes (1) the conceptualization of the ground-water flow system, (2) the development of the subregional digital flow model, (3) the simulation of the ground-water flow system, and (4) the sensitivity of the digital flow model to changes in selected hydraulic characteristics of the ground-water flow system.

Available hydrologic data provided most of the necessary information for the interpretation and conceptualization of the multiaquifer system. The physical boundaries of individual aquifers and confining units are presented in hydrogeologic maps by Meng and Harsh (1988). Hydraulic characteristics of aquifers and confining units were initially estimated from (1) analysis of geophysical and lithologic logs of water wells and geologic test holes, (2) laboratory tests of core samples, (3) data on specific capacity of wells, and (4) available selected aquifer tests. The ground-water flow system was simulated through the use of a digital flow model. Hydraulic characteristics of the ground-water flow system were adjusted to calibrate the model to measured water levels throughout the history of ground-water development (1891–1980). Sensitivity of model-generated water levels to selected variations in hydraulic characteristics was tested. The information presented is intended to assist those involved in the management of the ground-water resource in the Coastal Plain aquifers of Virginia.

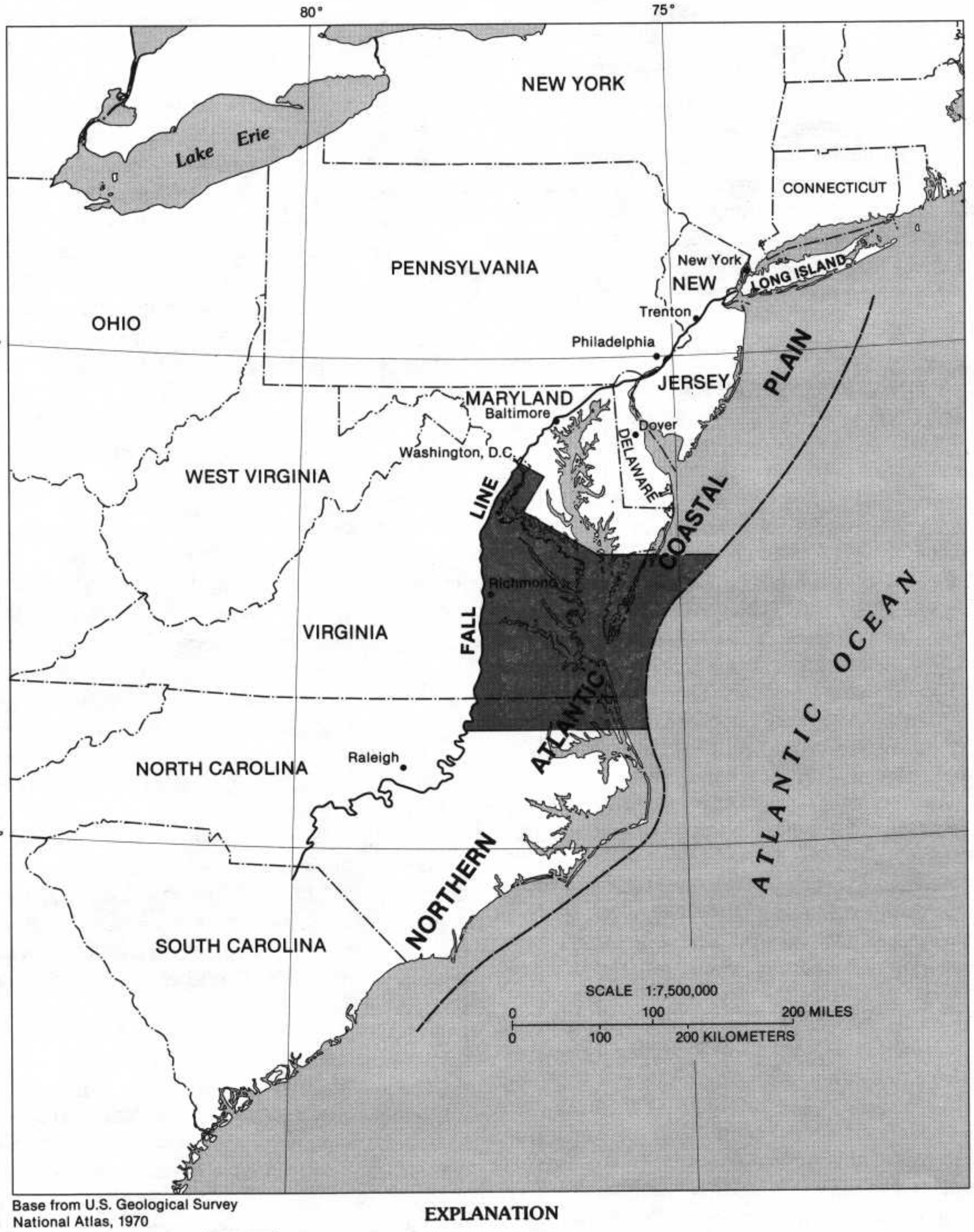
Data used to develop the subregional digital flow model were also used to develop a regional digital flow model of the northern Atlantic Coastal Plain aquifer system (Meisler, 1980). The regional model analyzed the entire ground-water flow system of the northern Atlantic Coastal Plain and provided lateral boundary flows to the individual subregional models.

GENERAL SETTING AND LOCATION OF STUDY AREA

The study area is located within the Atlantic Coastal Plain physiographic province and includes the entire Coastal Plain of Virginia and adjacent parts of the Coastal Plain of Maryland and North Carolina (fig. 1). The area covers about 17,000 square miles (mi^2) and is characterized by a gently seaward sloping land surface and a dissected lowland with a series of broad, seaward-facing, ocean-cut terraces trending north-south. The study area is underlain predominantly by unconsolidated clastic sediments of Early Cretaceous to Holocene age.

PREVIOUS INVESTIGATIONS

Important sources of data on the geology and hydrogeology of the Virginia Coastal Plain include reports by Richards (1945, 1948), Spangler and Peterson (1950), Bick and Coch (1969), Brown and others (1972), Johnson (1972), Teifke (1973), the Virginia Division of Mineral Resources (1980), and Meng and Harsh (1988). Darton (1896), Sanford (1913), Cederstrom (1945, 1957), Leggette and others (1966), Geraghty and Miller (1967, 1978a, 1978b, 1979a, 1979b), Sinnott (1968), the Virginia State Water Control Board (1973, 1974), Cushing and others (1973), Lichtler and Wait (1974), Brown and Cosner (1974), Siudyla and others (1977), Newton and Siudyla (1979), Harsh (1980), Siudyla and others (1981), and Fennema and Newton (1982) describe the geology and water resources in specific areas of the Coastal Plain of Virginia. Converse and others (1981) provide a comprehensive water-supply study for the City of Virginia Beach, Va. Brown and Silvey (1977) evaluate the feasibility of injecting freshwater into Cretaceous-age sand containing saline water at Norfolk, Va. Meisler (1981) documents the occurrence and distribution of salty ground water in the northern Atlantic Coastal Plain aquifer system. Larson (1981) describes the occurrence of salty ground water in the Coastal Plain aquifers of Virginia. Cosner (1975), Bal (1977, 1978), and Faust and others (1981) studied, by means of digital flow models, the movement of ground water in specific areas of the Virginia Coastal Plain. Layne-Western Company (1983) developed a steady-state electric analog model to simulate flow in the Cretaceous-age aquifers of Virginia and North Carolina.



EXPLANATION

STUDY AREA

ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Shows location of water that contains chloride concentrations of 10,000 milligrams per liter or less

FIGURE 1.—Location of study area within the northern Atlantic Coastal Plain.

ACKNOWLEDGMENTS

Acknowledgment is given to the Virginia State Water Control Board (VSWCB), the Virginia State Health Department, and the many water users in Virginia for furnishing information on ground-water withdrawals and water-supply wells. The authors wish to thank the VSWCB for providing core samples and completing an observation well in Gloucester County, Va. Thanks also is extended to the many drillers and consultants active in the area for providing access to well information.

CONCEPTUALIZATION OF GROUND-WATER FLOW SYSTEM

The ground-water flow system in the Coastal Plain of Virginia is a multiaquifer system consisting of an eastward-thickening wedge of unconsolidated sand and clay that unconformably rests on an uneven, eastward-sloping surface of crystalline rocks, referred to as the "basement." The Fall Line is the westernmost extent of these unconsolidated sediments and delineates their contact with the igneous and metamorphic rocks of the Piedmont physiographic province. The sediments attain a maximum thickness in northeastern Virginia; Onuschak (1972) reports that sediments are about 6,200 feet (ft) thick beneath the northern part of Virginia's Eastern Shore Peninsula. The wedge generally consists of a thick sequence of nonmarine deposits overlain by a thinner sequence of marine deposits. The sediments are mostly undeformed except for slight warping and tilting with associated minor faulting; they range in age from Early Cretaceous to Holocene and have a complex history of deposition and erosion (Meng and Harsh, 1988, p. C11).

The sediments are subdivided into a sequence of discrete lithologic layers that form a regionally correlative geohydrologic framework of aquifers and confining units (fig. 2) (Meng and Harsh, 1988). The framework includes an unconfined, or water-table, aquifer underlain by a series of confined aquifers separated by intervening confining units. The subsurface correlations of aquifers and confining units are based primarily on analyses of geophysical and lithologic logs of wells. Table 1 (all tables at end of report) shows the relation between stratigraphic formations and hydrogeologic units defined for the Coastal Plain of Virginia. Table 2 summarizes the correlation of the hydrogeologic units of the Virginia Coastal Plain by Meng and Harsh (1988) with those of the adjoining States of Maryland (D.A. Vroblesky, U.S. Geological Survey, written commun., 1984) and North Carolina (M.D. Winner, U.S. Geological Survey, written commun., 1984).

Not all aquifers are continuous over the entire study area. The Black Creek and Peedee aquifers of North Carolina and the Matawan and Severn aquifers of southern Maryland (aquifers 4 and 5, table 2) are missing for the most part in the Coastal Plain of Virginia. The Brightseat aquifer, not present in North Carolina, is combined with the upper Potomac aquifer in the digital flow model (aquifer 3, table 2) because of the absence of a continuous intervening confining unit and similarities in hydraulic properties. The areal extent of aquifers and confining units is shown on maps of aquifer transmissivity and confining unit leakance presented in later sections of this report and in a report by Meng and Harsh (1988).

HYDRAULIC PROPERTIES

Transmissivity and storage coefficient are the hydraulic properties used to describe the ability of an aquifer to transmit and store water. Most hydraulic properties of aquifers in the Coastal Plain of Virginia have been determined from aquifer tests. Drawdown and recovery data generally are collected from an observation well positioned near a high-capacity production well that penetrates more than one aquifer. Other estimates of aquifer properties are determined from specific capacity (yield per unit of drawdown) and single-well tests of production wells that penetrate more than one aquifer. Because most wells penetrate more than one aquifer, direct application of these tests to determine hydraulic properties of an individual aquifer is difficult. Table 3 lists the type of data and method of analysis used to compute transmissivity. Locations of aquifer test sites are shown in figure 3. Applying results from aquifer tests over large areas is difficult because values represent only the test area and because of the assumptions inherent in the methods—that an aquifer is homogeneous and that test wells penetrate the entire aquifer.

Data on the hydraulic properties of individual confining units are sparse. Some vertical hydraulic conductivities have been estimated from laboratory tests of core samples (table 4). The locations of core holes are shown in figure 3. Laboratory values should be used with caution, because undisturbed core samples are difficult to obtain and typically represent only a small interval of a highly complex hydrogeologic unit.

DESCRIPTION OF HYDROGEOLOGIC UNITS

Each aquifer and overlying confining unit is assigned an identification number for model simulation, from 10 through 1 in descending order from land surface (table 2). The following sections summarize the lithology and

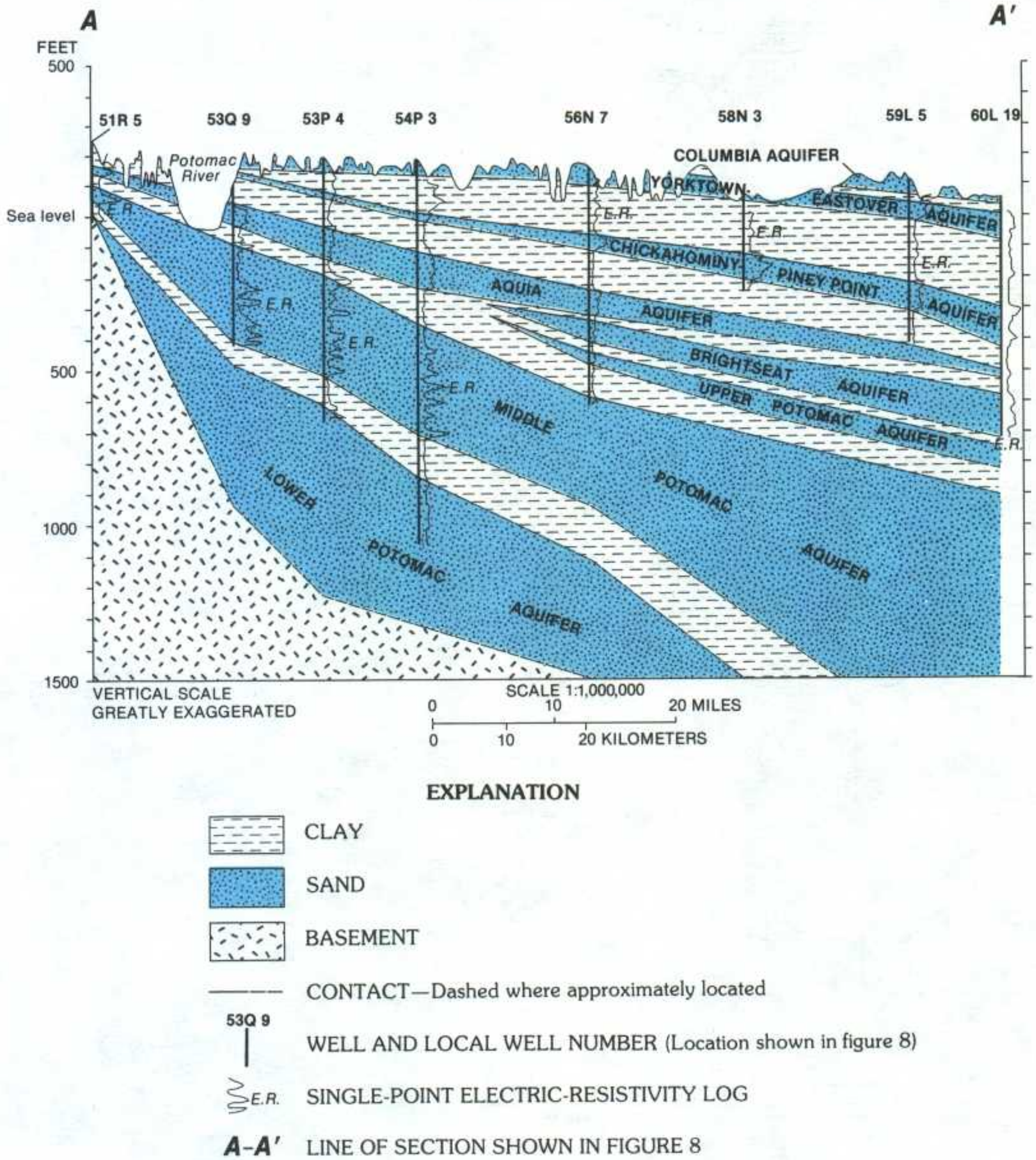


FIGURE 2.—Generalized hydrogeologic section of eastward-thickening wedge of alternating sand and clay.

hydraulic properties of aquifers and confining units of the study area. The reader is referred to Meng and Harsh (1988) for a more detailed description of the age, lithologic characteristics, stratigraphic position, depositional history, and areal extent of each hydrogeologic unit, except where otherwise referenced.

COLUMBIA AQUIFER

The Columbia aquifer, designated aquifer 10, is made up primarily of Holocene- and Pleistocene-age sediments that were deposited as channel fill and fluvial-marine terraces. The aquifer is composed of interbedded gravel, sand, silt, and clay and is unconfined throughout the study area. The aquifer is a major source of recharge to the underlying confined flow system and supplies water to rural and domestic users.

The saturated thickness of the Columbia aquifer ranges from about 15 ft near its western extent to about 80 ft in the southeastern part of the study area. Spatial variation in the hydraulic properties of the aquifer are not adequately defined by available data. Results from an aquifer test conducted at Northwest River Park in Chesapeake, Va., indicate a transmissivity of 250 feet squared per day (ft^2/d) (Siudyla and others, 1981). A specific yield of 0.15 was estimated by Cushing and others (1973) from analysis of aquifer-test data collected on the Eastern Shore Peninsula of Virginia.

FIGURE 3.—Locations of core holes and aquifer test sites in the Virginia Coastal Plain.

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

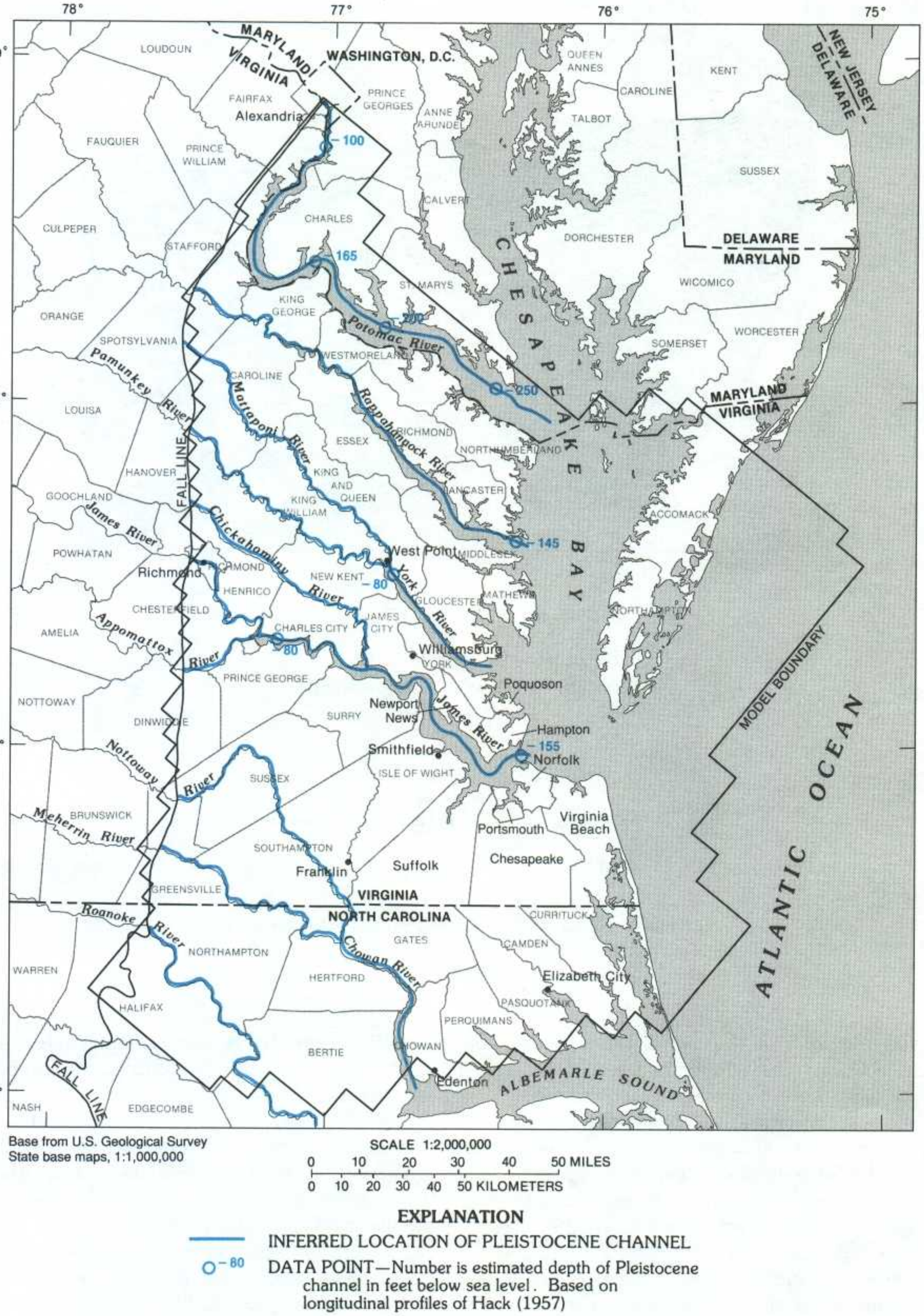


FIGURE 4.—Approximate locations and depths of Pleistocene channels.

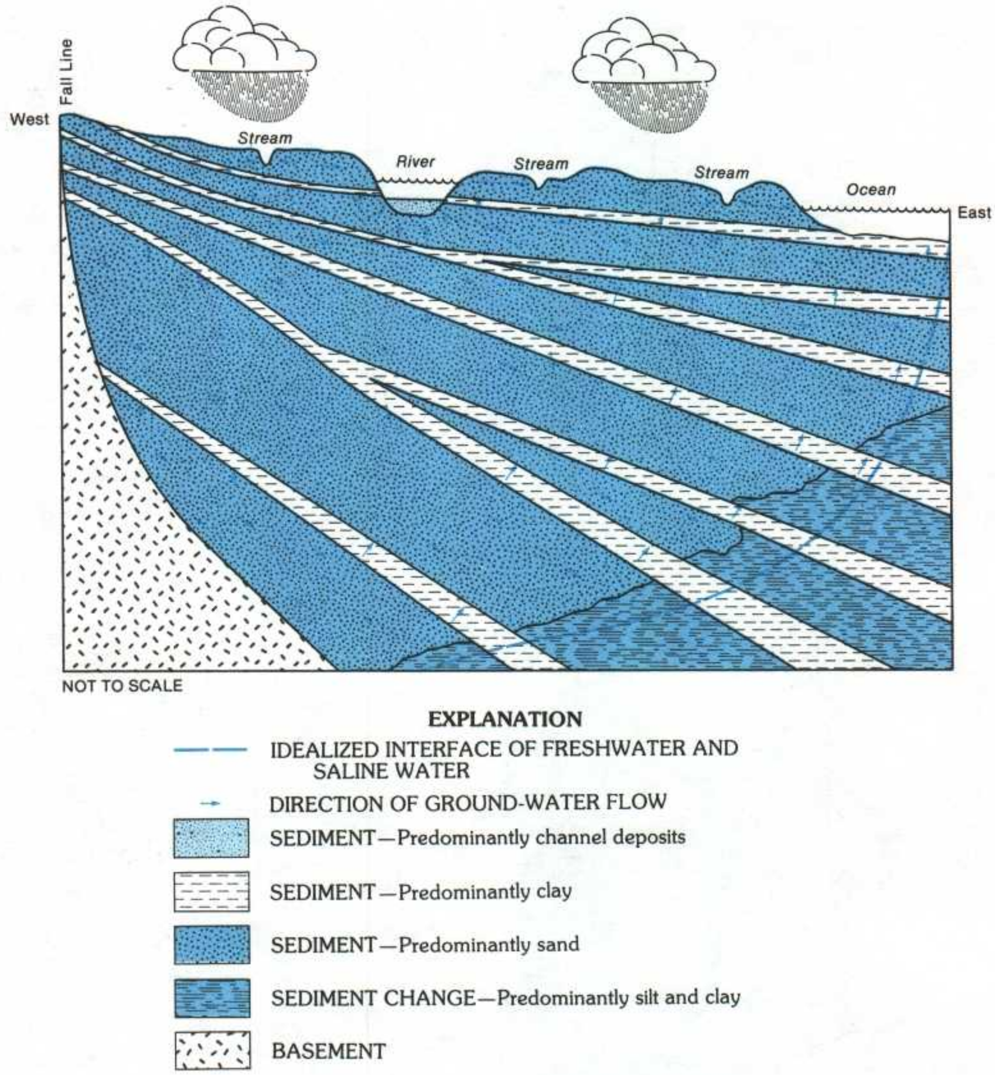


FIGURE 5.—Generalized prepumping ground-water flow system.

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 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).

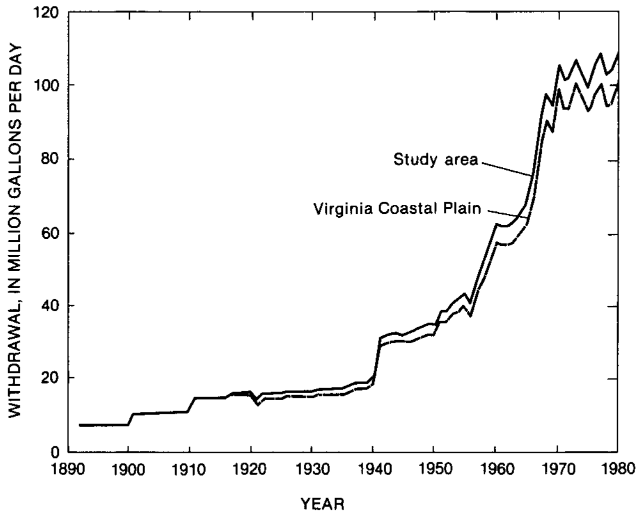


FIGURE 6.—Estimated annual ground-water withdrawal from Coastal Plain aquifers, 1891–1980.

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

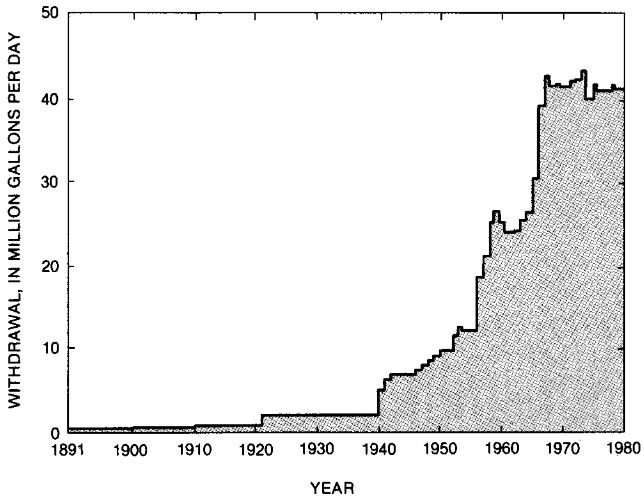


FIGURE 7.—Average annual withdrawal from the lower, middle, and upper Potomac aquifers in the Franklin area, Virginia, 1891–1980.

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.

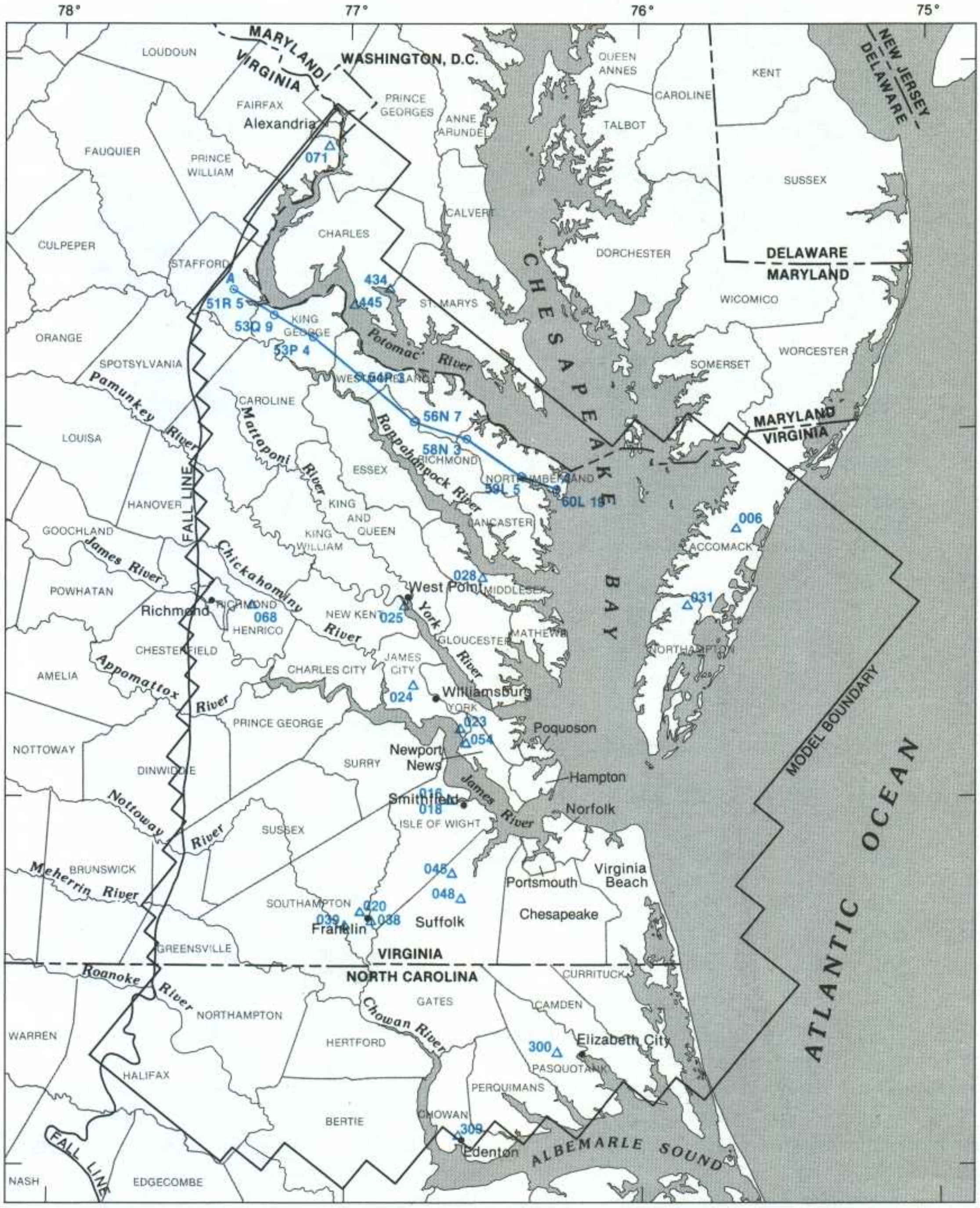
MODEL DESCRIPTION

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.

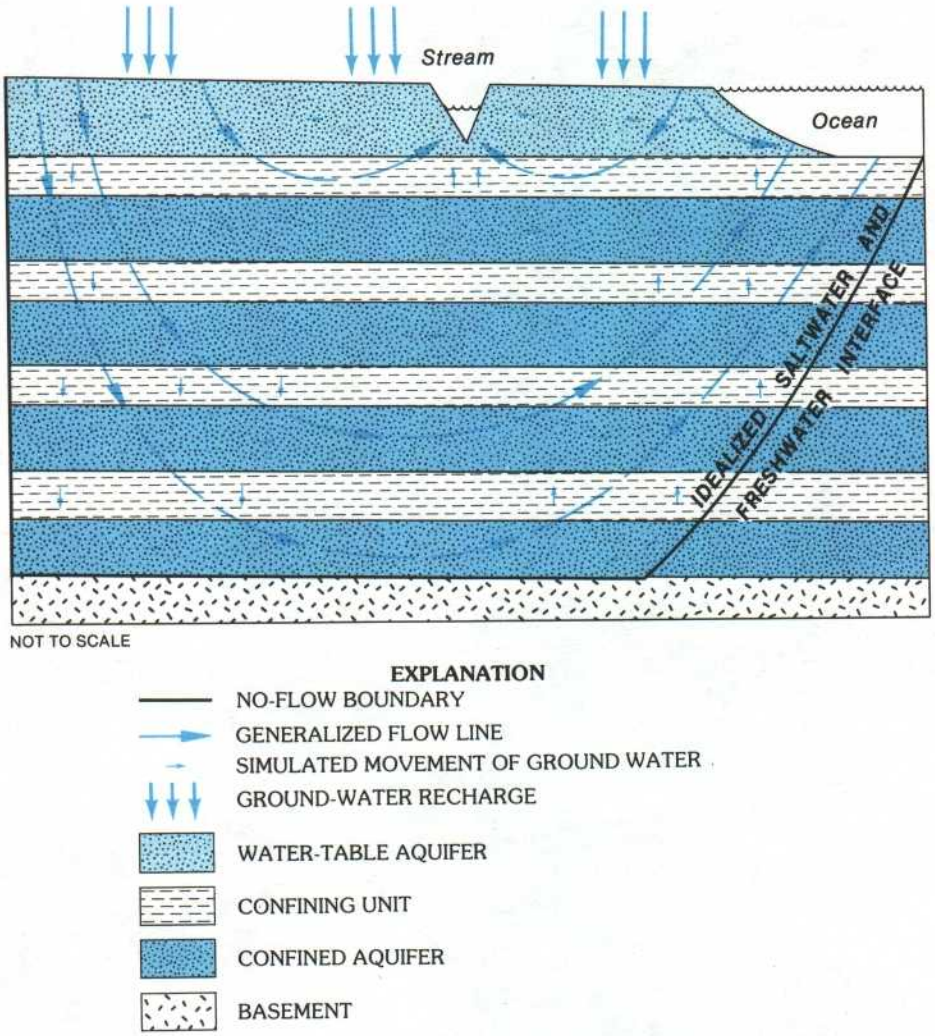


FIGURE 9.—Model conceptualization of prepumping ground-water system.

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-

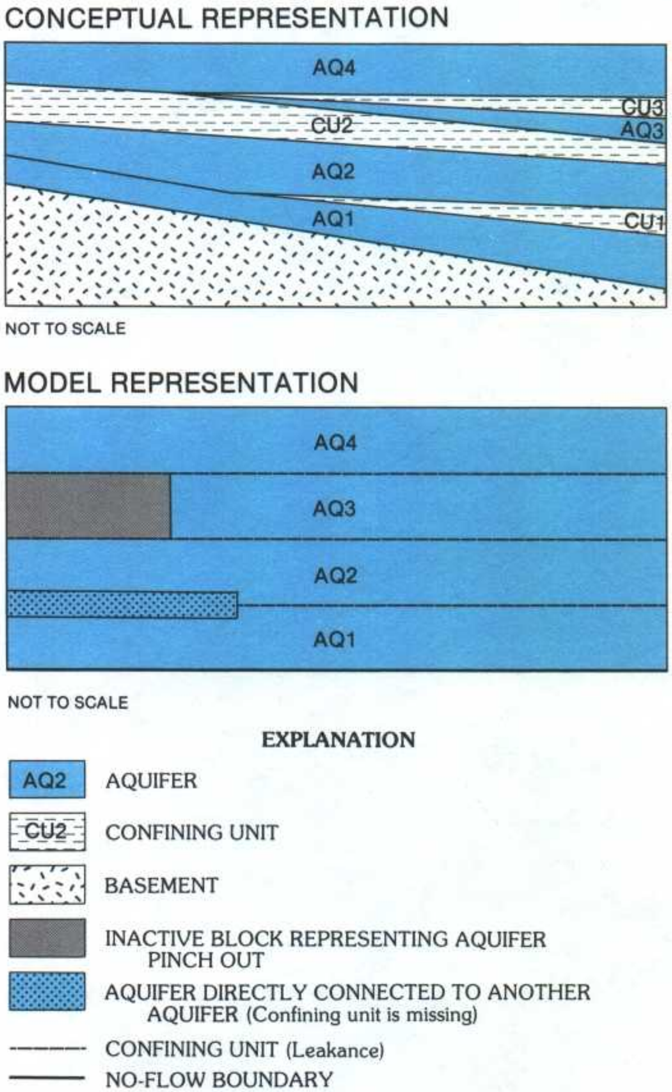


FIGURE 10.—Conceptual and model representations of aquifers and confining units.

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

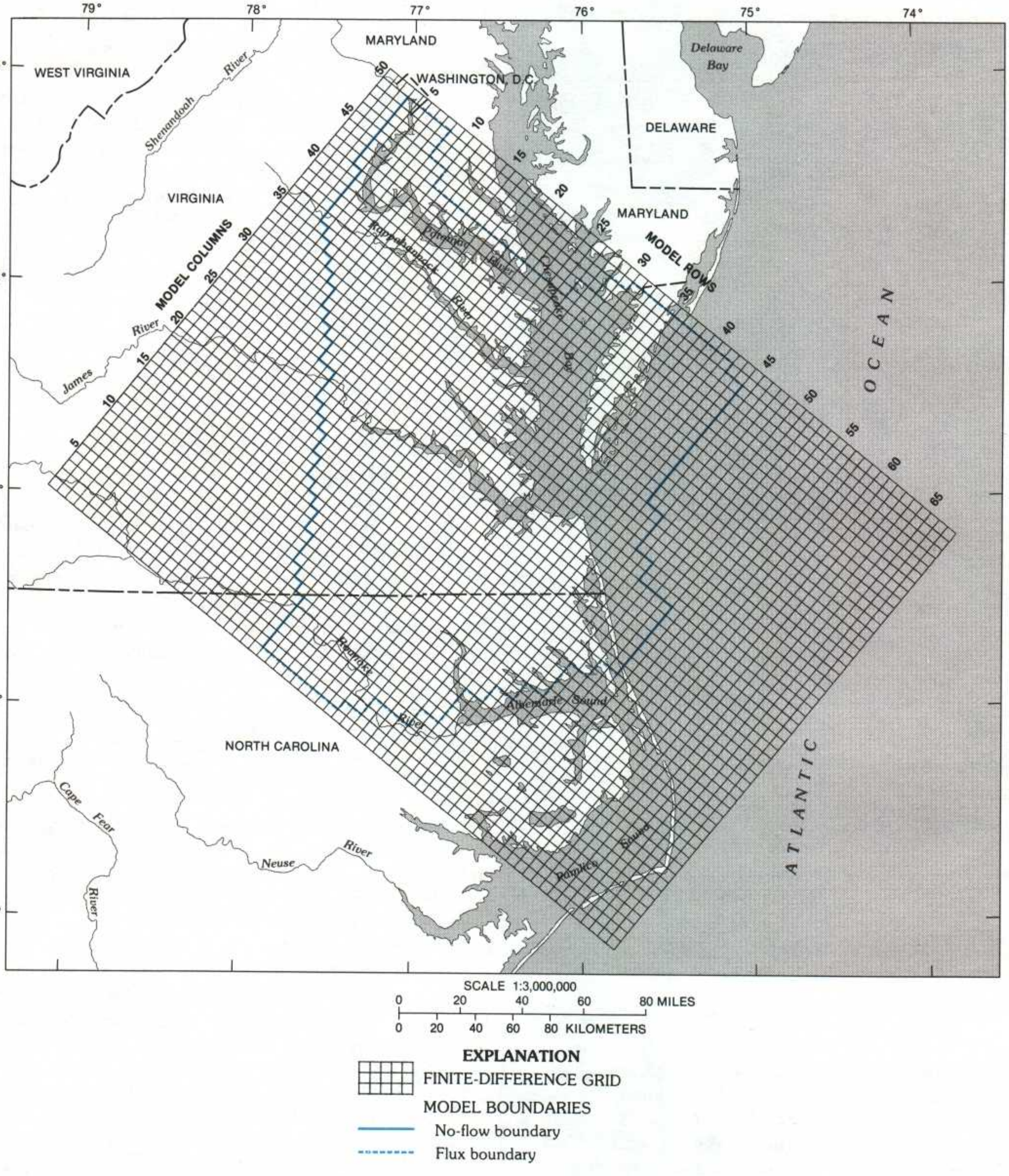


FIGURE 11.—Finite-difference grid and model boundaries.

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

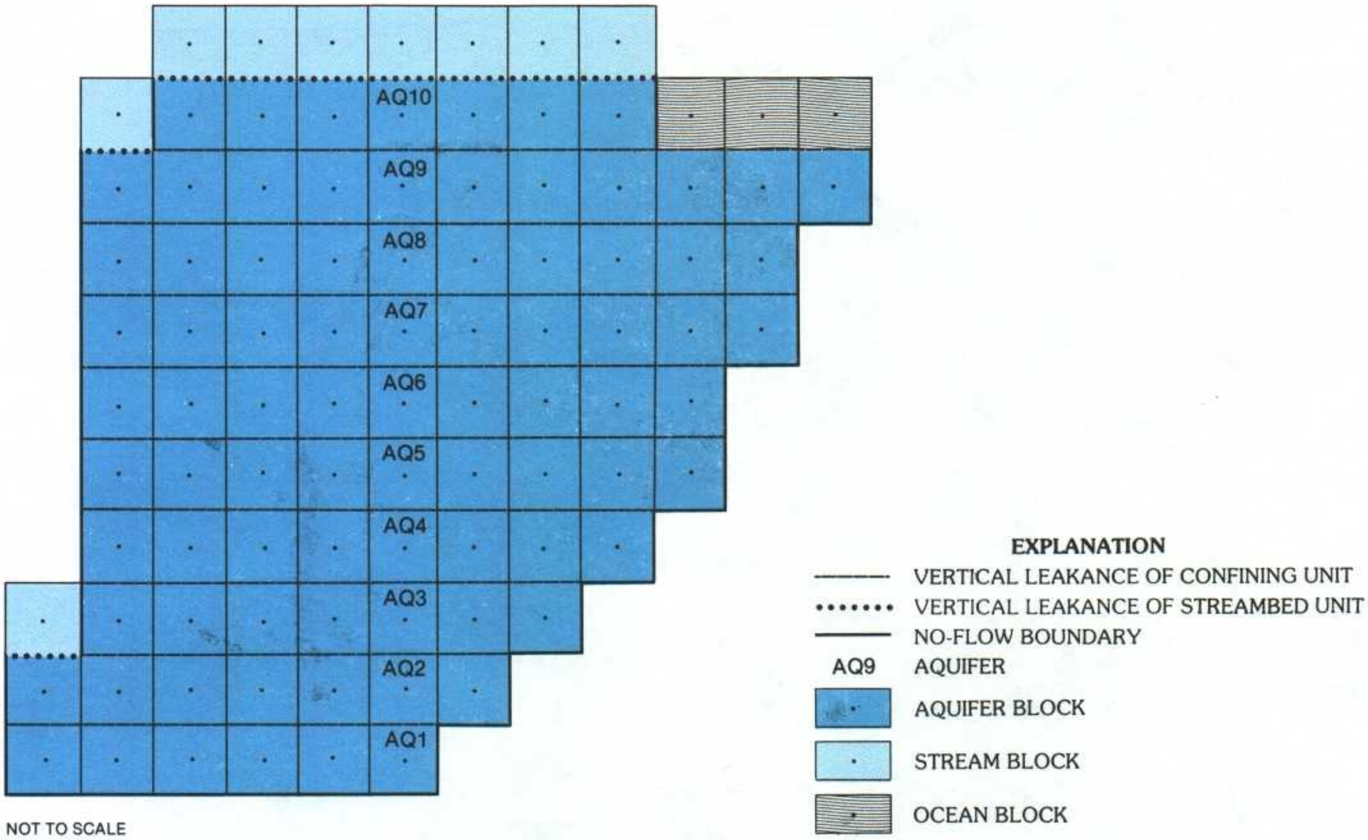


FIGURE 12.—Cross section of finite-difference grid and boundary conditions.

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

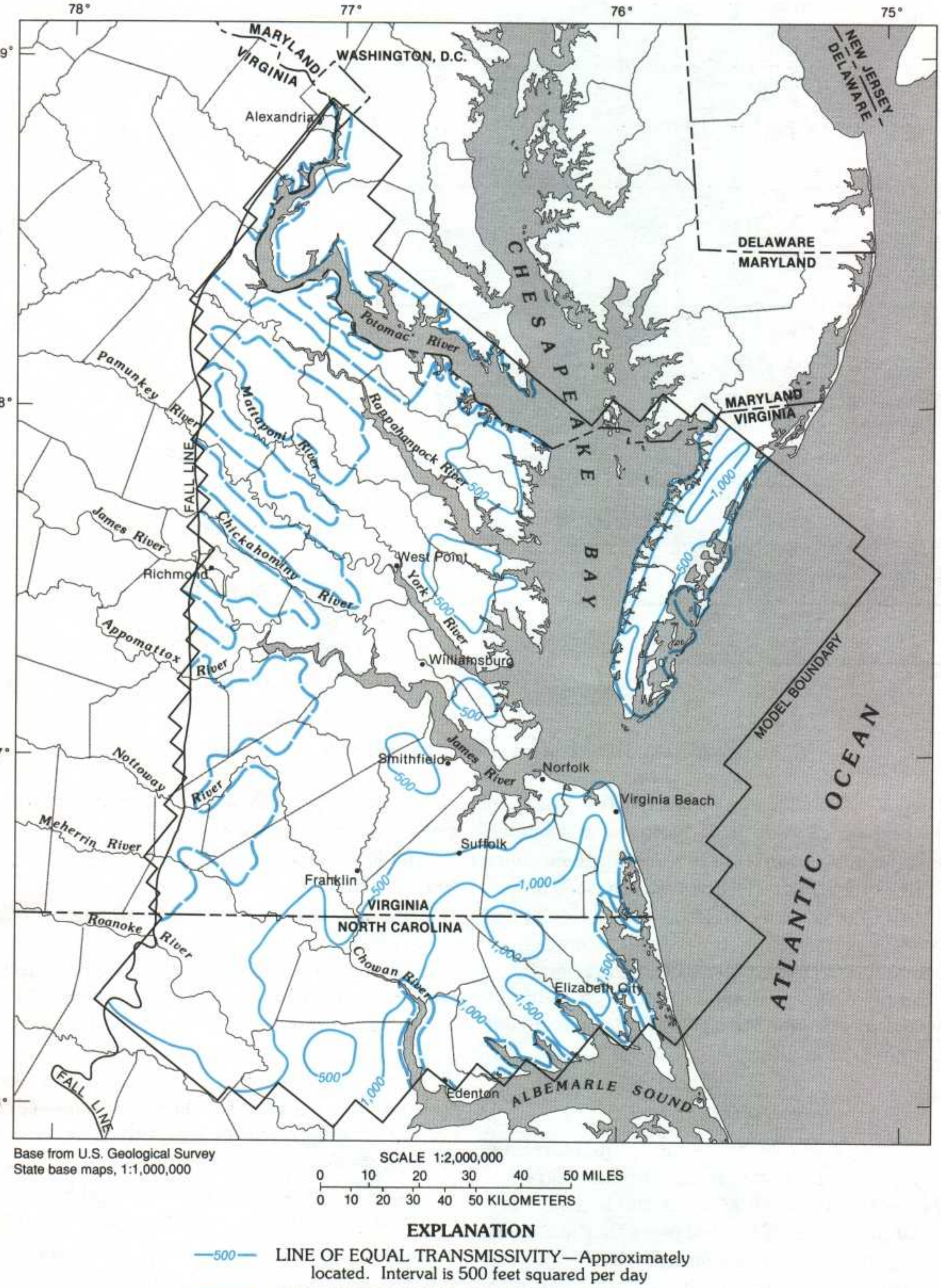
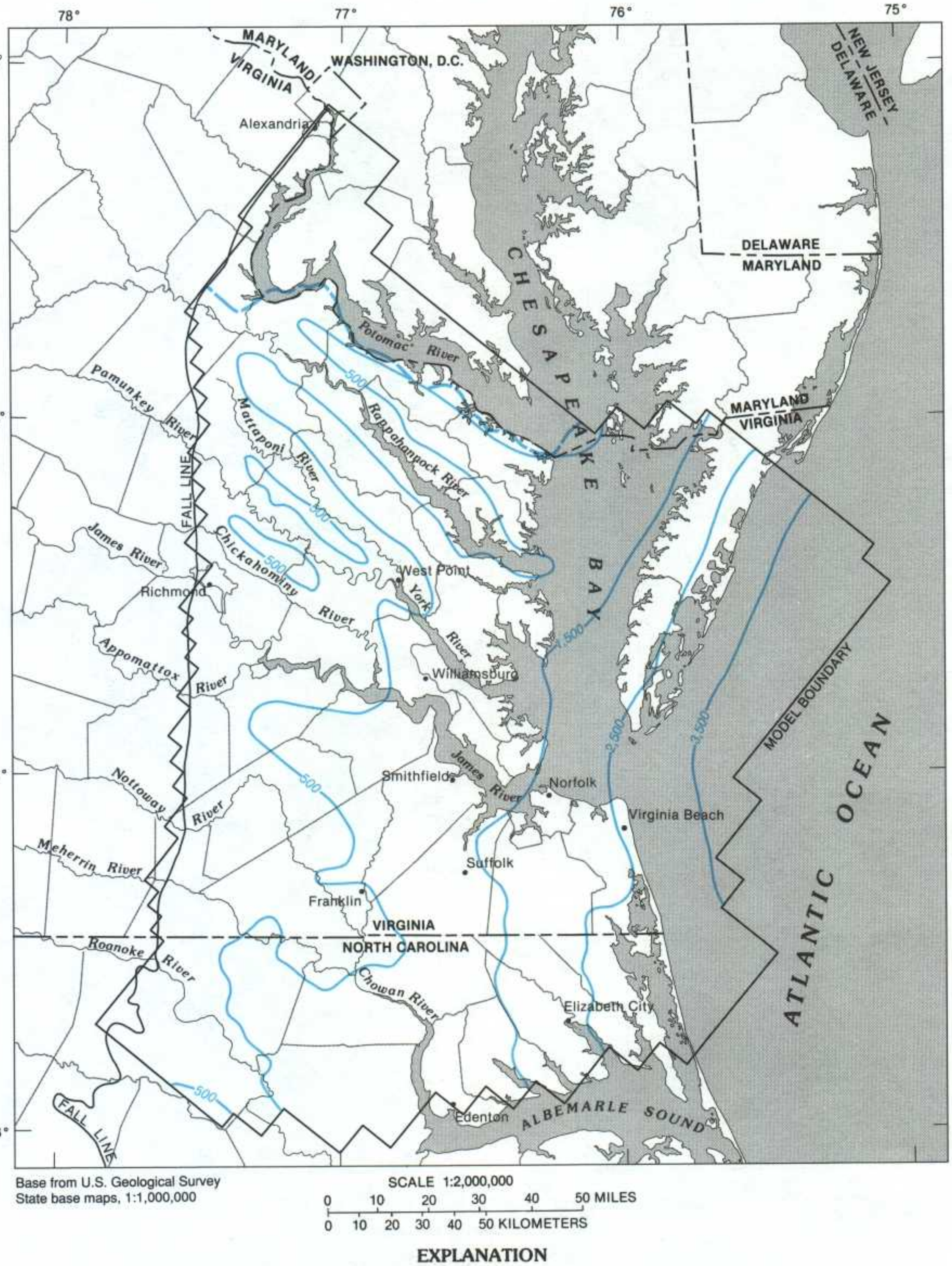


FIGURE 13.—Transmissivity of the Columbia aquifer used in model simulations.



EXPLANATION

—500— LINE OF EQUAL TRANSMISSIVITY—Approximately located. Interval, in feet squared per day, is variable

— — APPROXIMATE LIMIT OF YORKTOWN-EASTOVER AQUIFER

FIGURE 14.—Transmissivity of the Yorktown-Eastover aquifer used in model simulations.

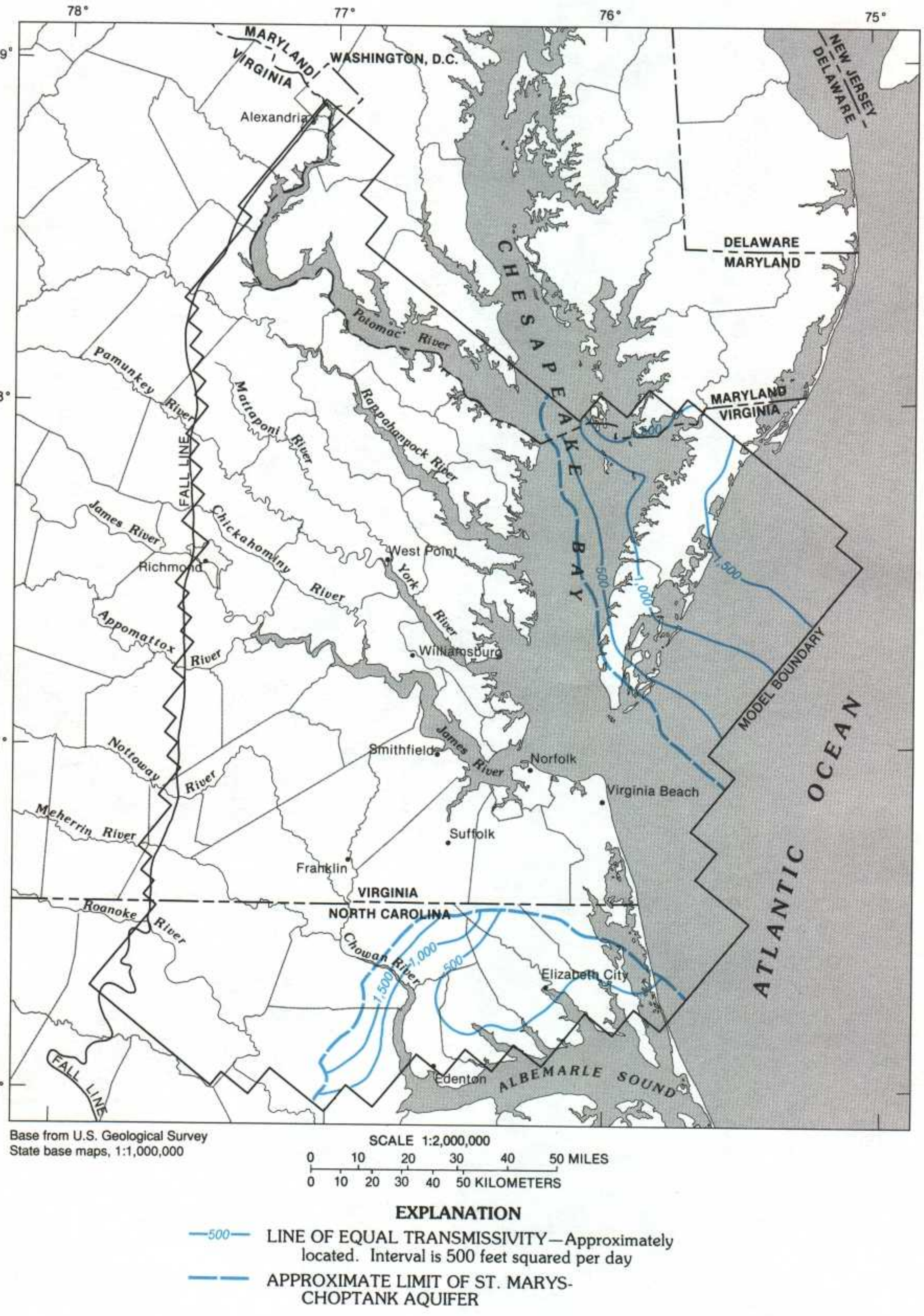


FIGURE 15.—Transmissivity of the St. Marys-Choptank aquifer used in model simulations.

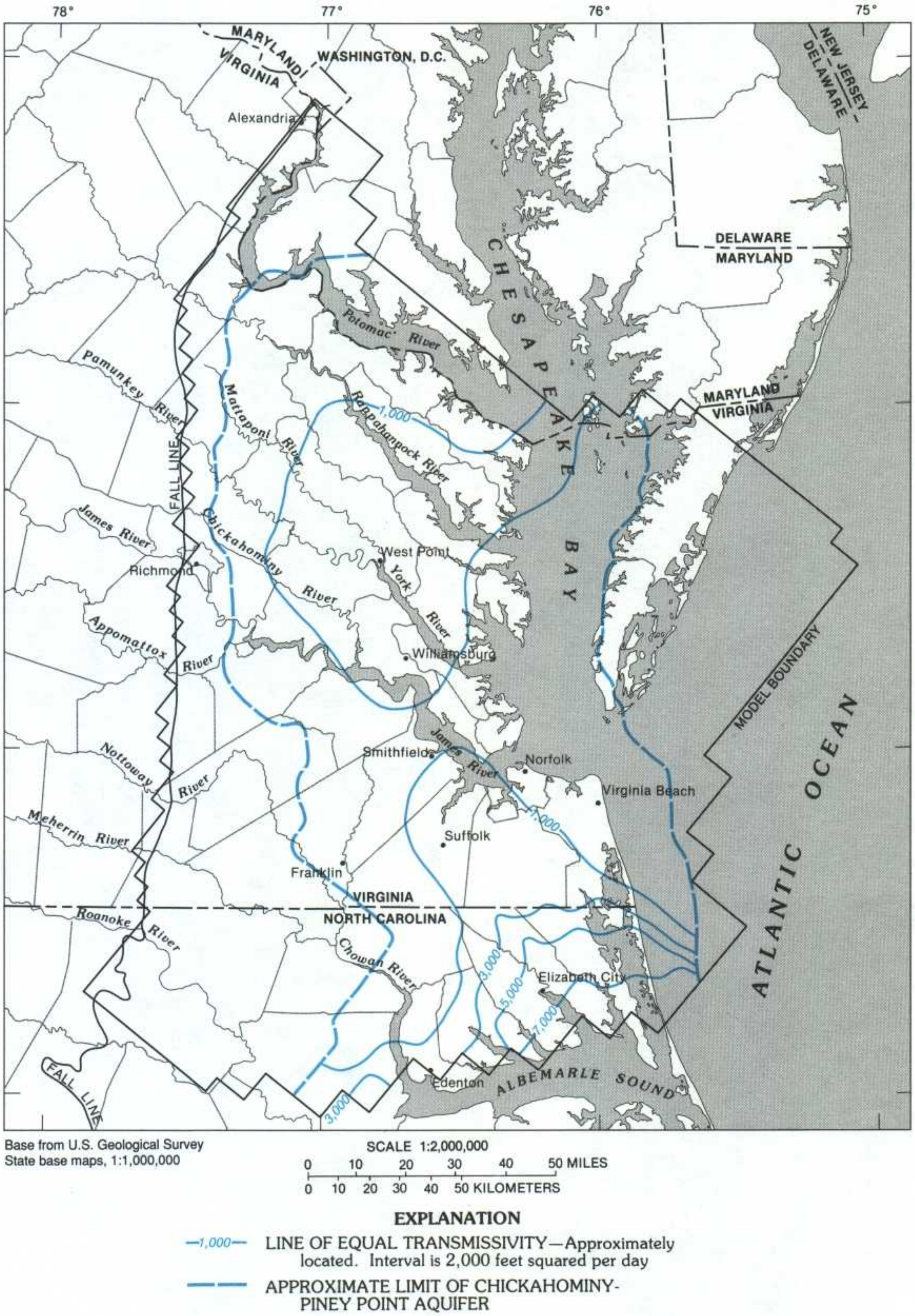
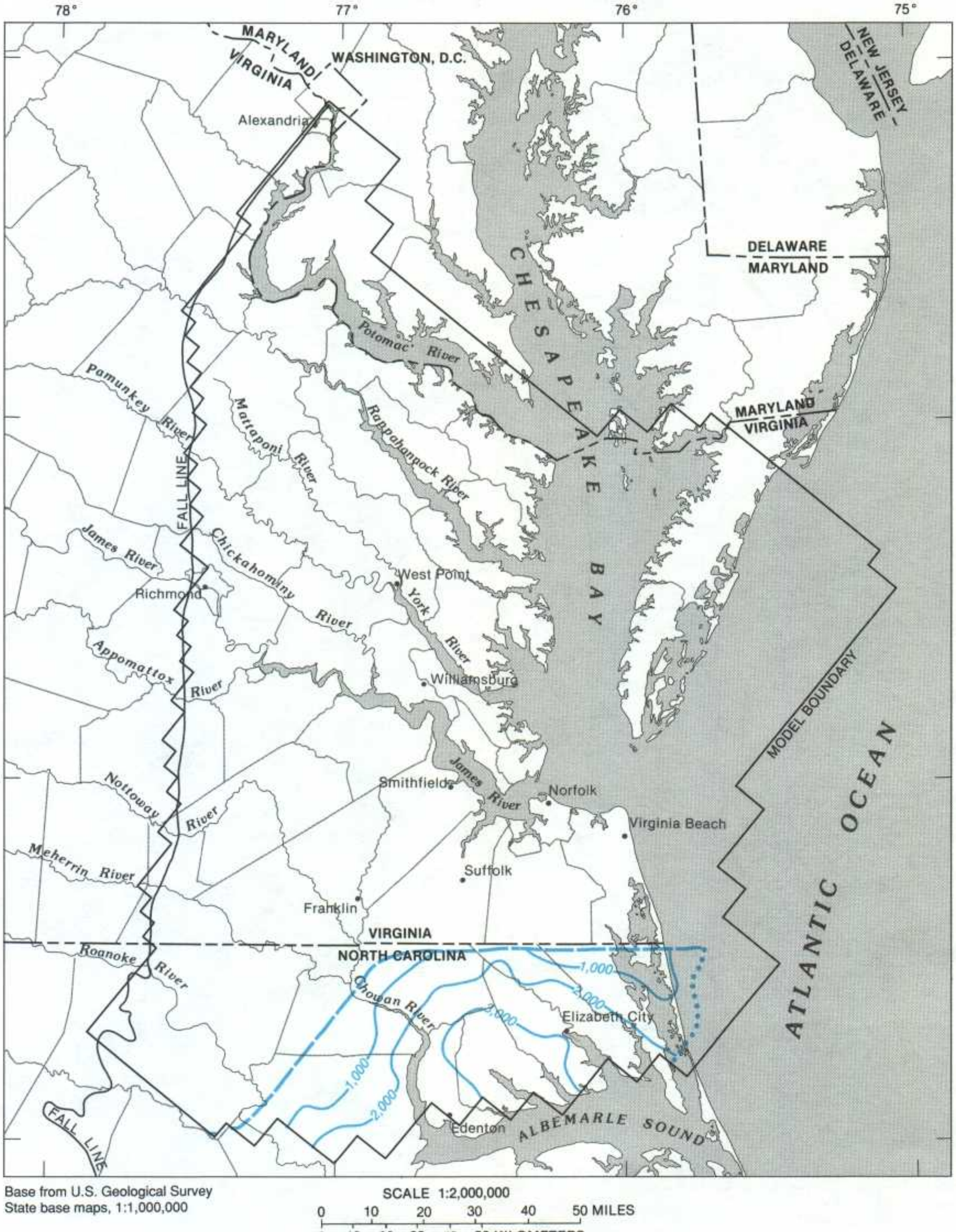


FIGURE 16.—Transmissivity of the Chickahominy-Piney Point aquifer used in model simulations.

FIGURE 17.—Transmissivity of the Aquia aquifer used in model simulations.



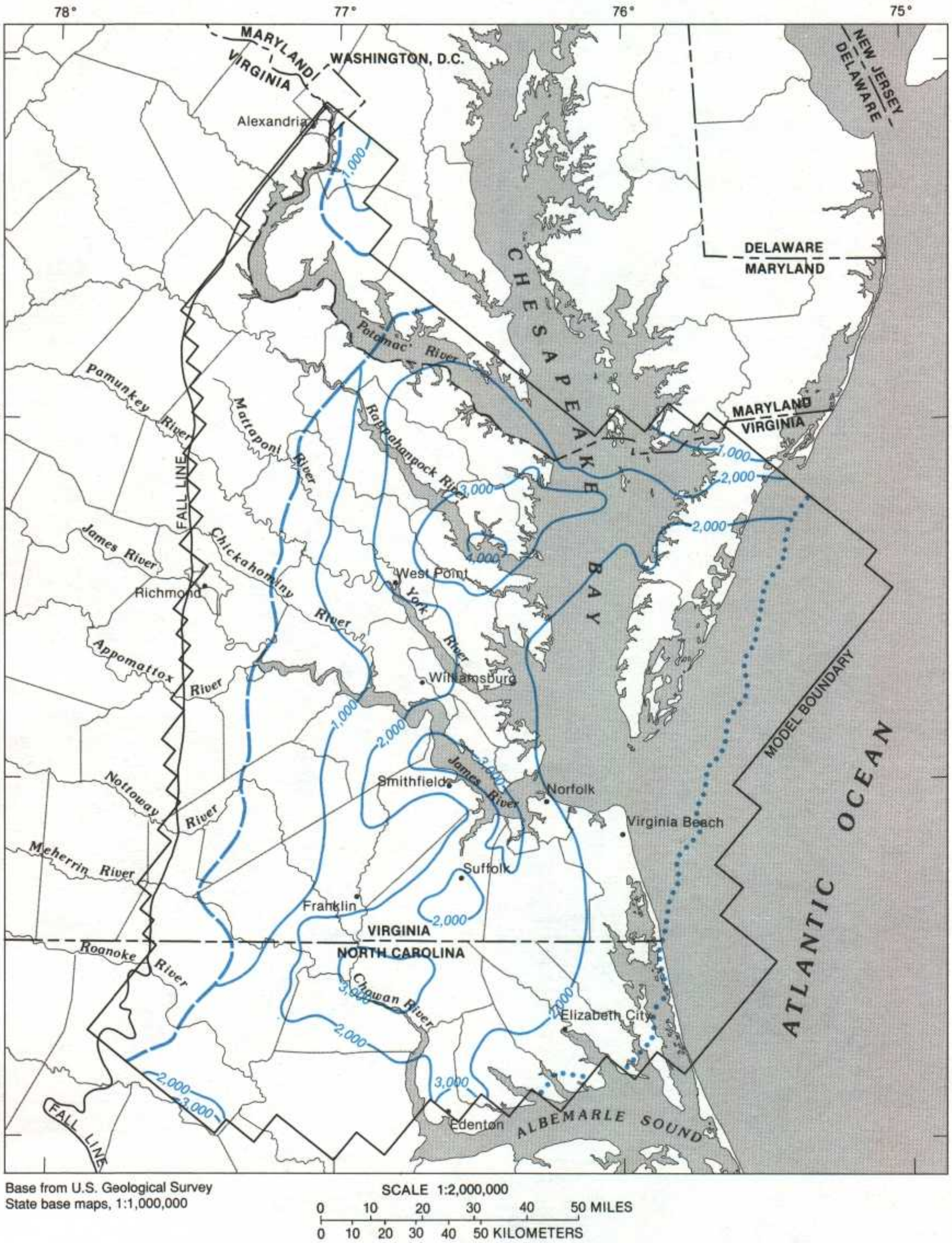
EXPLANATION

—1,000— LINE OF EQUAL TRANSMISSIVITY—Approximately located. Interval is 1,000 feet squared per day

— — APPROXIMATE LIMIT OF AQUIFER 4

••••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

FIGURE 18.—Transmissivity of aquifer 4 used in model simulations.



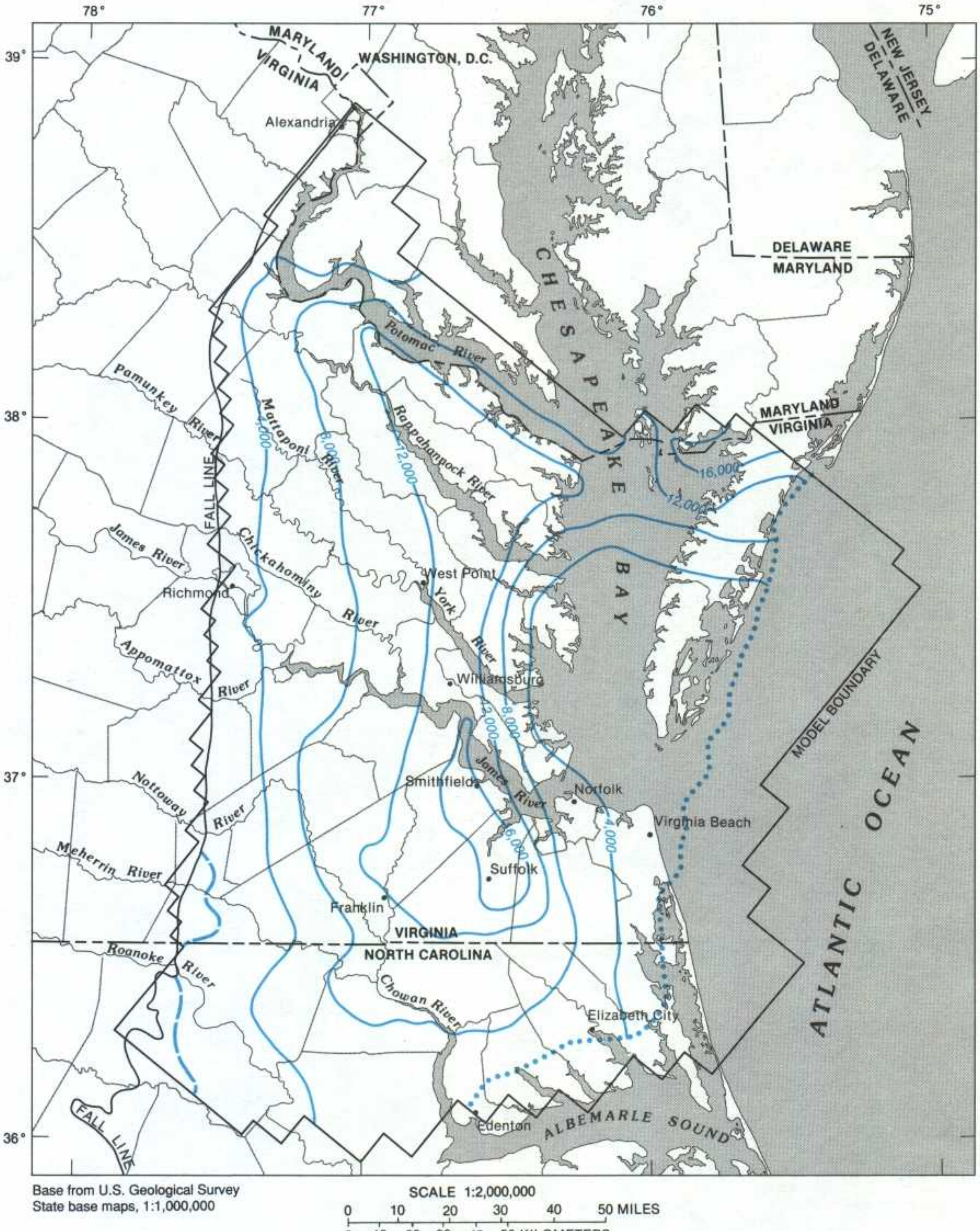
EXPLANATION

—1,000— LINE OF EQUAL TRANSMISSIVITY—Approximately located. Interval is 1,000 feet squared per day

— — APPROXIMATE LIMIT OF BRIGHTSEAT-UPPER POTOMAC AQUIFER

•••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 miligrams per liter chloride

FIGURE 19.—Transmissivity of the Brightseat-upper Potomac aquifer used in model simulations.



EXPLANATION

–12,000– LINE OF EQUAL TRANSMISSIVITY—Approximately located. Interval is 4,000 feet squared per day

—— APPROXIMATE LIMIT OF MIDDLE POTOMAC AQUIFER

•••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

FIGURE 20.—Transmissivity of the middle Potomac aquifer used in model simulations.

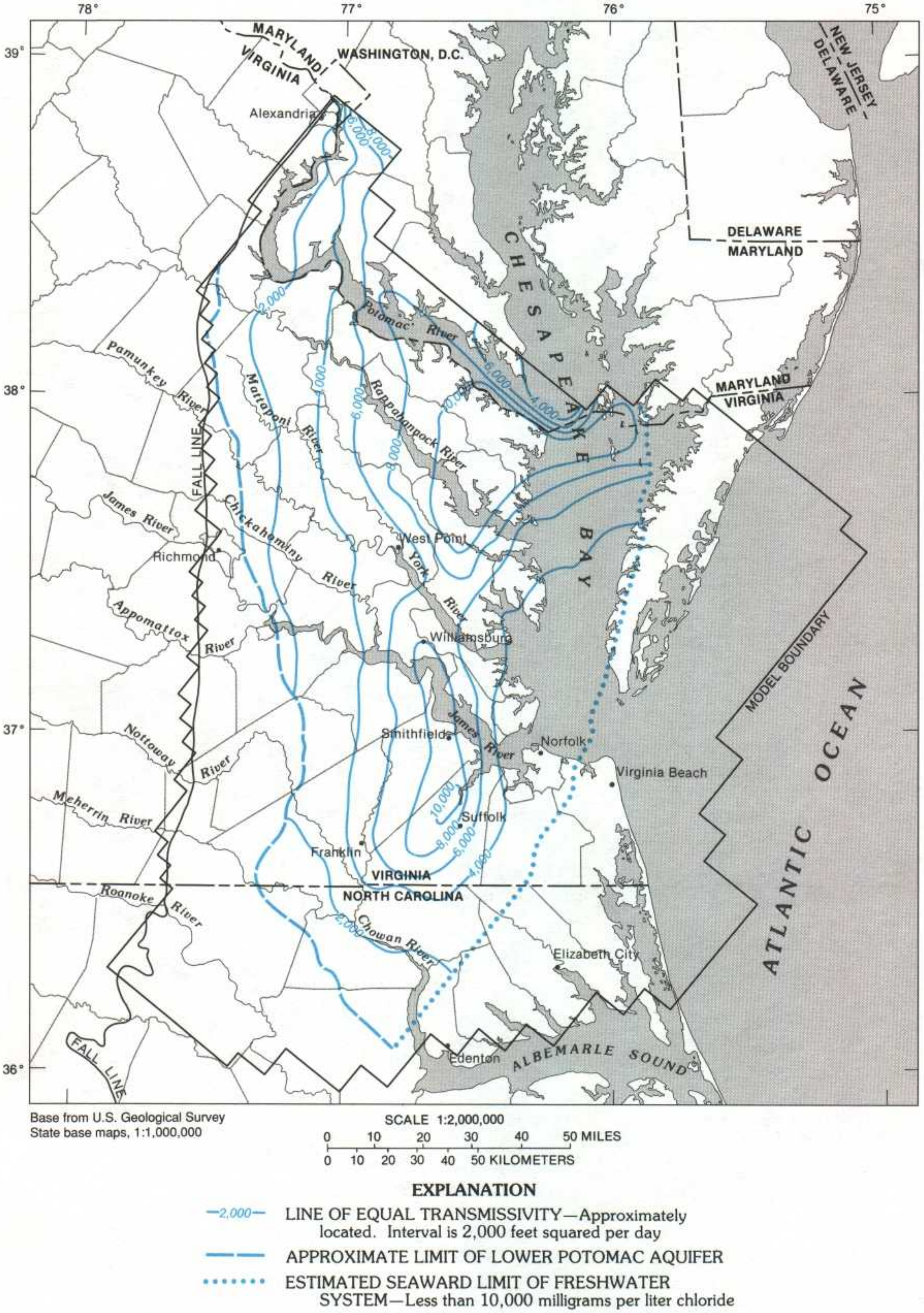


FIGURE 21.—Transmissivity of the lower Potomac aquifer used in model simulations.

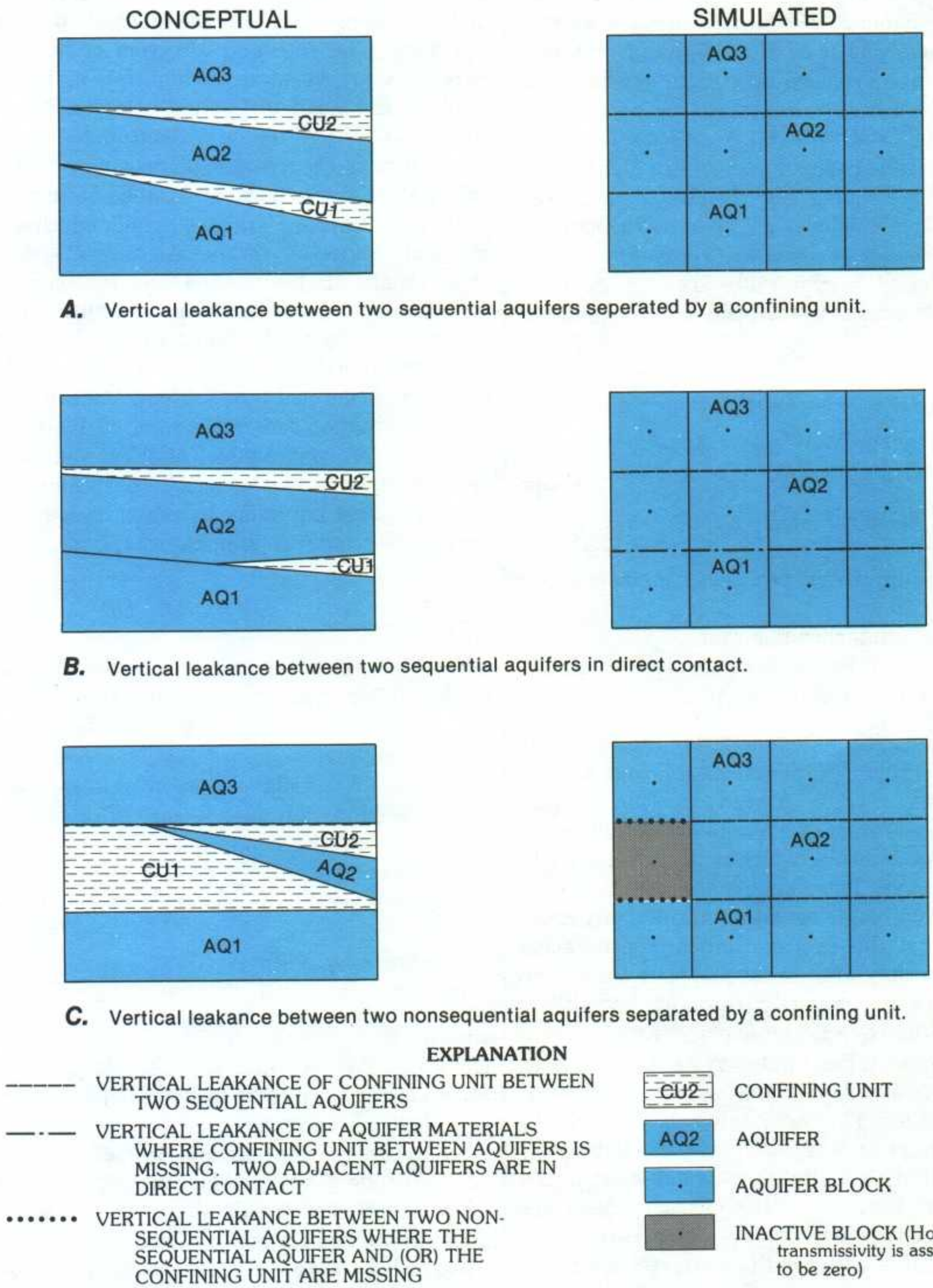


FIGURE 22.—Schematic diagrams of the conceptual and simulated aquifer contacts.

by assigning a zero transmissivity. To allow vertical flow between two nonsequential blocks, leakance values are needed to connect the nonsequential aquifers. Leakance values for missing confining units were computed by multiplying the leakance value calculated for the existing confining unit by the number of simulated confining units between the nonsequential aquifers. This procedure allowed vertical flow between the nonsequential aquifer blocks and simulated the true vertical leakage between aquifers.

In areas where confining unit material was eroded and replaced by more permeable stream deposits, vertical leakance was increased one or two orders of magnitude (Chapelle and Drummond, 1983). An increase of two orders of magnitude was used if a confining unit was completely eroded and replaced by stream deposits. An order-of-magnitude increase was used for a confining unit partially eroded and replaced by stream deposits. The degree of hydraulic connection between the stream and the aquifer underlying the confining unit was increased with this procedure. Figures 23 through 30 show the vertical leakance used for simulation of the confining units present in the study area. In general, vertical leakance decreases toward the east as confining units thicken.

Ground-Water Recharge

Recharge entering the water-table aquifer was estimated by the following equation:

$$QRE = P - OF - ET \qquad (1)$$

where

QRE = rate of ground-water recharge, in inches per year;
P = precipitation, in inches per year;
OF = overland flow, in inches per year; and
ET = evapotranspiration, in inches per year.

Average annual precipitation in the study area is about 43 inches per year (in/yr) (National Oceanic and Atmospheric Administration, 1980). A study by Cushing and others (1973, p. 35) shows that average overland flow on the Eastern Shore Peninsula, which is part of the study area, is about 6.5 in/yr. This value is assumed to represent the average hydrologic condition in the study area. About 50 percent of the average annual precipitation (21.5 in/yr) in the study area is estimated to be evaporated and transpired by vegetation (Geraghty and Miller, 1978b; Harsh, 1980). Hence, the average rate of areal recharge to the water-table aquifer system is about 15 in/yr. This value was assigned to blocks representative of the water-table aquifer. The water-table aquifer includes the Columbia aquifer and those parts of underlying aquifers that crop out. A digital-flow-model study in the Coastal Plain of central and southern Delaware (Johnston, 1977) shows that 14 in/yr is a good estimate of the long-term recharge rate for the water-table aquifer in the Coastal Plain of Delaware. Undoubtedly, ground-water recharge rates vary spatially throughout the model area; however, data are insufficient to define these local variations. The recharge rate was assumed constant during all model simulations.

Streambed Leakance

Streambed leakance, as used in this report, controls the movement of water between streams and the water-table aquifer. It is defined as the ratio of the vertical hydraulic conductivity of the streambed sediment to its thickness. The rate and direction of flow through the streambed are calculated by multiplying streambed leakance by the head difference between the water-table aquifer and stage in the stream and the area through which flow is occurring. This assumes that the aquifer material adjacent to the streambed is fully saturated.

Few quantitative data are available that define the physical properties of the streambed sediment. However, an alternative method was developed to calculate streambed leakance in order to simulate flow between the water-table aquifer and streams. This method calculates streambed leakance from the simulated flow to the underlying confined flow system, the estimated ground-water recharge, and the estimated hydraulic gradient between the water-table aquifer and streams. The method equates two equations describing stream base flow. The first equation, based on conservation of mass for steady-state, prepumping conditions, is of the form

$$BF = QRE - DP \qquad (2)$$

where

BF = base flow per unit area, in feet per second;
QRE = volumetric rate per unit area of ground-water recharge to water-table aquifer, in feet per second; and
DP = deep percolation or volumetric rate per unit area of flow into (positive) or out of (negative) underlying confined aquifer system, in feet per second.

The second equation, based on Darcy's law, states

$$BF = \frac{K'}{M}(h_a - h_s) = SL\ (h_a - h_s) \qquad (3)$$

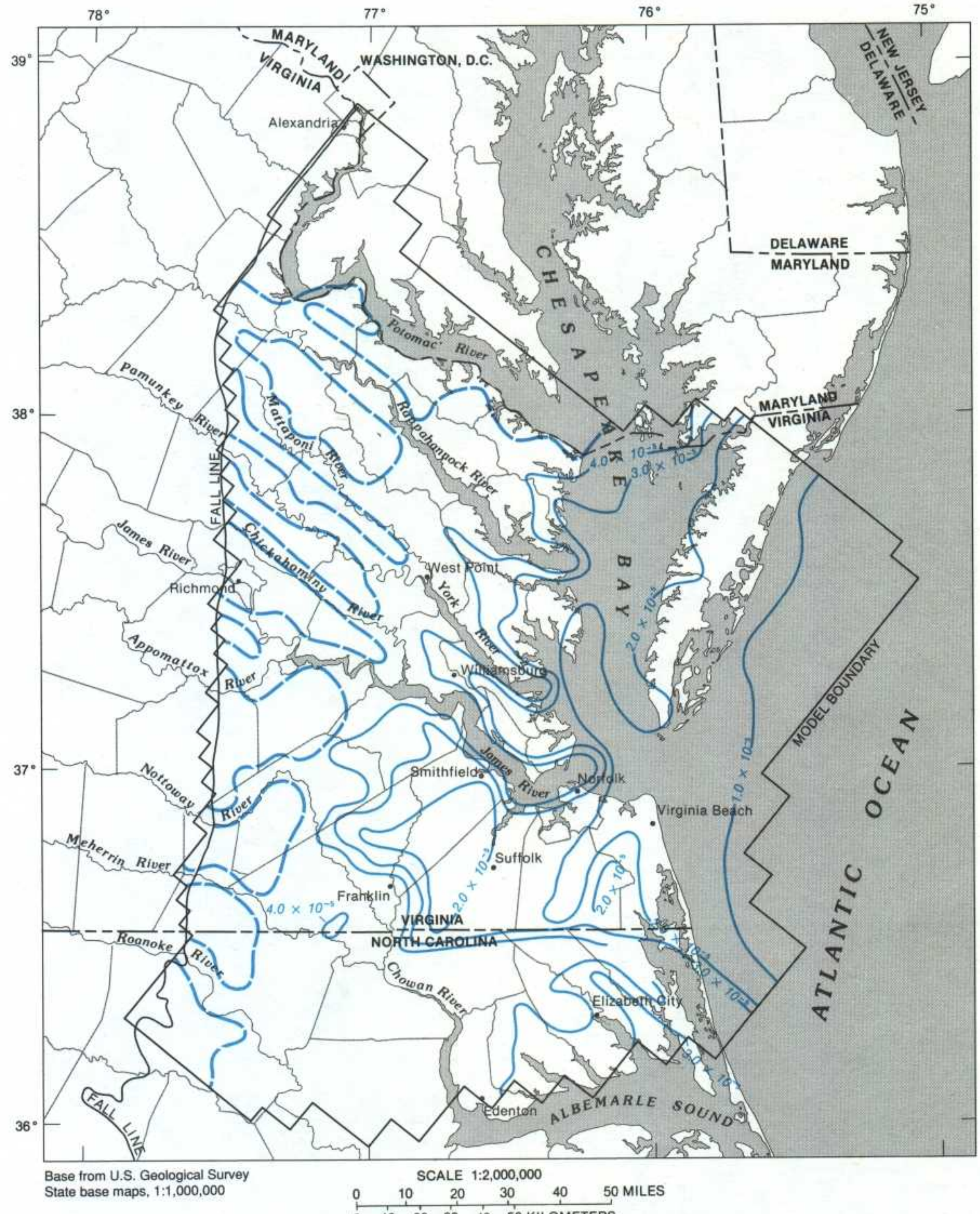
where

BF = base flow per unit area, in feet per second;
K' = vertical hydraulic conductivity of streambed, in feet per second;
M = thickness of streambed, in feet;
h_a = altitude of water table, in feet;
h_s = elevation of stream stage, in feet; and
SL = streambed leakance, in seconds^{-1}.

Equating the two expressions for base flow results in the following expression:

$$SL = \frac{QRE - DP}{(h_a - h_s)} \qquad (4)$$

The method requires calculation of deep percolation (DP), the volumetric rate of water per unit area moving between the confined flow system and the water-table aquifer. Block values of deep percolation were computed

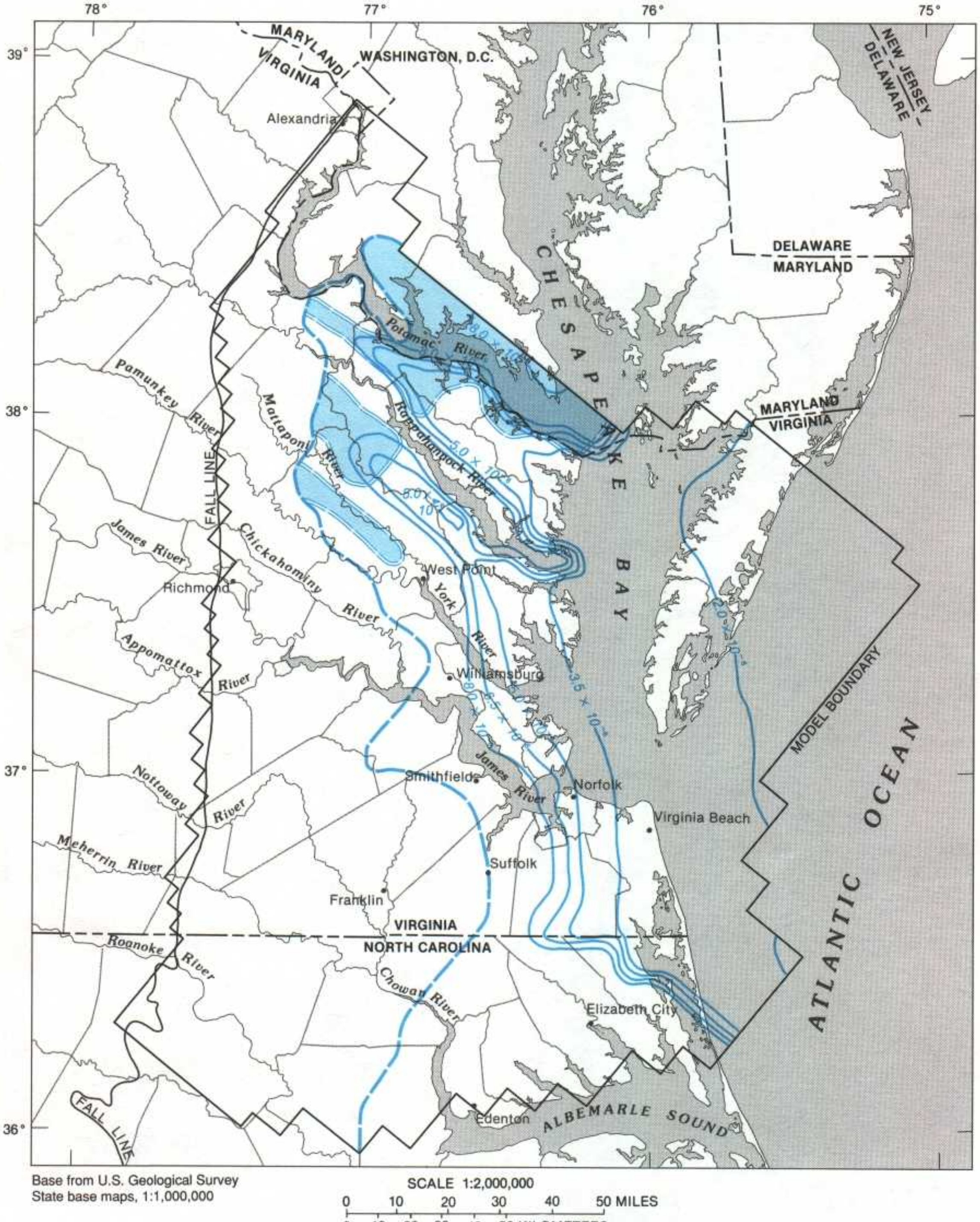


EXPLANATION

1.0×10^{-5} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 1.0×10^{-5} day^{-1}

APPROXIMATE LIMIT OF YORKTOWN CONFINING UNIT

FIGURE 23.—Vertical leakance of the Yorktown confining unit used in model simulations.



EXPLANATION

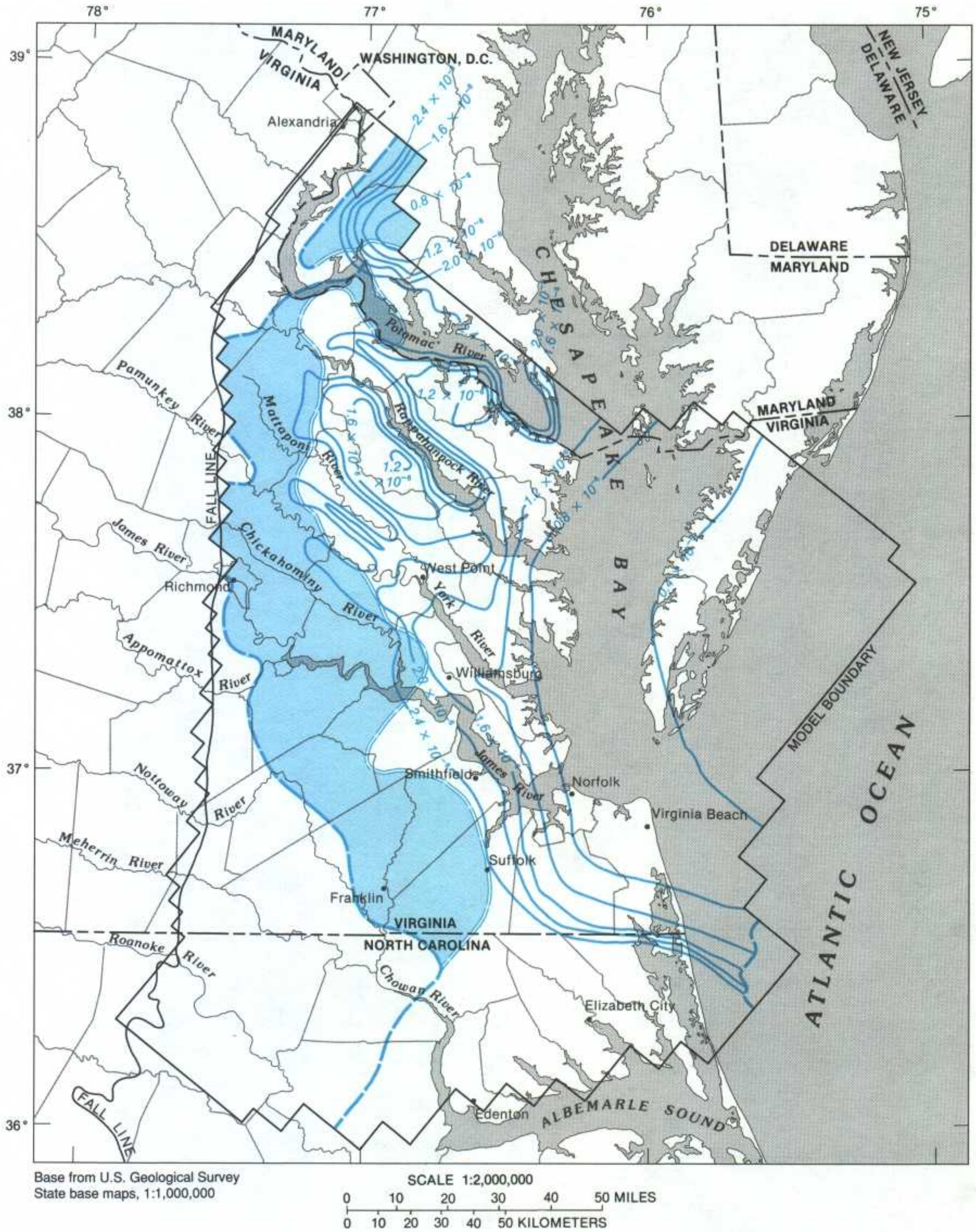
-8.0×10⁻⁵ APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 1.5×10^{-6} day^{-1}

APPROXIMATE LIMIT OF ST. MARYS CONFINING UNIT

APPROXIMATE LIMIT OF YORKTOWN CONFINING UNIT

AREAS REQUIRING MODIFICATION OF THE CALCULATED VALUE OF LEAKANCE BECAUSE UPPER CONFINING UNIT MISSING—Discussed in the section "Vertical Leakance"

FIGURE 24.—Vertical leakance of the St. Marys confining unit used in model simulations.



EXPLANATION

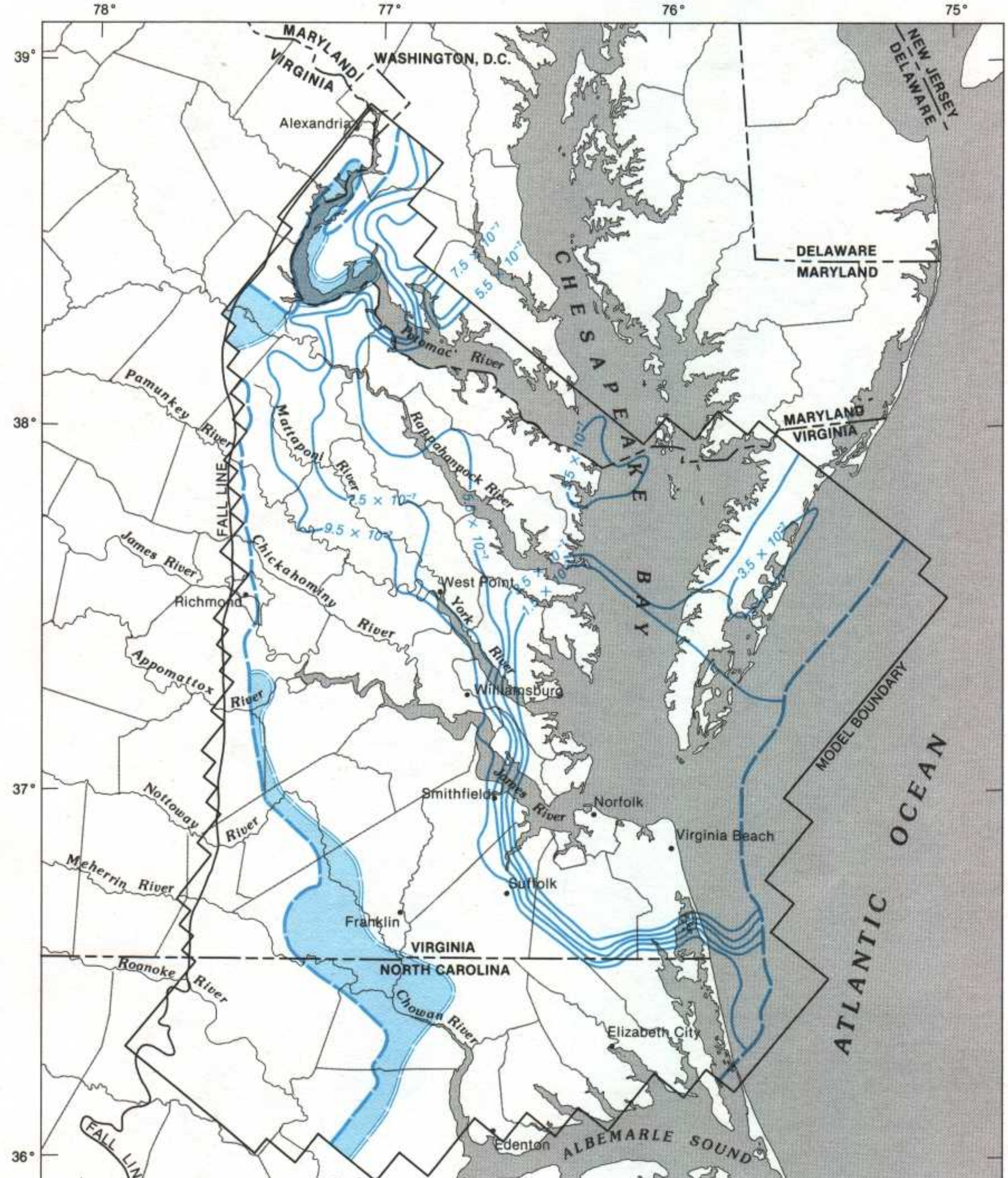
2.4 × 10⁻⁶ APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity/confining unit thickness. Interval is 0.4×10^{-6} day^{-1}

APPROXIMATE LIMIT OF CALVERT CONFINING UNIT

APPROXIMATE LIMIT OF ST. MARYS CONFINING UNIT

AREA REQUIRING MODIFICATION OF THE CALCULATED VALUE OF LEAKANCE BECAUSE UPPER CONFINING UNIT MISSING—Discussed in the section "Vertical Leakance"

FIGURE 25.—Vertical leakance of the Calvert confining unit used in model simulations.



EXPLANATION

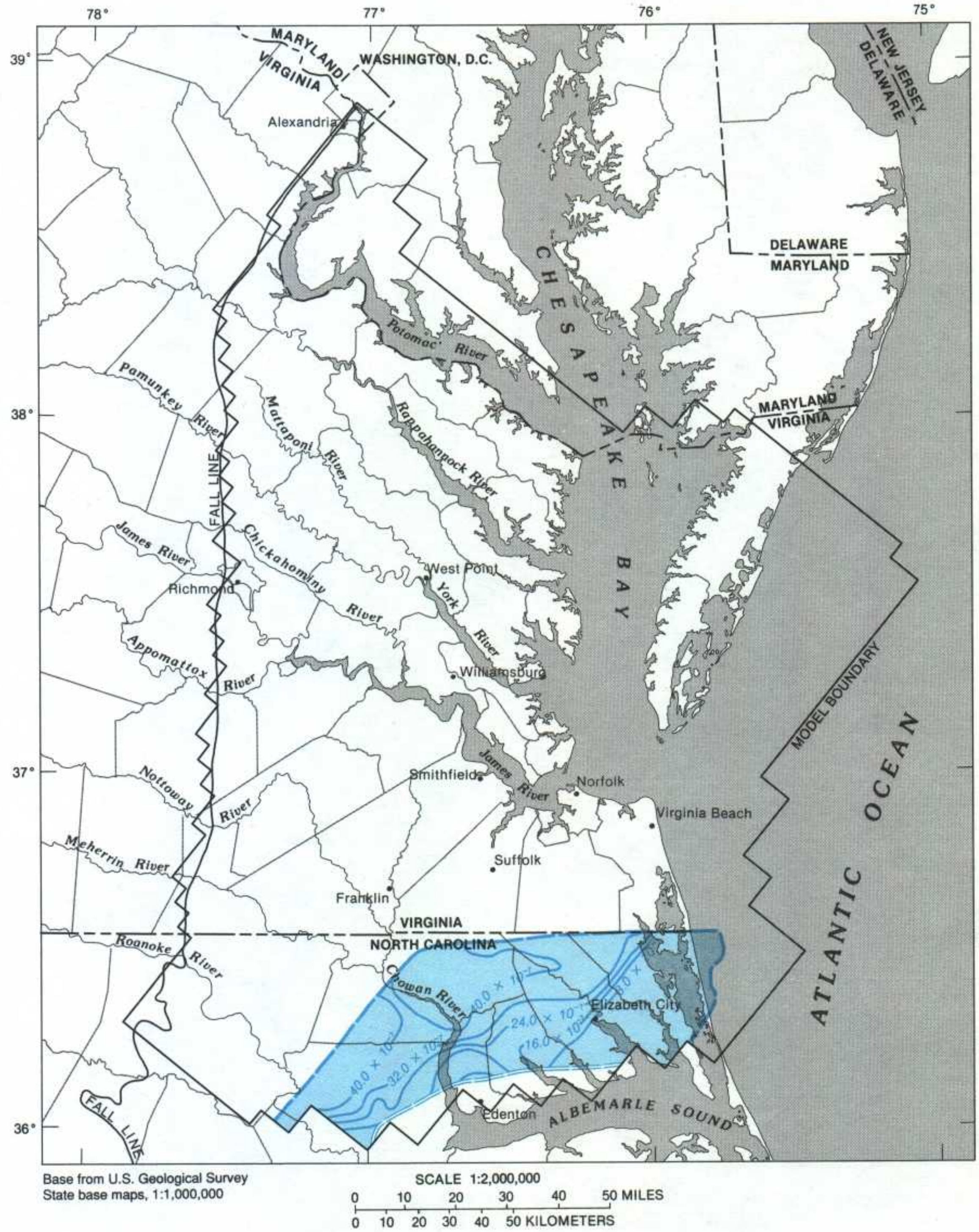
—3.5×10⁻⁷ APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 2.0×10^{-7} day^{-1}

APPROXIMATE LIMIT OF NANJEMOY-MARLBORO CONFINING UNIT

APPROXIMATE LIMIT OF CALVERT CONFINING UNIT

AREAS REQUIRING MODIFICATION OF THE CALCULATED VALUE OF LEAKANCE BECAUSE UPPER CONFINING UNIT MISSING—Discussed in the section "Vertical Leakance"

FIGURE 26.—Vertical leakance of the Nanjemoy-Marlboro confining unit used in model simulations.



EXPLANATION

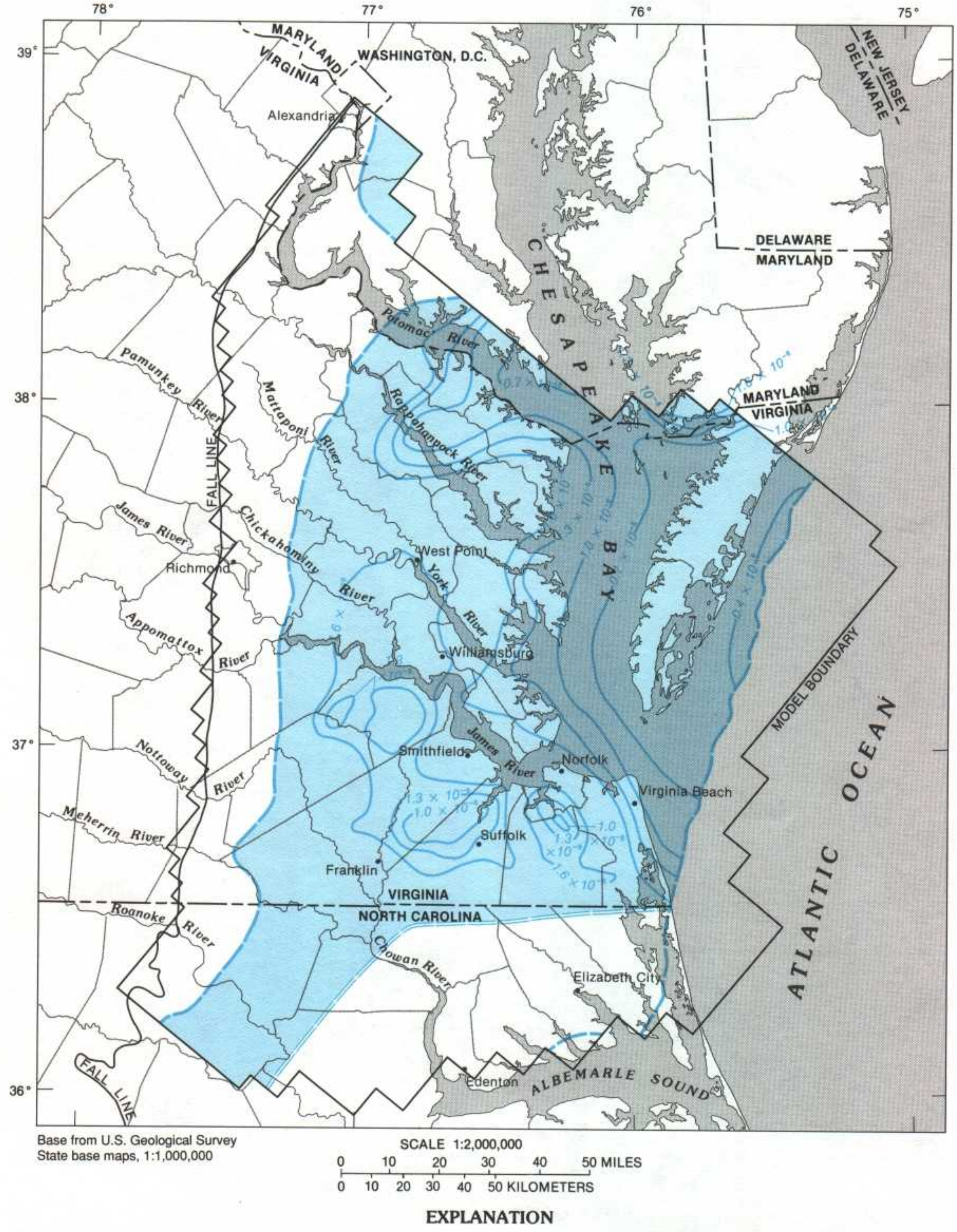
8.0×10^{-7} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 8.0×10^{-7} day^{-1}

APPROXIMATE LIMIT OF CONFINING UNIT 4

APPROXIMATE LIMIT OF CONFINING UNIT 5

AREAS REQUIRING MODIFICATION OF THE CALCULATED VALUE OF LEAKANCE BECAUSE UPPER CONFINING UNIT MISSING—Discussed in the section "Vertical Leakance"

FIGURE 27.—Vertical leakance of confining unit 4 used in model simulations.



EXPLANATION

-1.6×10^{-6} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is $.03 \times 10^{-6}$ day^{-1}

APPROXIMATE LIMIT OF BRIGHTSEAT-UPPER POTOMAC CONFINING UNIT

APPROXIMATE LIMIT OF CONFINING UNIT 4

AREAS REQUIRING MODIFICATION OF THE CALCULATED VALUE OF LEAKANCE BECAUSE UPPER CONFINING UNIT MISSING—Discussed in the section "Vertical Leakance"

FIGURE 28.—Vertical leakance of the Brightseat-upper Potomac confining unit used in model simulations.

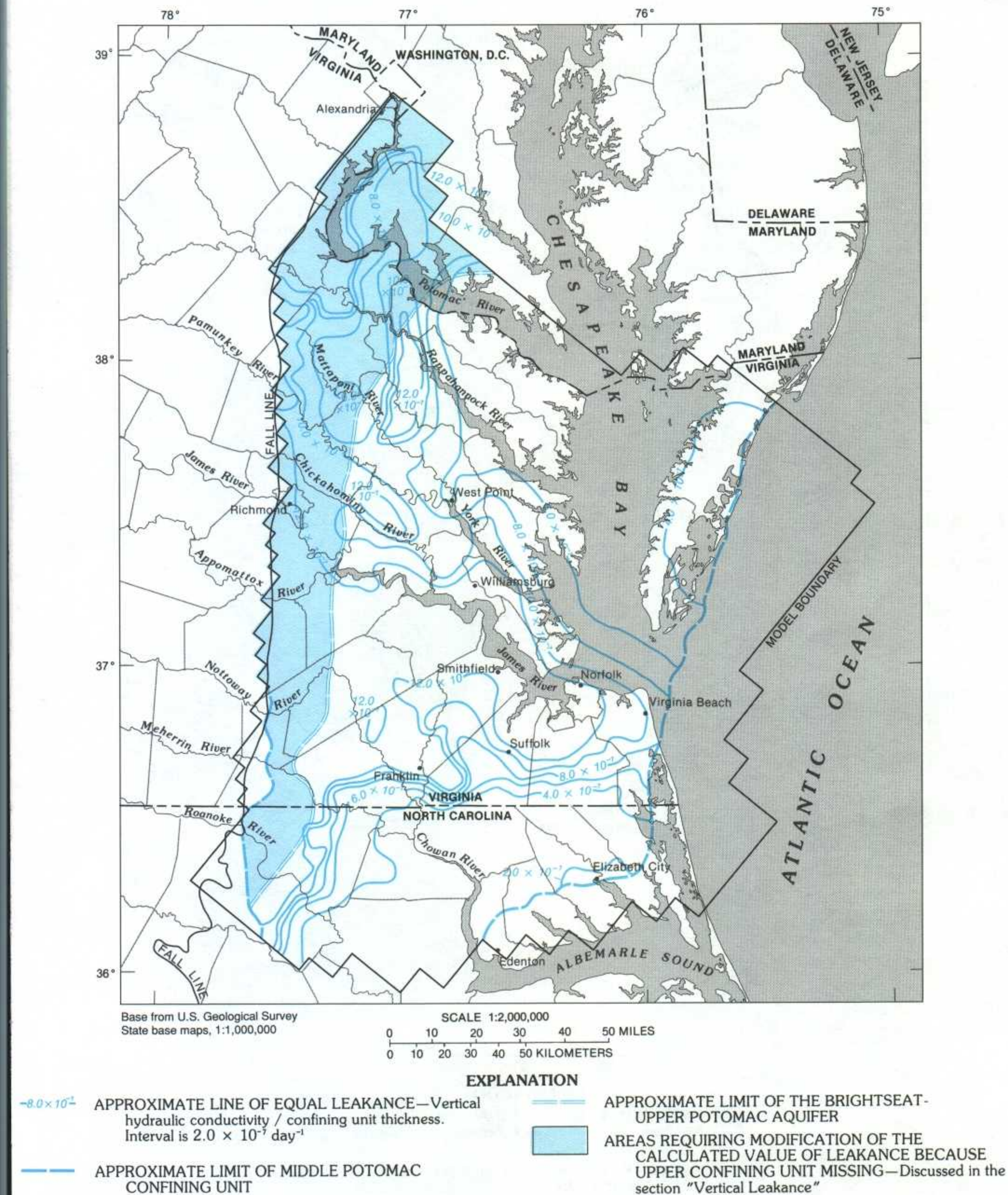
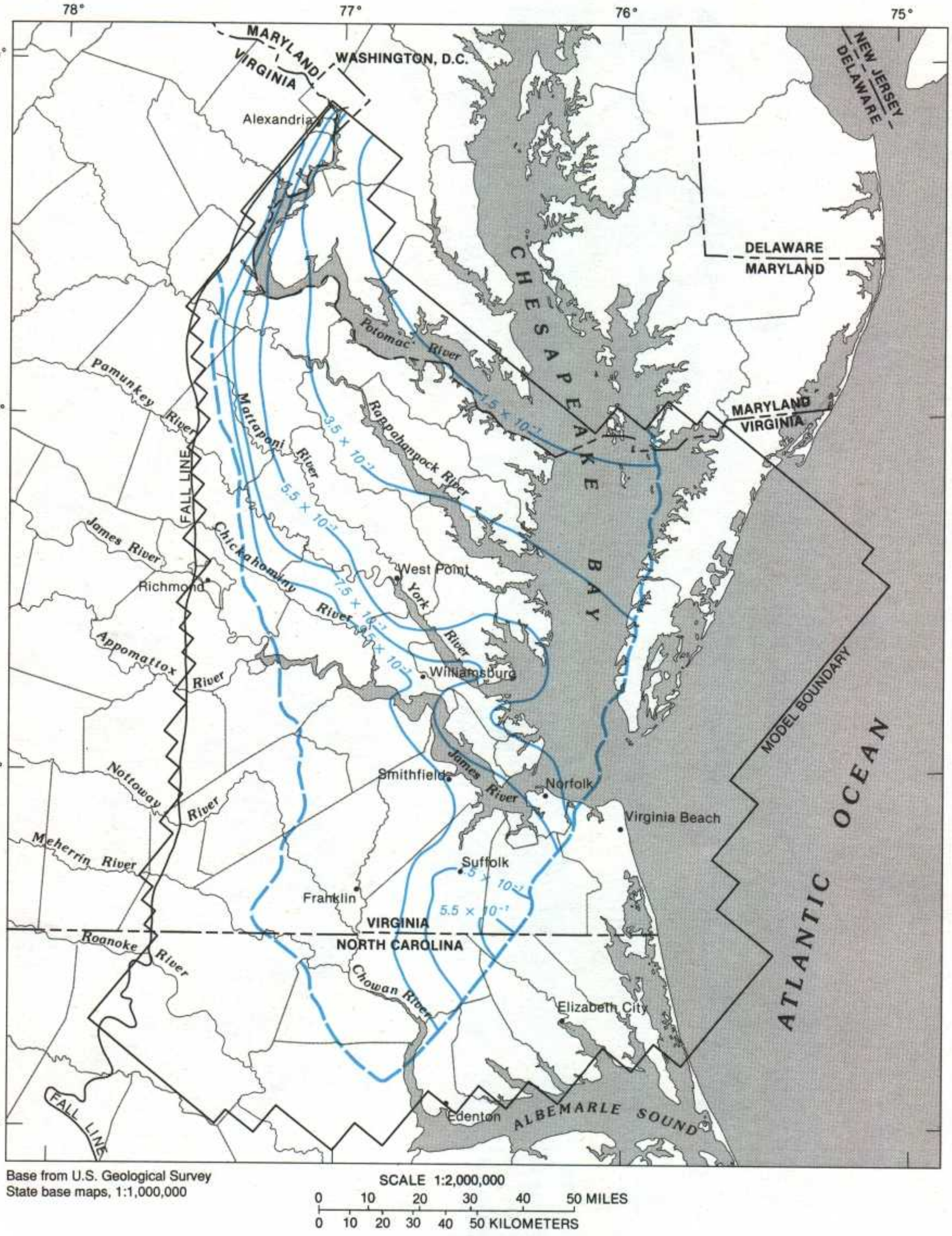


FIGURE 29.—Vertical leakance of the middle Potomac confining unit used in model simulations.



EXPLANATION

-1.5×10^{-7} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 2.0×10^{-7} day^{-1}

APPROXIMATE LIMIT OF LOWER POTOMAC CONFINING UNIT

FIGURE 30.—Vertical leakance of the lower Potomac confining unit used in model simulations.

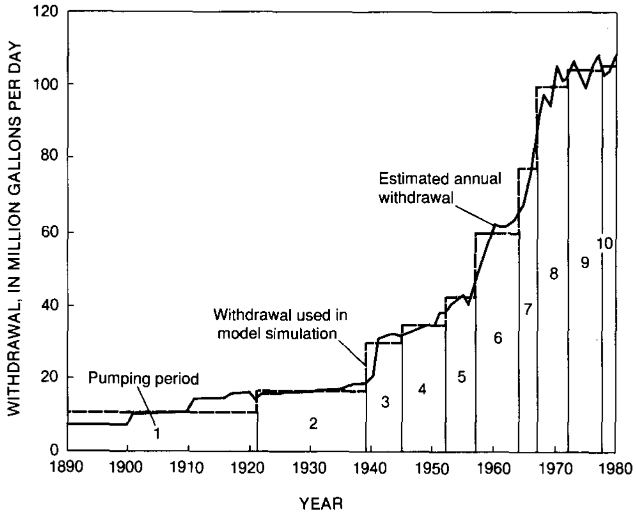


FIGURE 31.—Estimated annual withdrawal and average withdrawal calculated for simulated pumping periods.

with a steady-state simulation of the prepumping ground-water flow system. This simulation treated the water-table aquifer as a constant-head boundary. Constant-head values for each block were interpolated from historic water-level measurements and 1:24,000 U.S. Geological Survey topographic maps. Given knowledge of block values of *QRE*, equation 2 calculated stream base flow values for each block in the study area. Stream stage elevation for each grid block was estimated from surface-water altitudes on 1:24,000 U.S. Geological Survey topographic maps. Streambed leakance for each block was calculated from equation 4. Streambed leakance was assumed to be constant over the simulated history of ground-water development. Because *DP* depends on prepumping water-level distribution, values of *DP* were recalculated for each change in a model input value during model calibration.

TIME DISCRETIZATION AND GROUND-WATER WITHDRAWAL

The history of ground-water development is divided into pumping periods—time intervals during which withdrawals are represented by a constant average pumping rate. The length and number of pumping periods were based on availability of water-level data and on significant changes in withdrawal trends in the northern Atlantic Coastal Plain. Ten pumping periods covering 90 yr were used to simulate the period of ground-water development: 1891–1920, 1921–39, 1940–45, 1946–52, 1953–57, 1958–64, 1965–67, 1968-72, 1973–77, and 1978–80. Each pumping period begins on January 1 and ends on December 31 for the years listed. Figure 31 compares estimated annual withdrawal with average withdrawal calculated for each pumping period. The regional model uses identical pumping periods in order to provide flux values along the lateral boundaries of its component subregional models.

Withdrawals for each pumping period were estimated from the average annual withdrawal rates for individual water users discussed in the section "Ground-Water Use." Users within a nodal block were added to determine the total withdrawal rate from that block. Table 8 lists the withdrawal rates for each aquifer by pumping period. The general trend in withdrawal is a steady increase through pumping period 8. Total withdrawal stabilizes at about 105 Mgal/d for pumping periods 9 and 10. The middle Potomac aquifer has the largest withdrawal for pumping periods 2 through 10. The table includes only those water users reporting withdrawal of more than 10,000 gal/d; therefore, rates do not necessarily indicate the relative importance of aquifers supplying water for domestic purposes.

LATERAL BOUNDARY FLOW

Lateral boundary flow is the movement of ground water across a vertical cross section of the aquifer designated the lateral model boundary. At this boundary, the aquifer continues beyond the limits of the model. The use of this boundary reduces the size of the model grid by eliminating the need to include all of an aquifer in the model simulation.

Lateral boundary flow for each pumping period was approximated with flux values. Fluxes were simulated through recharge or discharge wells placed in blocks located along lateral model boundaries and were calculated with the regional flow model, which extends beyond the lateral limits of its component subregional models (P.P. Leahy, U.S. Geological Survey, oral commun., 1984). Flux values were computed from Darcy's law, which states that flux is proportional to the simulated head gradient across the two blocks adjacent to the lateral flow boundary and to the harmonic mean of their transmissivity. Fluxes were computed for, and were assumed constant throughout, each pumping period. The regional model grid correlates with the model grid of this study, and flux values were assigned to the appropriate model-grid blocks. Because the regional model is made up of the hydraulic properties of the individual subregional models, boundary fluxes were recalculated each time a subregional model updated an aquifer and confining unit characteristic in model calibration. Table 9 gives the lateral boundary flow into and out of each aquifer computed for each pumping period.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

STRATEGY OF CALIBRATION

Calibration of the digital flow model involves areally adjusting hydraulic characteristics until the simulated response is similar to the observed response of the ground-water flow system both prior to and throughout the history of ground-water development. Success of the model simulation is evaluated through comparisons between model-generated and measured water levels at selected observation wells. Simulated water level at an observation well was interpolated from model-generated water levels in the three nearest blocks.

Historic water-level measurements began about 1860 and are summarized in reports by Darton (1896) and Sanford (1913). Prepumping potentiometric maps constructed by Siudyla and others (1977), Bal (1978), Newton and Siudyla (1979), and Cosner (1975) supplemented early water-level data. Reports on ground-water availability by Cederstrom (1945, 1968), Sinnott (1967), and files of the U.S. Geological Survey and the Virginia State Water Control Board provided additional water-level data for the period of ground-water development. Although numerous measurements of water level were available, only those that represent water levels in an individual aquifer were used for calibration.

The calibration procedure began by comparing measured water levels with those simulated by the model using the initial estimates of the hydraulic characteristics. The hydraulic characteristics were adjusted to minimize differences between model-simulated and measured water levels. The procedure was repeated using revised values of hydraulic characteristics until simulated water levels closely approximated measured levels.

The model was first calibrated to simulate the prepumping ground-water flow system. These results provided hydraulic characteristics and initial water levels for simulation of pumping conditions. Because the simulation of pumping conditions is dependent on hydraulic characteristics and initial water levels from prepumping simulations, calibration involved alternating prepumping and pumping simulations until hydraulic characteristics were acceptable in both simulations.

Prepumping Conditions

Simulation of prepumping conditions is based on the assumption that no major withdrawals occurred in the Coastal Plain of Virginia and adjoining States and that the system was in an approximate state of hydraulic equilibrium. Therefore, the prepumping flow system was simulated under a steady-state condition.

Two conceptualizations were used to simulate the water-table aquifer under prepumping conditions (fig. 32). In the first conceptualization, the water-table aquifer and coastal water were represented as a constant-head boundary defined by the average altitude of the water table or freshwater equivalent elevation of the coastal water surface (fig. 32*B*). The simulation was used to quantify the flow into or out of the underlying confined aquifer system, previously referred to as *DP* (deep percolation). In the second conceptualization, a constant-head boundary, representing elevations of stream stage, was placed above the blocks representing the water-table aquifer (fig. 32*C*) in order to allow lateral flow and fluctuation of water levels in the water-table aquifer. Streambed leakance values, calculated using *DP* values computed from the first conceptualization, controlled the vertical flow of water between the water-table aquifer and streams.

The simulated potentiometric-surface maps shown in figures 33 through 40 represent the steady-state solution of prepumping conditions. The maps include measured water levels available for each aquifer. Differences between the simulated potentiometric-surface maps and the prepumping maps constructed by Cosner (1975), Siudyla and others (1977), Bal (1978), and Newton and Siudyla (1979) are minor. Model-generated water levels in the Chickahominy-Piney Point, Aquia, Brightseat-upper Potomac, and middle Potomac aquifers (figs. 35, 36, 38, 39) are in close agreement with measured water levels. The hydraulic gradients determined from the prepumping potentiometric surfaces of aquifers define flow directions; figures 33 through 40 indicate a regional movement of water from the Fall Line toward coastal water and local movement from interfluves toward major river valleys. The bending of potentiometric contours upstream, especially in the deeper confined aquifers under major river valleys, is an effect of erosion into the aquifer by ancient and present-day streams.

The direction of simulated flow across confining units into or out of the underlying confined aquifer under prepumping conditions is shown in figures 41 through 48; water moves upward across confining units toward major river valleys and coastal water, and downward under interfluves. Recharge to the deeper confined aquifers is concentrated along a band adjacent to the Fall Line.

The direction of simulated flow into or out of the confined flow system under prepumping conditions is shown in figure 49. Simulated rates of recharge and discharge varied up to 3.2 and 2.8 in/yr, respectively. The highest rates of recharge into the confined flow system are concentrated along the Fall Line. Table 10 summarizes the computed volumetric leakage rates across each confining unit. The middle Potomac aquifer is

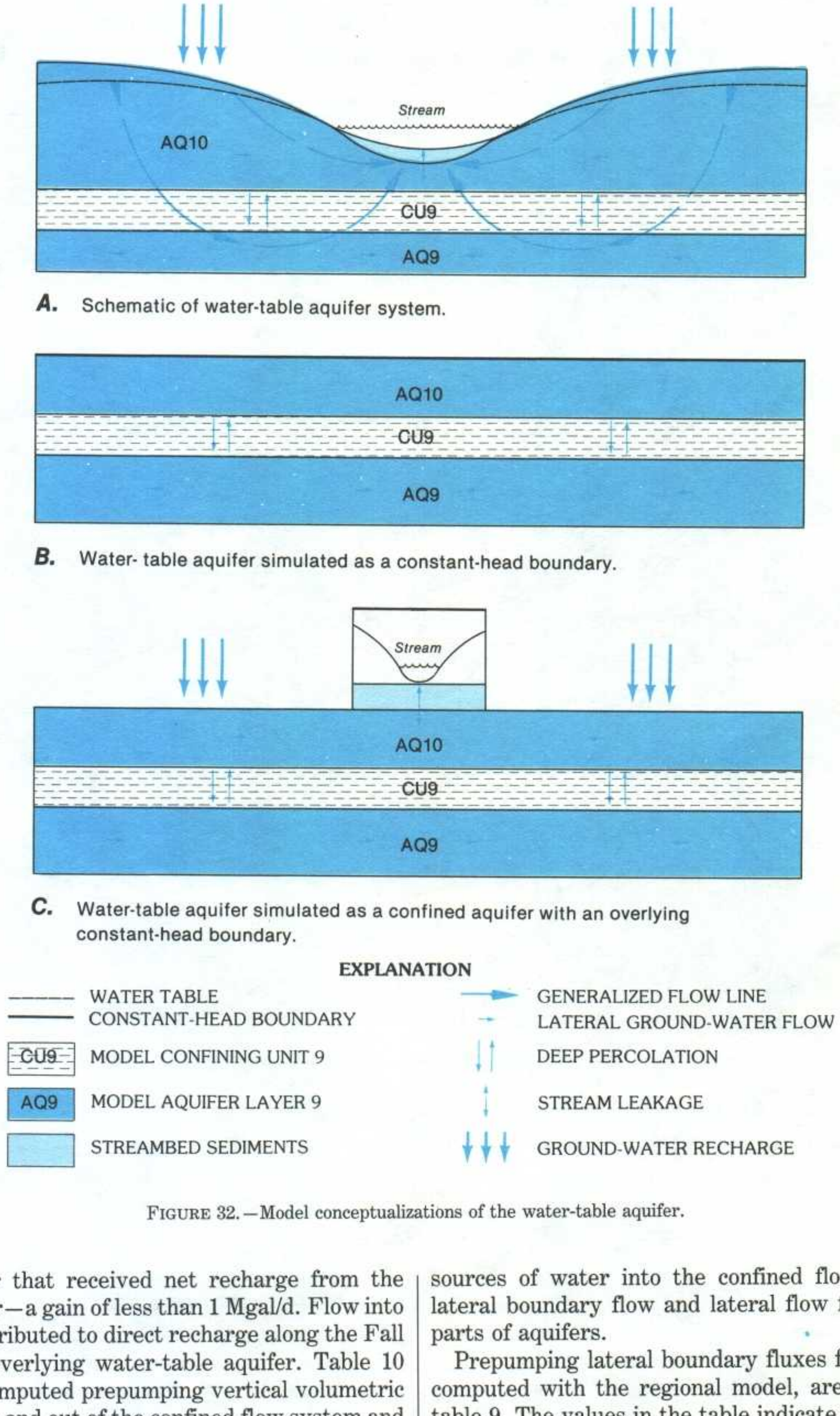
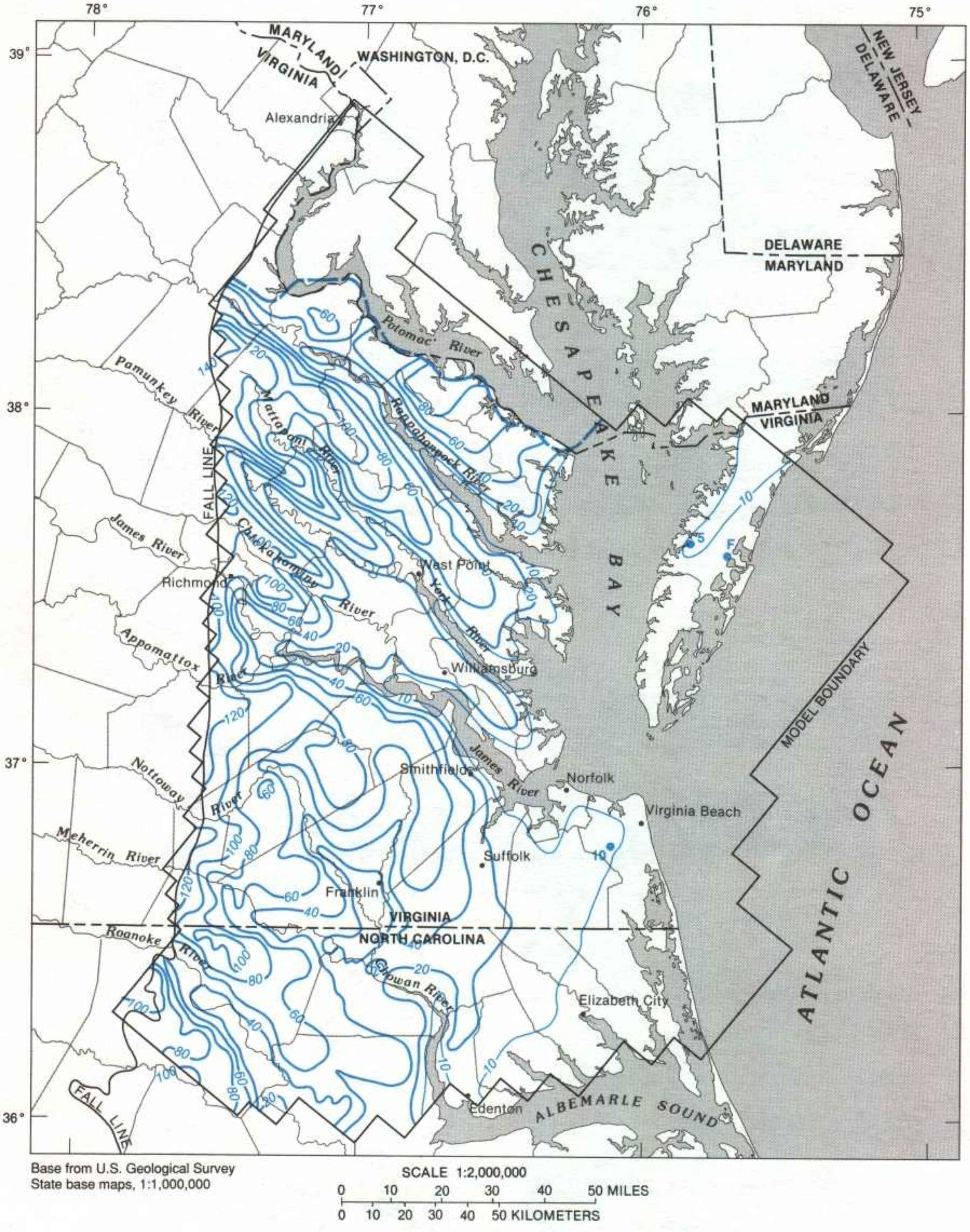


FIGURE 32.—Model conceptualizations of the water-table aquifer.

the only aquifer that received net recharge from the overlying aquifer—a gain of less than 1 Mgal/d. Flow into the aquifer is attributed to direct recharge along the Fall Line from the overlying water-table aquifer. Table 10 also gives the computed prepumping vertical volumetric leakage rate into and out of the confined flow system and shows that approximately 124 Mgal/d of water moved out of and 119 Mgal/d moved into the confined system. Other sources of water into the confined flow system were lateral boundary flow and lateral flow from unconfined parts of aquifers.

Prepumping lateral boundary fluxes for each aquifer, computed with the regional model, are summarized in table 9. The values in the table indicate that flow across lateral boundaries was not a significant component in the overall ground-water budget of individual aquifers. Low



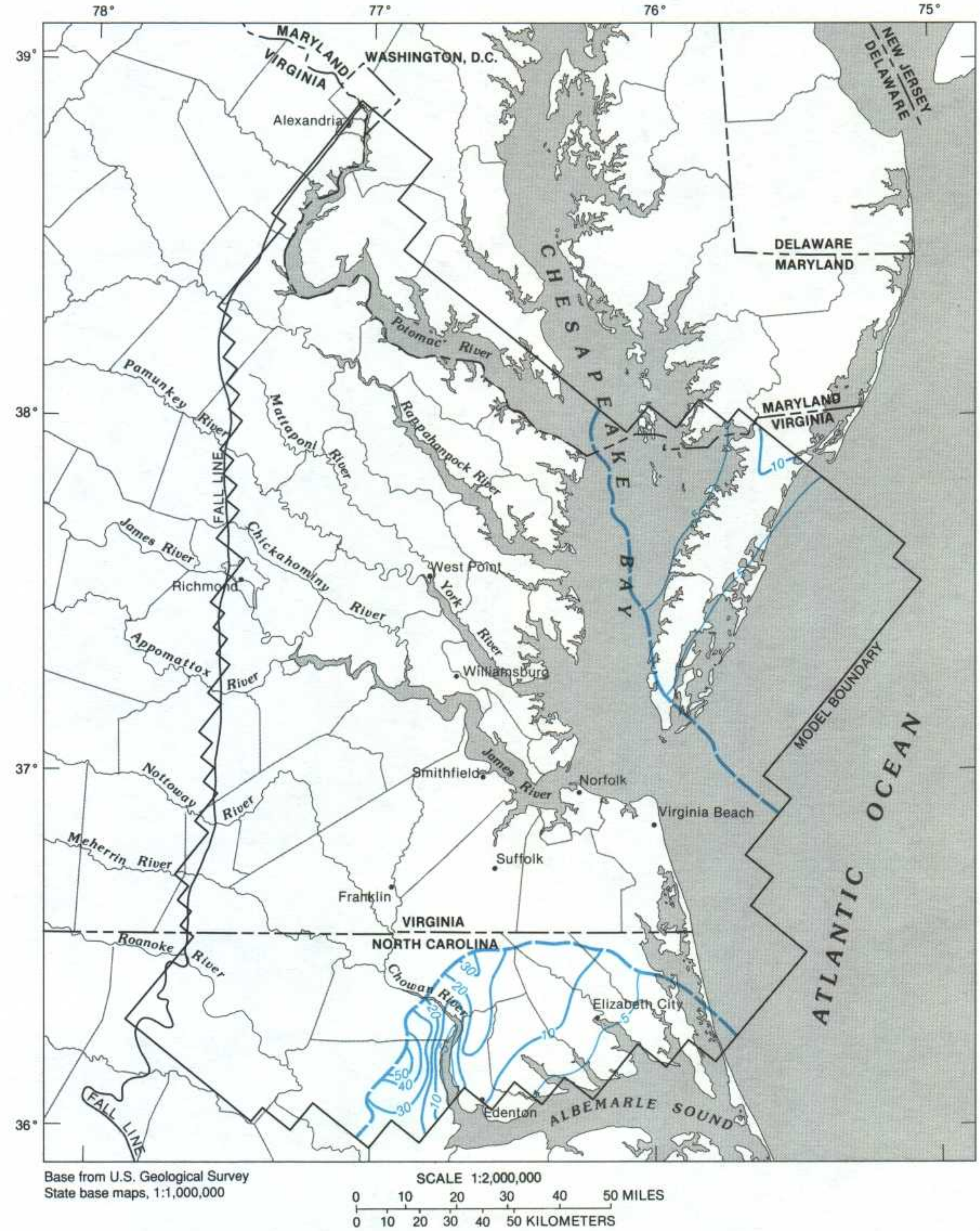
EXPLANATION

—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet with supplemental contour at 10 feet. Datum is sea level

— — APPROXIMATE LIMIT OF YORKTOWN-EASTOVER AQUIFER

•5 WELL—Number is measured altitude of water level, in feet, above sea level. Letter F indicates flowing well

FIGURE 33.—Simulated prepumping potentiometric surface of the Yorktown-Eastover aquifer and measured water levels.

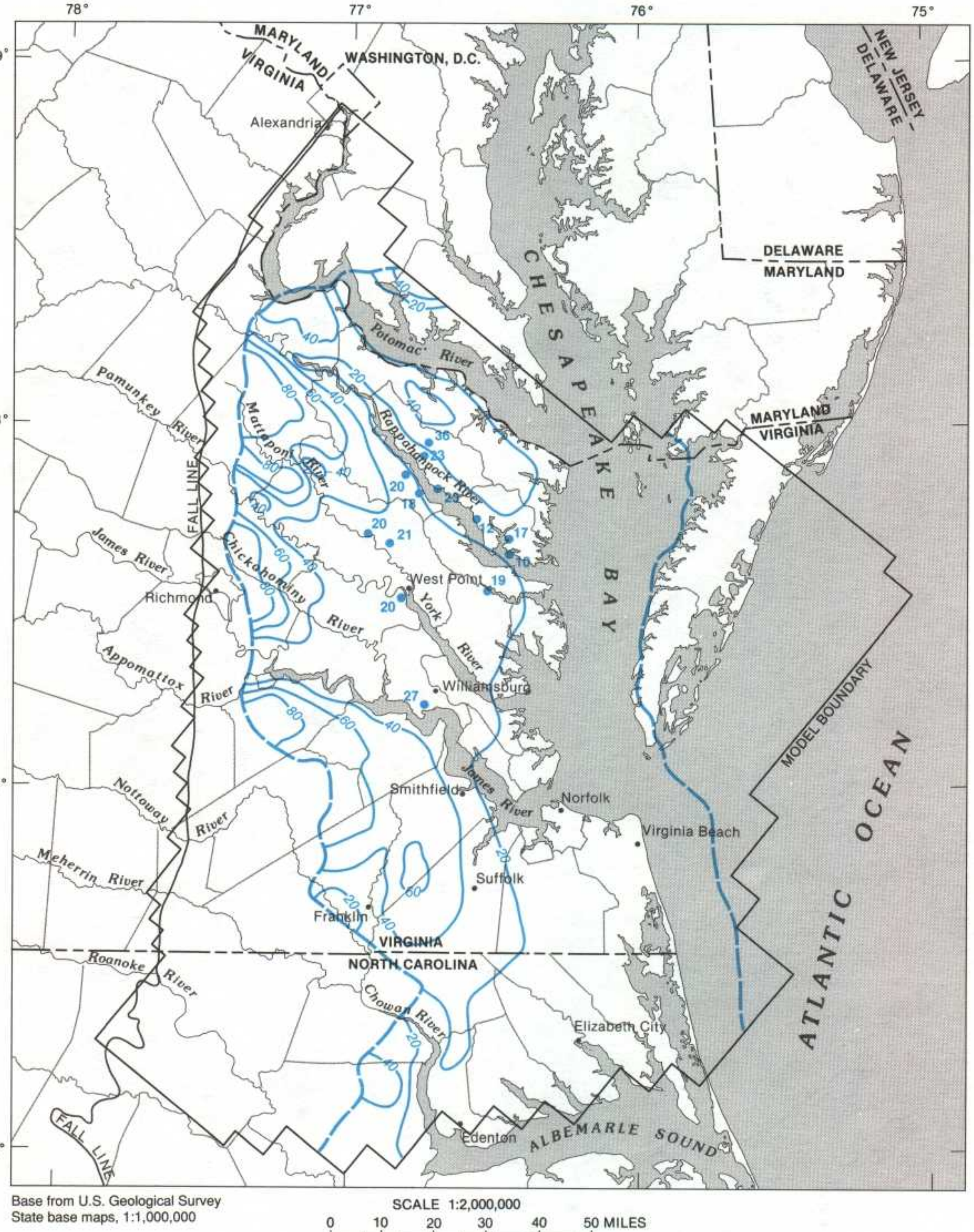


EXPLANATION

—10— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 10 feet with supplemental contour at 5 feet. Datum is sea level

— — APPROXIMATE LIMIT OF ST. MARYS-CHOPTANK AQUIFER

FIGURE 34.—Simulated prepumping potentiometric surface of the St. Marys-Choptank aquifer.



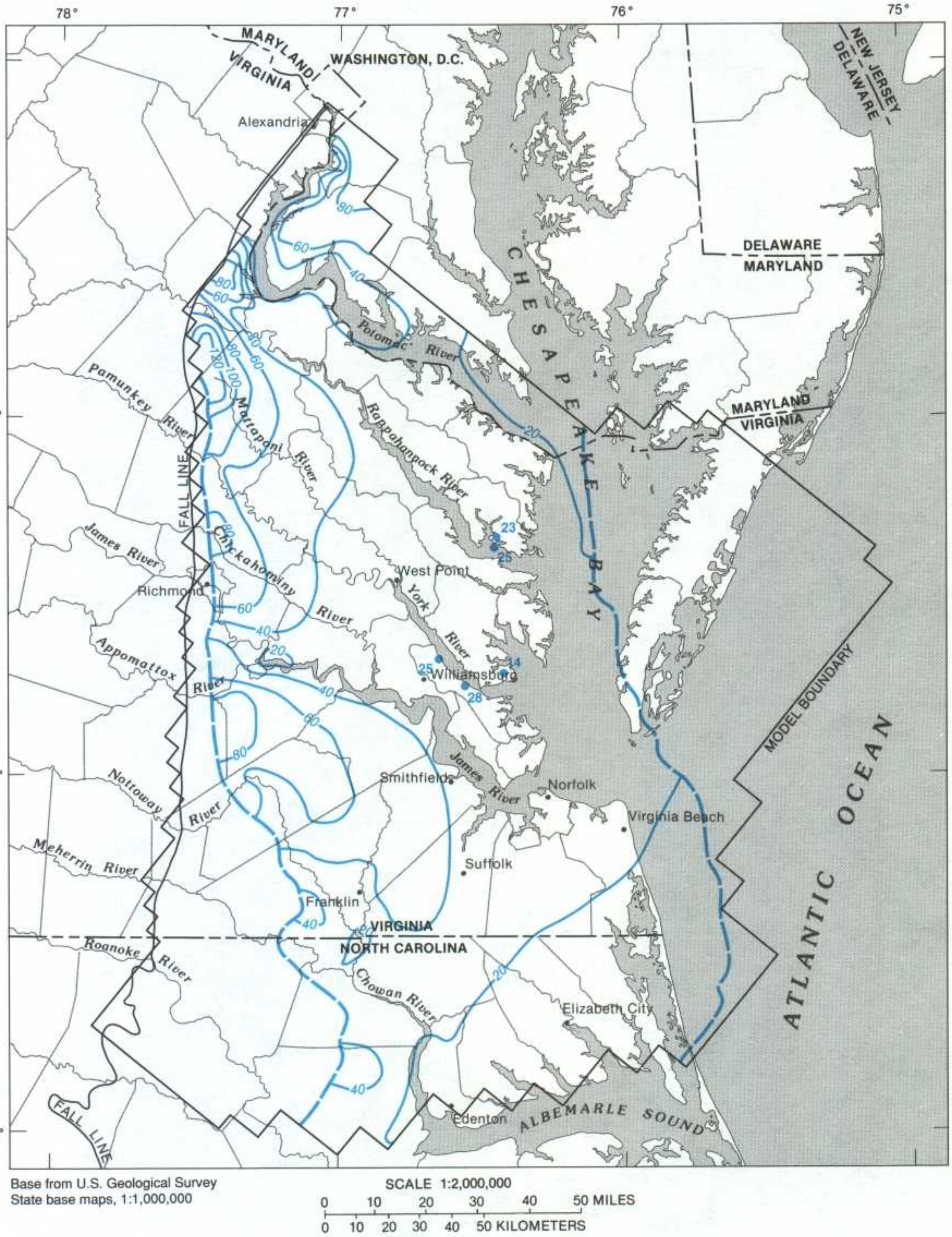
EXPLANATION

—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet. Datum is sea level

— — APPROXIMATE LIMIT OF CHICKAHOMINY-PINEY POINT AQUIFER

•12 WELL—Number is measured altitude of water level, in feet above sea level

FIGURE 35.—Simulated prepumping potentiometric surface of the Chickahominy-Piney Point aquifer and measured water levels.



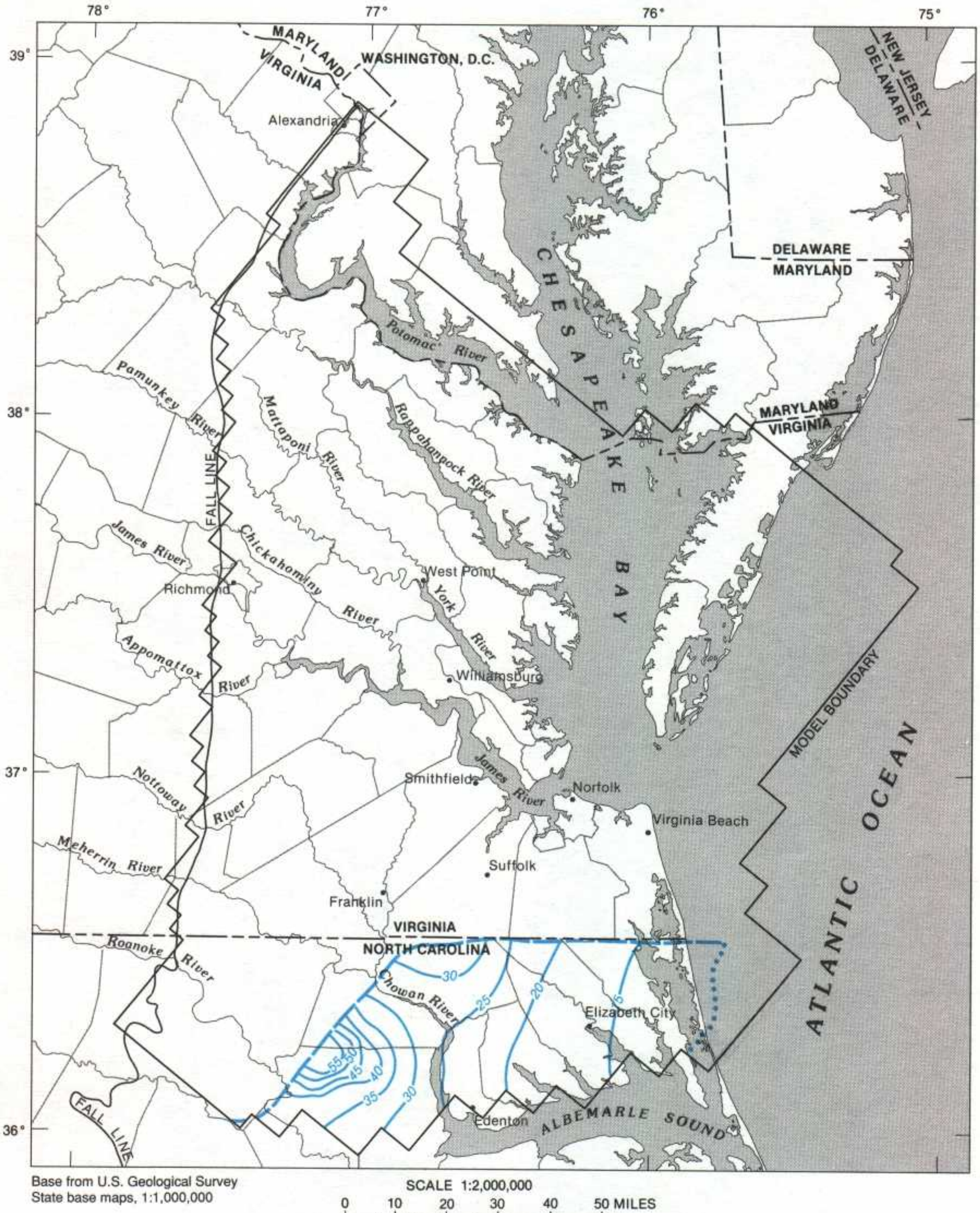
EXPLANATION

POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet. Datum is sea level

APPROXIMATE LIMIT OF AQUIA AQUIFER

WELL—Number is measured altitude of water level, in feet, above sea level

FIGURE 36.—Simulated prepumping potentiometric surface of the Aquia aquifer and measured water levels.



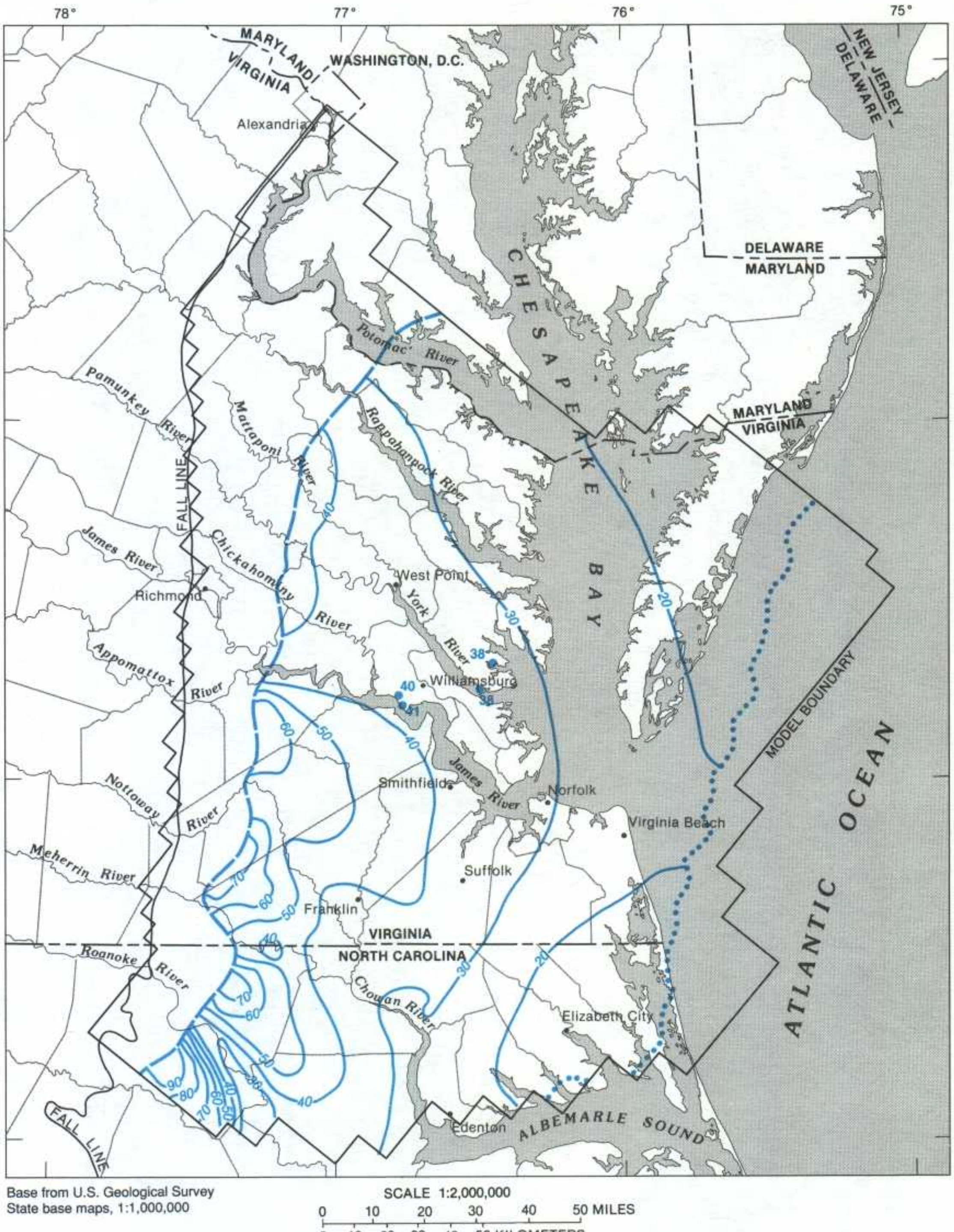
EXPLANATION

—15— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 5 feet. Datum is sea level

— — APPROXIMATE LIMIT OF AQUIFER 4

••••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

FIGURE 37.—Simulated prepumping potentiometric surface of aquifer 4.



EXPLANATION

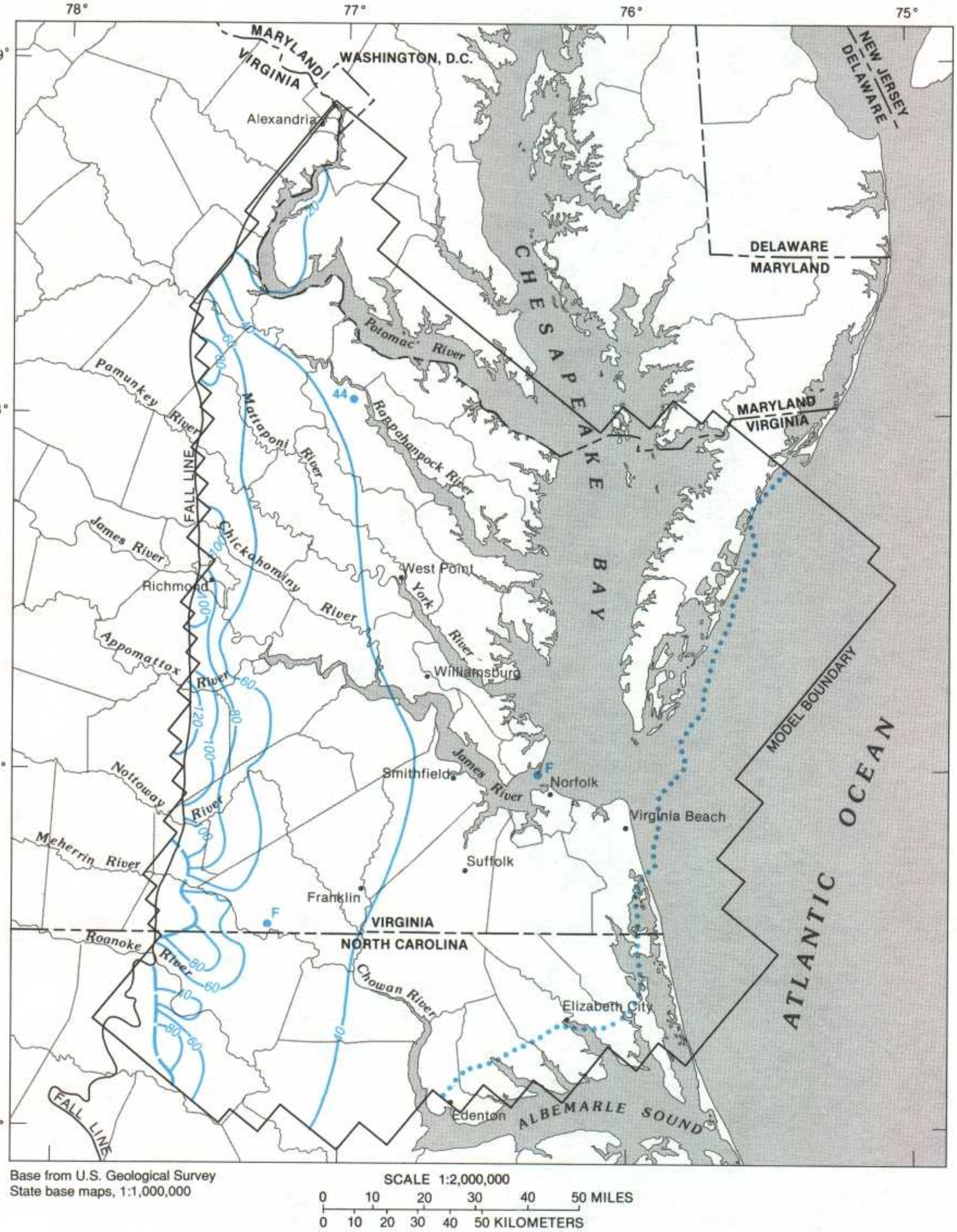
—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 10 feet. Datum is sea level

— — APPROXIMATE LIMIT OF BRIGHTSEAT-UPPER POTOMAC AQUIFER

••••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

•38 WELL—Number is measured altitude of water level, in feet, above sea level

FIGURE 38.—Simulated prepumping potentiometric surface of the Brightseat-upper Potomac aquifer and measured water levels.



EXPLANATION

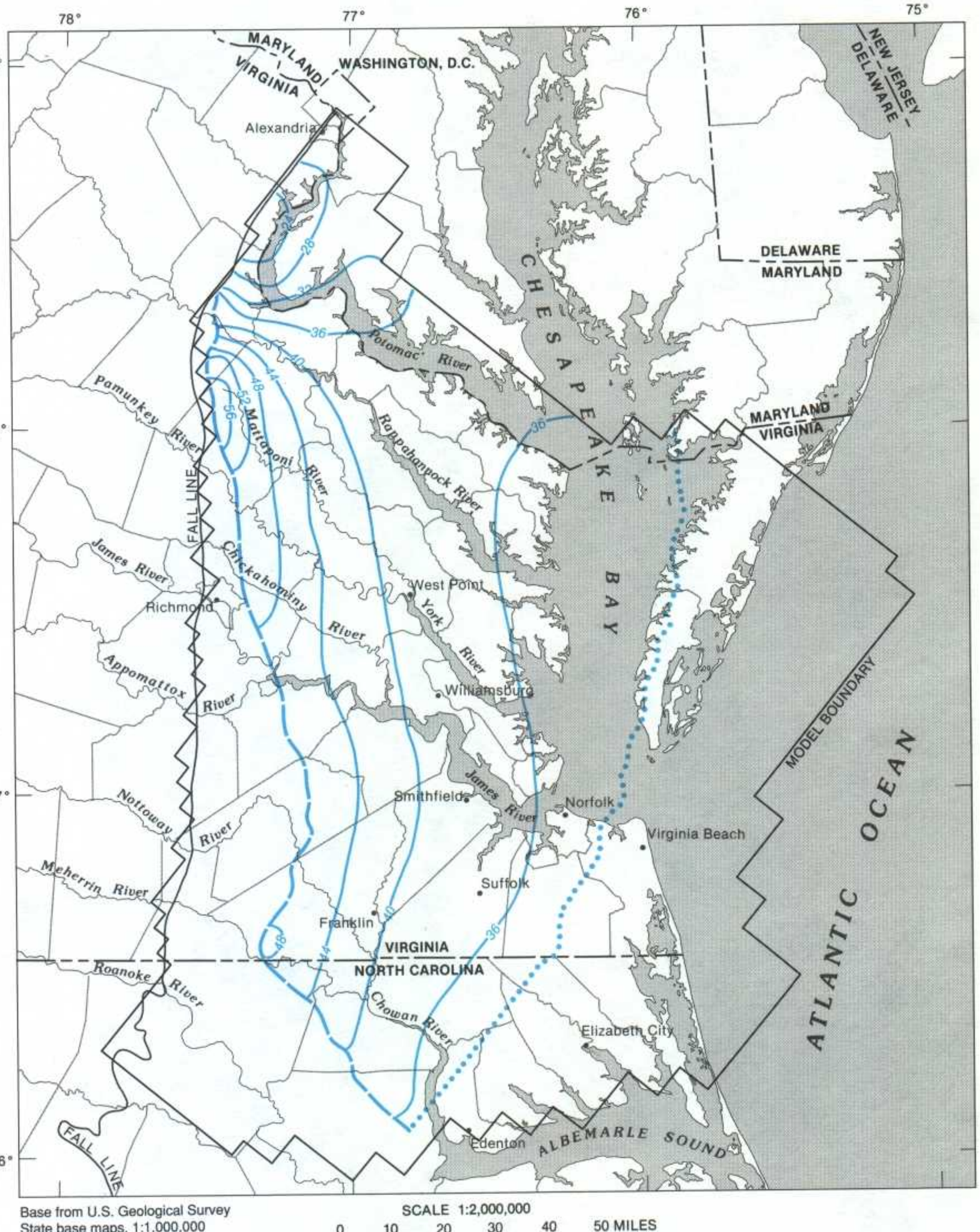
—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet. Datum is sea level

— — APPROXIMATE LIMIT OF MIDDLE POTOMAC AQUIFER

••••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

•44 WELL—Number is measured altitude of water level, in feet, above sea level. Letter F indicates flowing well

FIGURE 39.—Simulated prepumping potentiometric surface of the middle Potomac aquifer and measured water levels.



EXPLANATION

—40— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 4 feet. Datum is sea level

— — APPROXIMATE LIMIT OF LOWER POTOMAC AQUIFER

······· ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

FIGURE 40.—Simulated prepumping potentiometric surface of the lower Potomac aquifer.

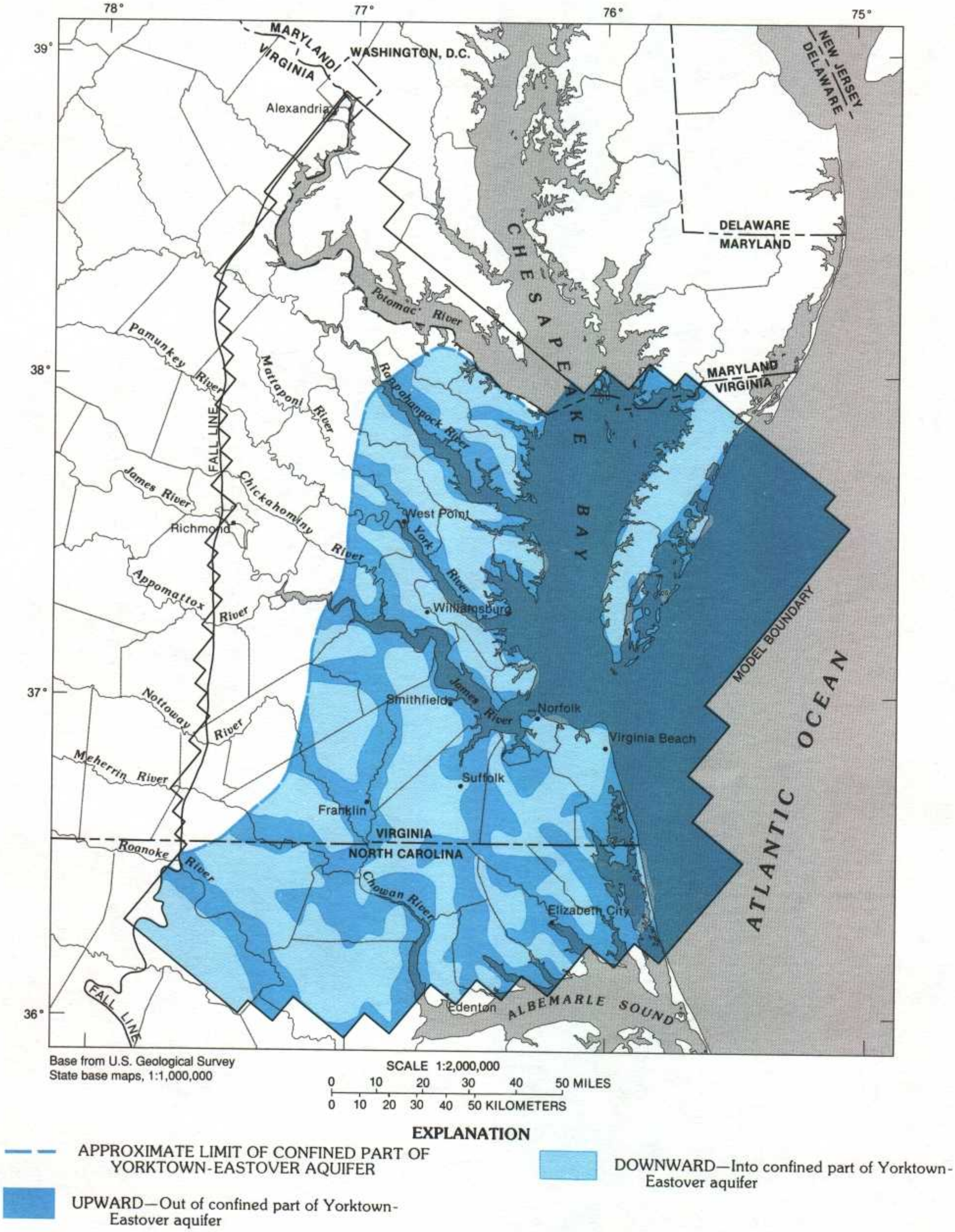


FIGURE 41.—Direction of simulated prepumping flow across the Yorktown confining unit.

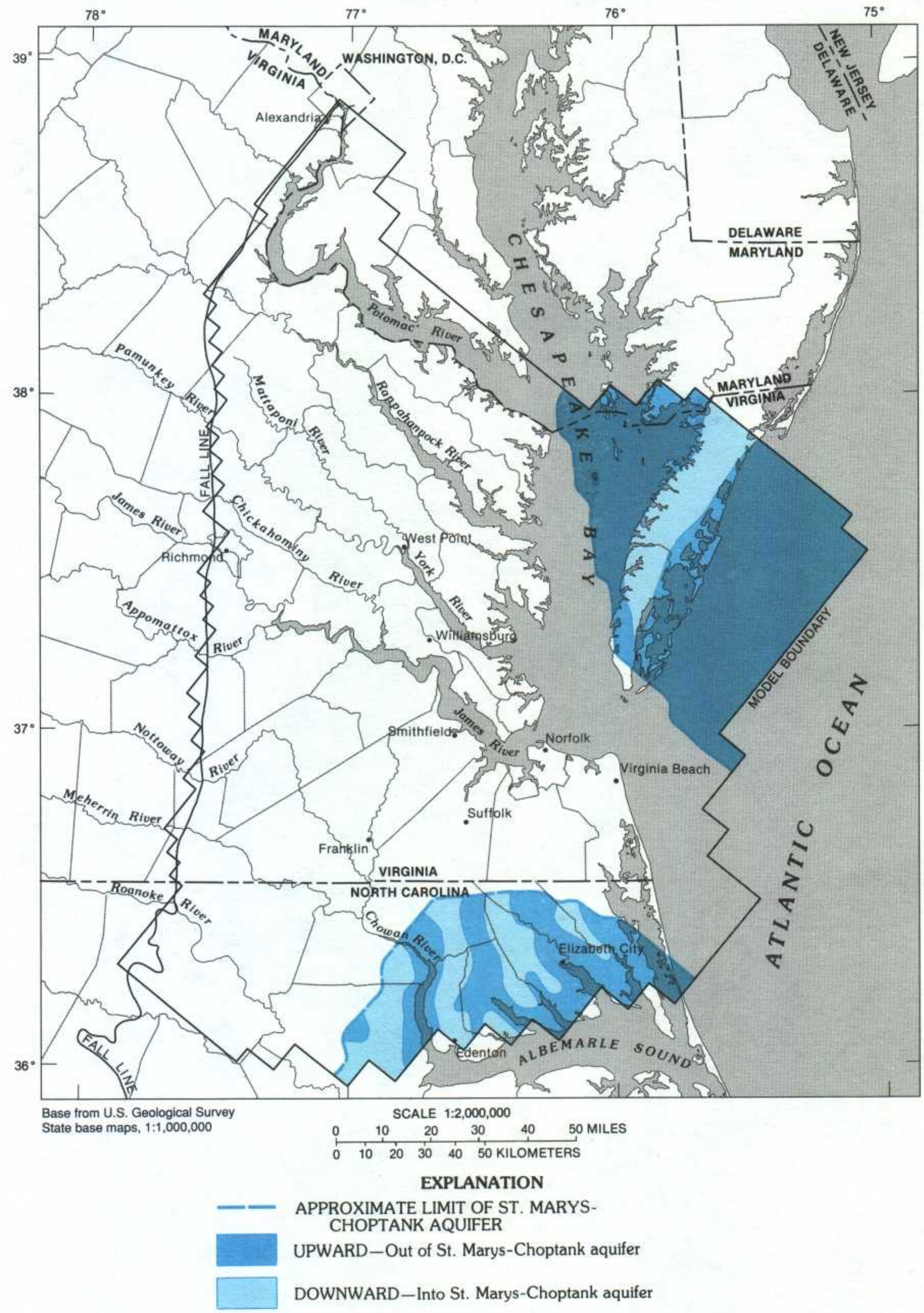


FIGURE 42.—Direction of simulated prepumping flow across the St. Marys confining unit.

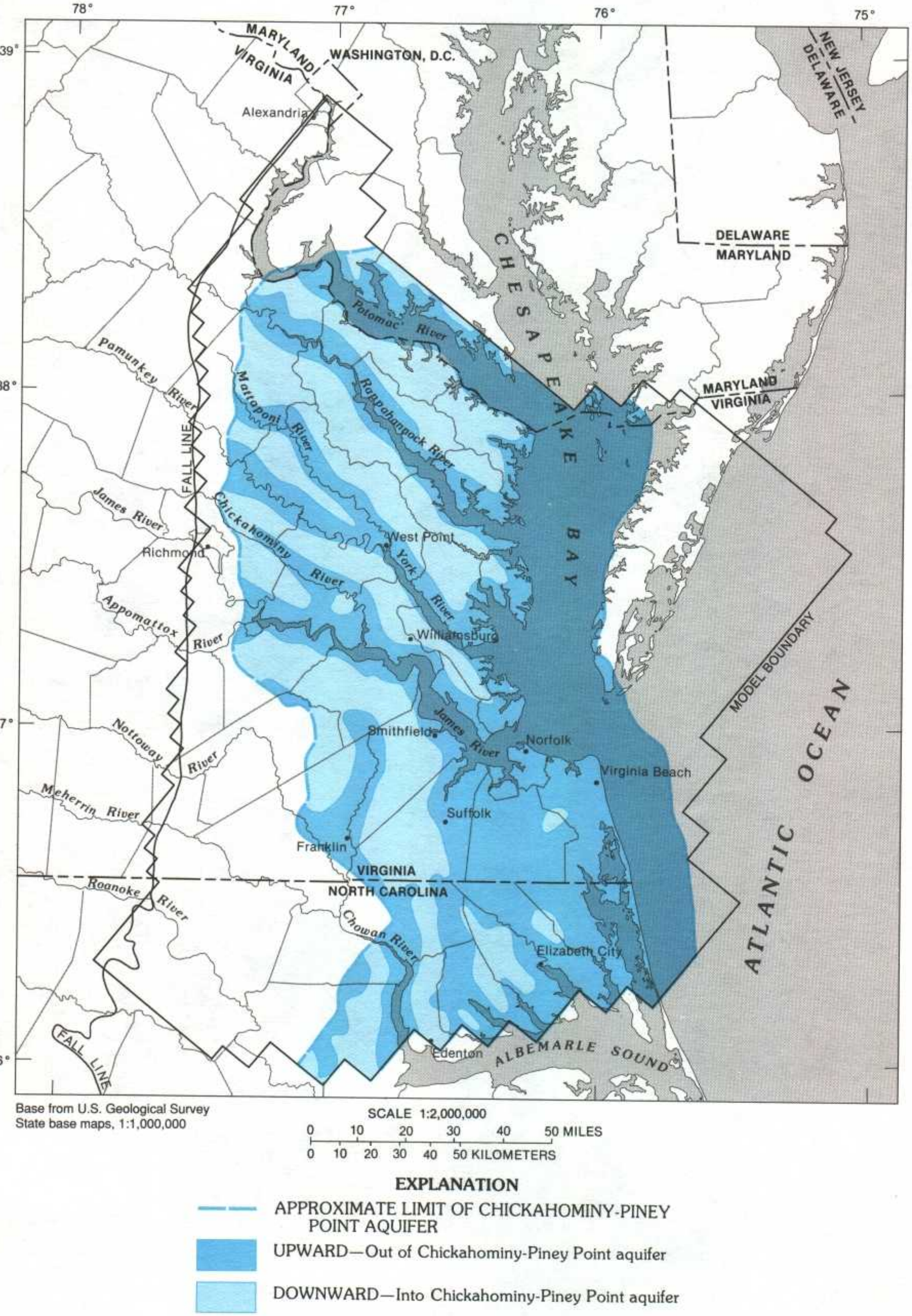


FIGURE 43.—Direction of simulated prepumping flow across the Calvert confining unit.

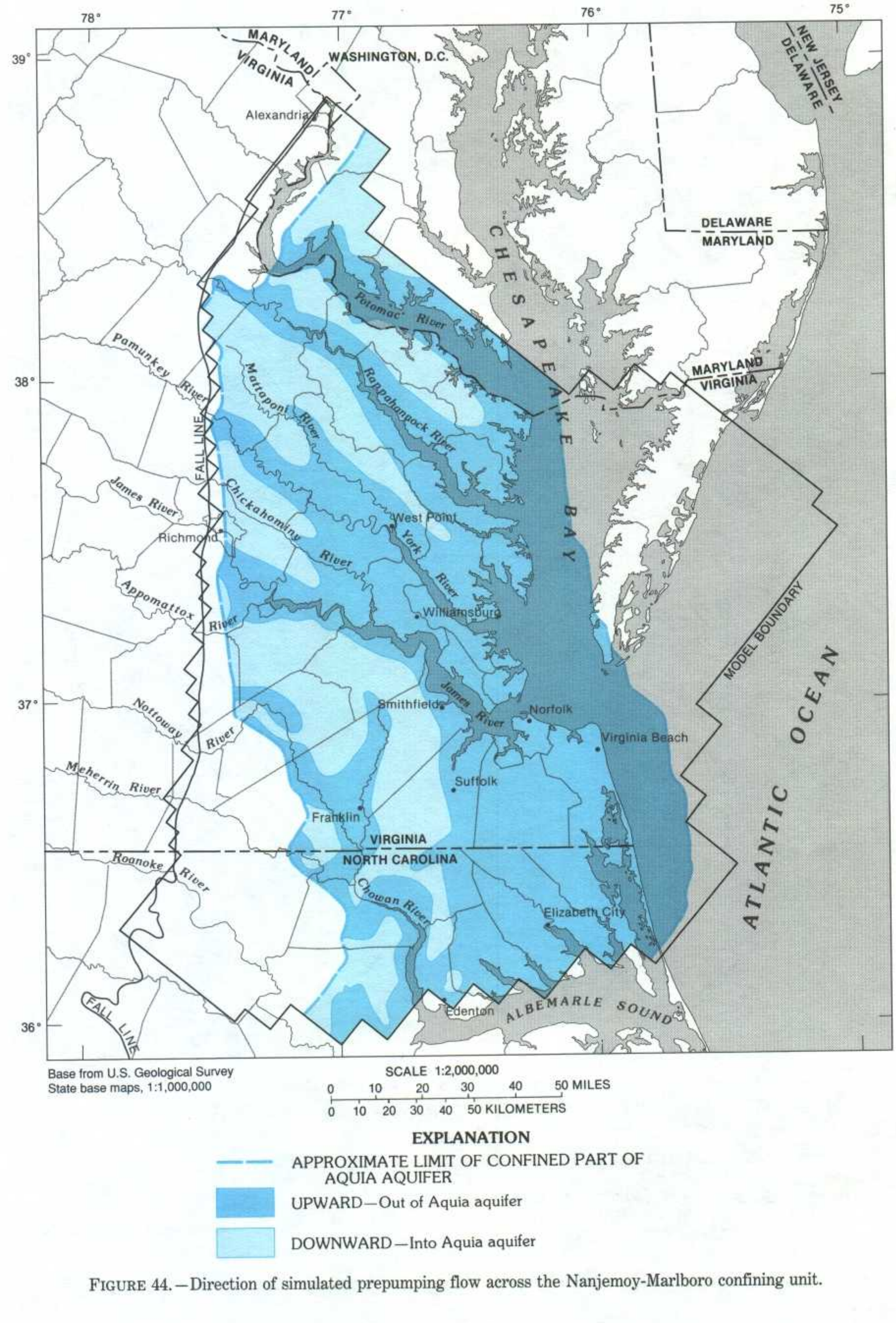


FIGURE 44.—Direction of simulated prepumping flow across the Nanjemoy-Marlboro confining unit.

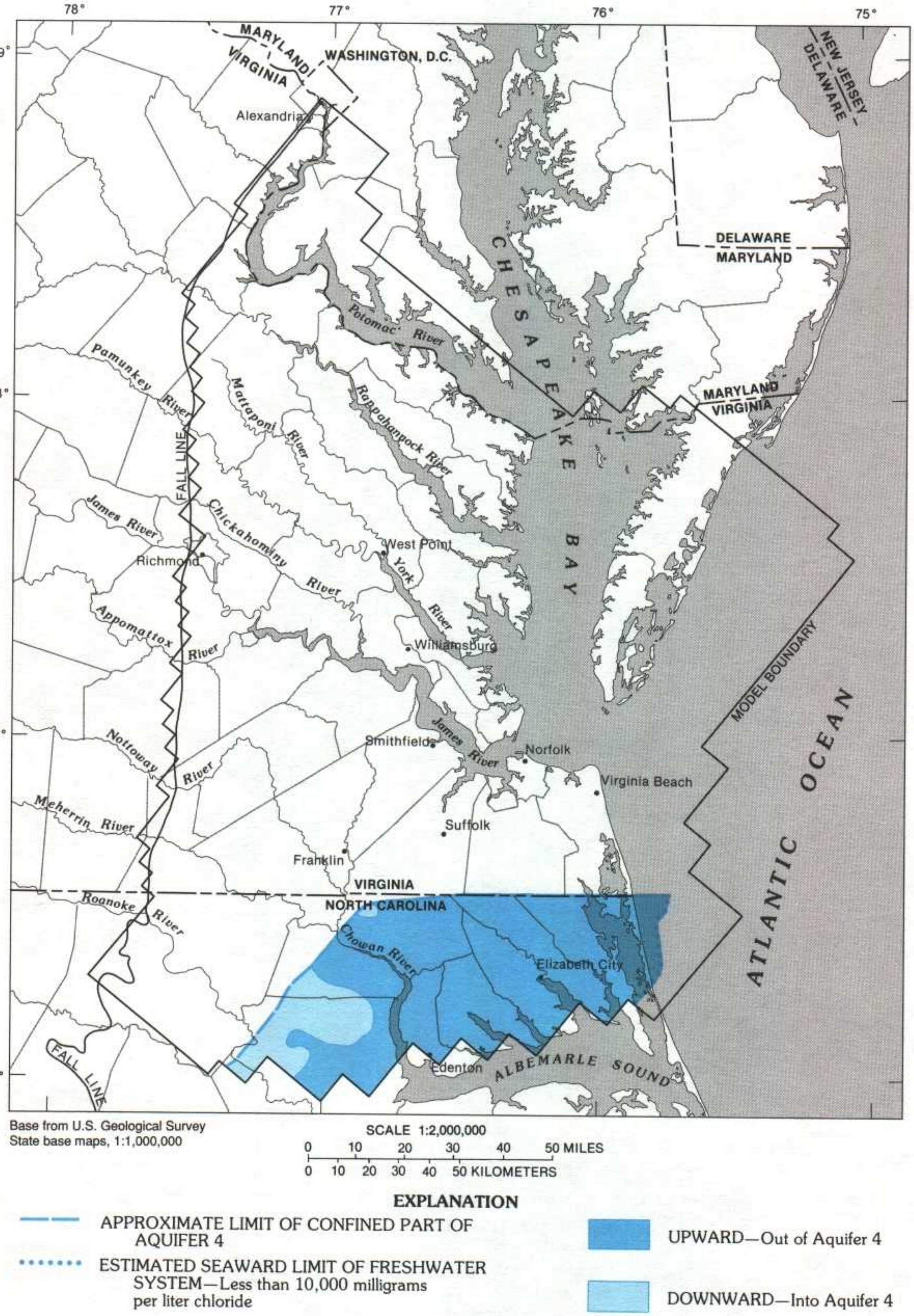


FIGURE 45.—Direction of simulated prepumping flow across confining unit 4.

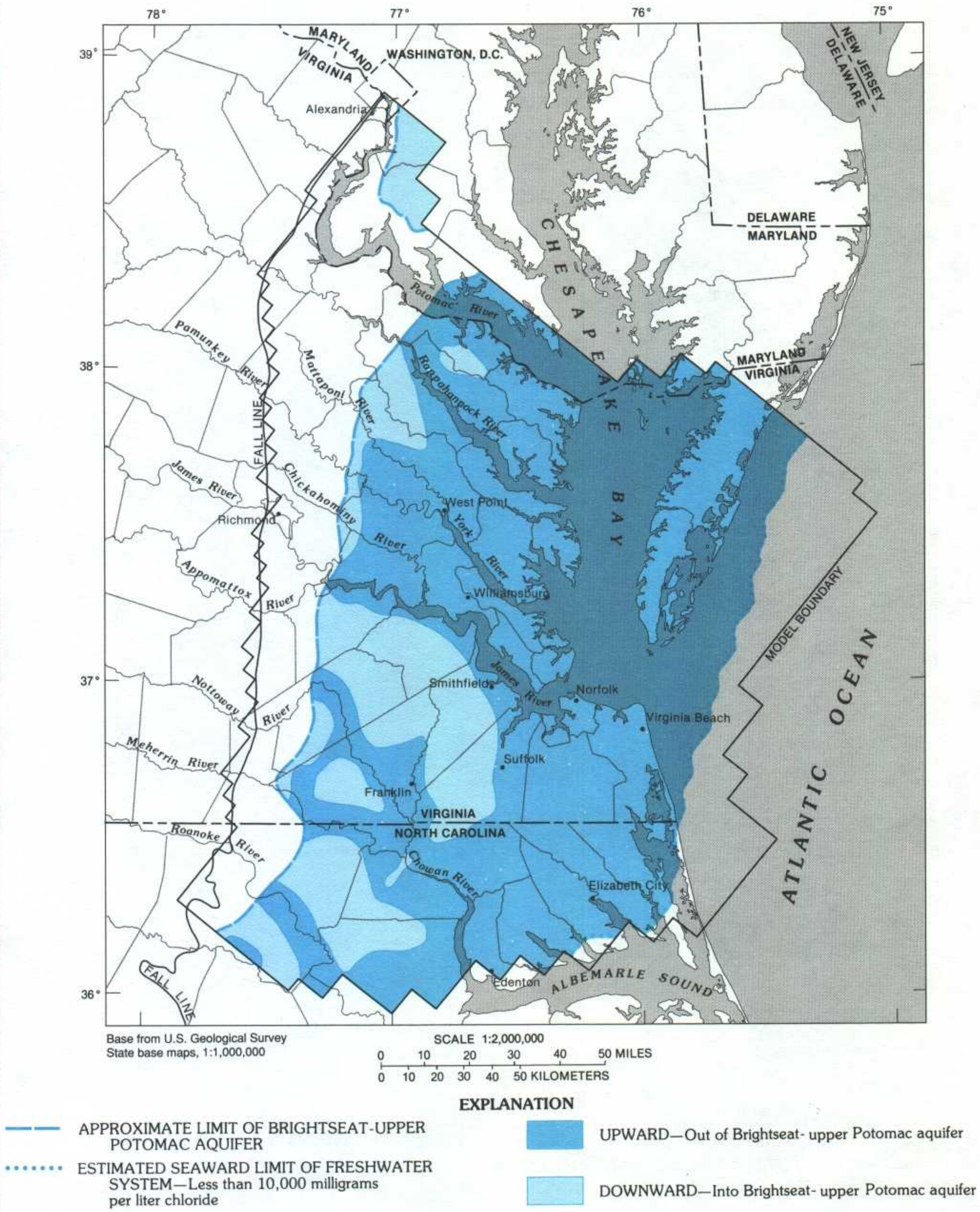


FIGURE 46.—Direction of simulated prepumping flow across the Brightseat-upper Potomac confining unit.

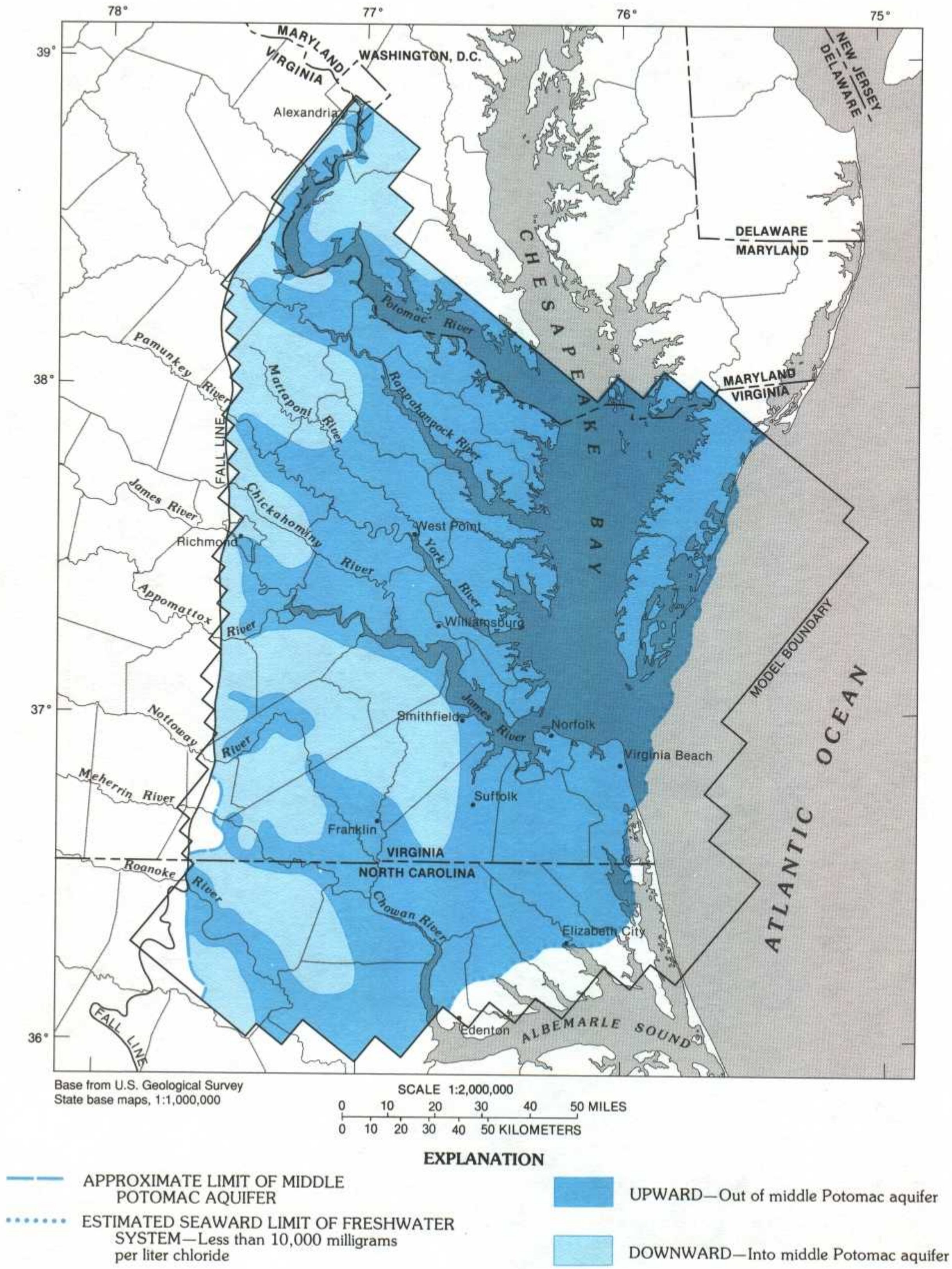


FIGURE 47.—Direction of simulated prepumping flow across the middle Potomac confining unit.

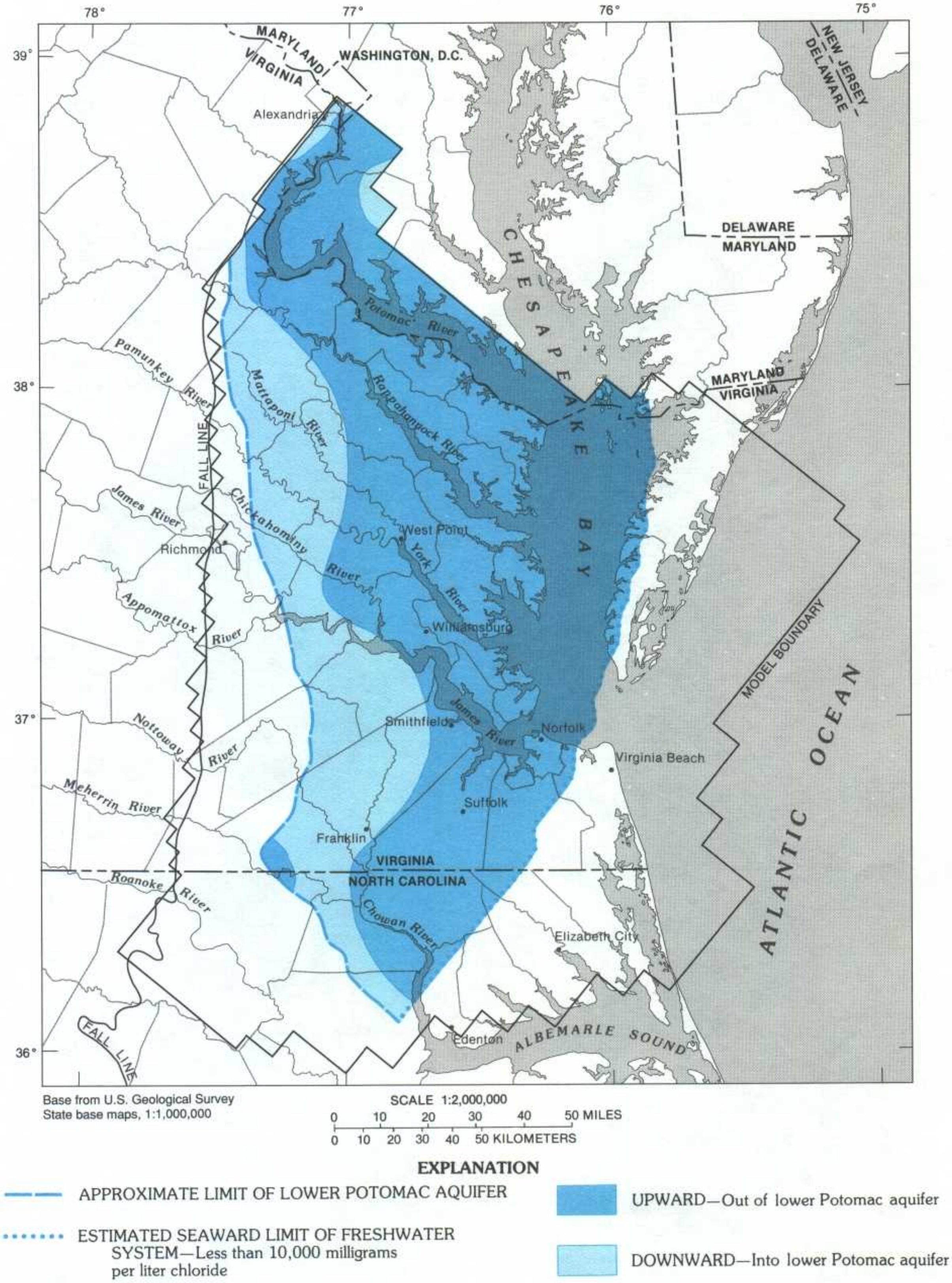


FIGURE 48.—Direction of simulated prepumping flow across the lower Potomac confining unit.

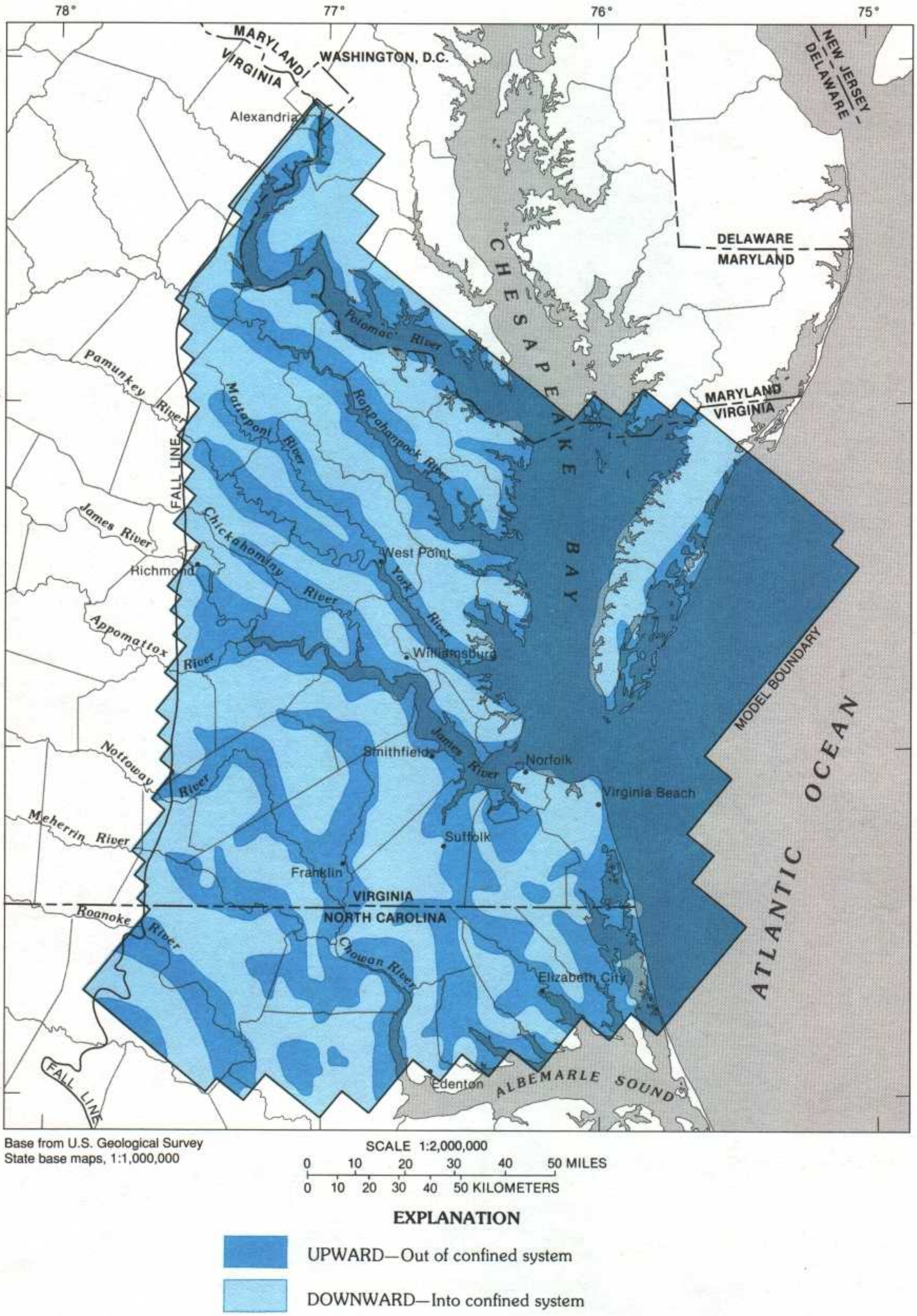


FIGURE 49.—Direction of simulated prepumping flow into and out of confined system.

values for the prepumping simulation indicate that the selected positions of the lateral flow boundaries approximately coincide with flow lines or no-flow boundaries.

Pumping Conditions

The digital flow model simulates 90 yr of pumping beginning January 1, 1891, and ending December 31, 1980, under transient conditions. The 10 pumping periods previously discussed were used for transient simulations. The water-table aquifer was simulated without consideration for dewatering of the aquifer material. Therefore, the transmissivity of the water-table aquifer was constant over the entire period of transient simulation. This assumption is considered reasonable because regional drawdown in the water-table aquifer is negligible. However, the storage coefficient was assigned a value that represents a more reasonable storage condition of a water-table aquifer. Other hydraulic characteristics and initial water levels were equivalent to those used to simulate prepumping conditions.

Two methods were used to compare model-simulated and measured historic water levels: (1) simulated potentiometric-surface maps, constructed for each aquifer and pumping period, were compared with measured water levels, and (2) simulated hydrographs were compared with measured hydrographs at 89 observation wells. Figures 50 through 57 show the simulated potentiometric-surface maps of the major aquifers at the end of the final pumping period (1980). The maps include water levels measured at different times during 1980. Hence, simulated water levels are expected to differ slightly from those measured, because the simulated potentiometric surfaces represent the water-level distribution in each aquifer on December 31, 1980. Overall, measured water levels agree with levels simulated by the model.

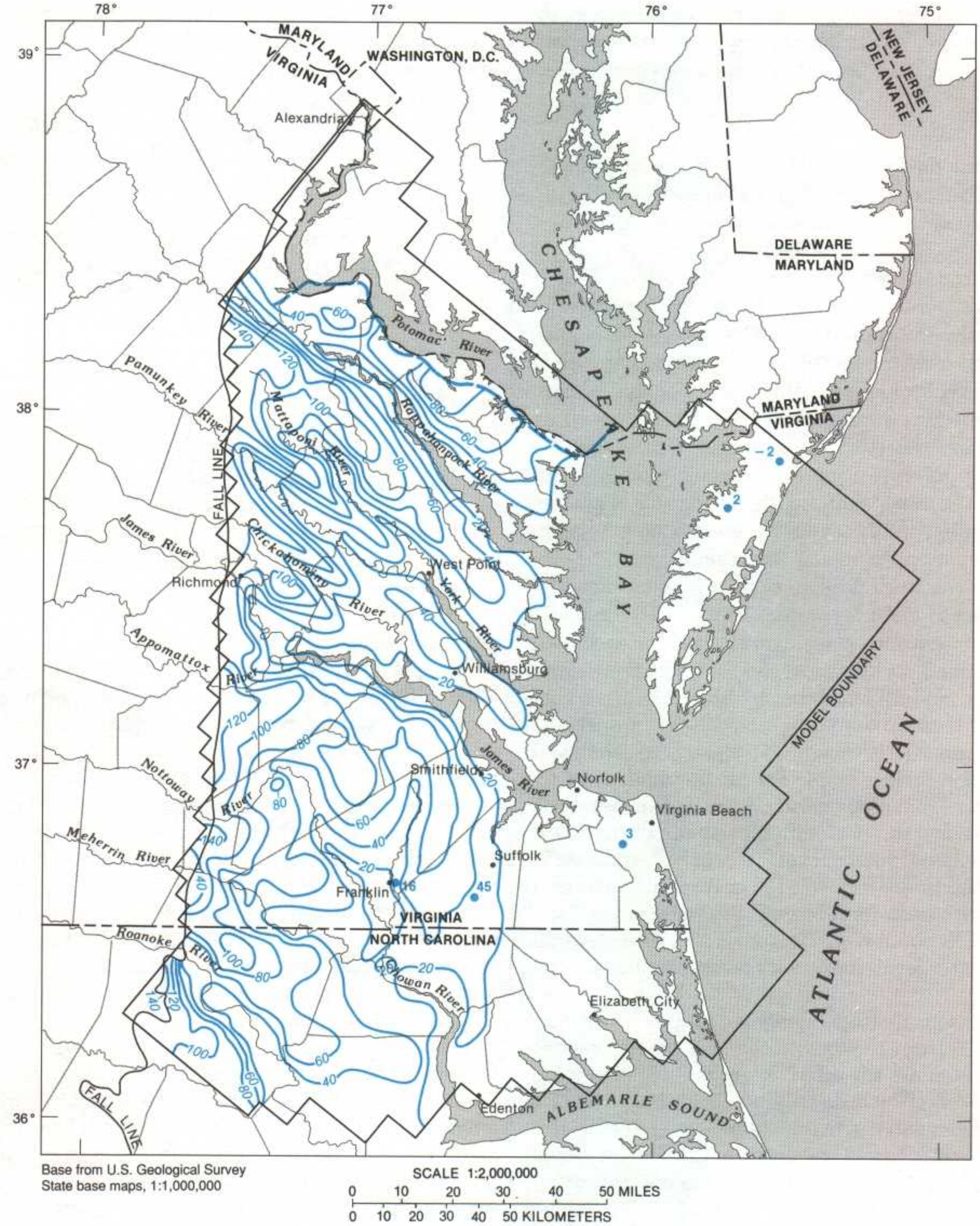
A comparison of prepumping potentiometric-surface maps (figs. 33 through 40) with the 1980 potentiometric-surface maps shows the effect of ground-water development on the water-level distribution in each aquifer. The maps of the simulated ground-water flow system in 1980 show lower water levels and cones of depression around major pumping centers. The potentiometric-surface maps of the Aquia, Brightseat-upper Potomac, middle Potomac, and lower Potomac aquifers show that cones of depression developed and coalesced near the cities of Williamsburg, Franklin, and Suffolk and the town of West Point (figs. 53, 55 through 57). The simulated potentiometric surface of the Chickahominy-Piney Point aquifer shows a decline in water levels near the town of West Point and the City of Williamsburg (fig. 52). The hydraulic gradients, determined from the potentiometric surfaces of 1980 in the major aquifers, indicate that flow directions changed considerably from those simulated for prepumping flow conditions and that the direction of flow in 1980 was toward the major pumping centers.

Measured and simulated hydrographs show the agreement between measured and model-generated water levels for the history of ground-water development. Figures 58 through 61 show hydrographs for 16 of the 89 observation wells used to calibrate the model. The locations of these 16 wells are shown in figure 62. Most are near major ground-water users (fig. 8). The middle Potomac aquifer, near Franklin, shows the largest simulated water-level decline from prepumping flow conditions, about 210 ft in well 55B 22 (fig. 60).

In addition to simulating water-level changes, the model provides a water budget, which quantifies the individual components of flow into and out of the ground-water flow system. The relative magnitudes of the individual flow components define their significance during a simulated pumping period and over the entire period of simulation. Table 11 summarizes the individual flow components into and out of the ground-water flow system at the end of each simulated pumping period. A comparison of the prepumping period and the final pumping period (1978–80) water budgets indicates that (1) pumpage from the model area increased by about 105 Mgal/d, (2) lateral boundary outflow increased by about 5 Mgal/d, (3) ground-water flow to streams and coastal water decreased by about 107.5 Mgal/d, (4) lateral boundary inflow increased by about 0.7 Mgal/d, and (5) water released from aquifer storage increased by about 1.6 Mgal/d. The slight difference between total inflow and total outflow is attributed to the numerical truncation error of the digital simulation. The most significant effect of ground-water development over the period of simulation was the decrease in ground-water flow to streams and coastal water. The increase in lateral boundary outflow is attributed to large withdrawals from outside the model area.

Tables 8, 9, and 10 can be used to evaluate water budgets for the confined aquifers. Pumpage (table 8) and lateral boundary flow (table 9) are averaged over the length of each pumping period. Flow into and out of an aquifer across the overlying confining unit is calculated at the end of each pumping period. A comparison of the water budgets of individual confined aquifers indicates that the major source of water replacing water pumped was increased vertical flow into the aquifers through the intervening confining units and decreased vertical flow out of the aquifers (table 10).

The direction of simulated flow across confining units into or out of the underlying confined aquifers in 1980 is shown in figures 63 through 70. Comparison with figures 41 through 48 shows the change in the direction of vertical flow across confining units that resulted from the



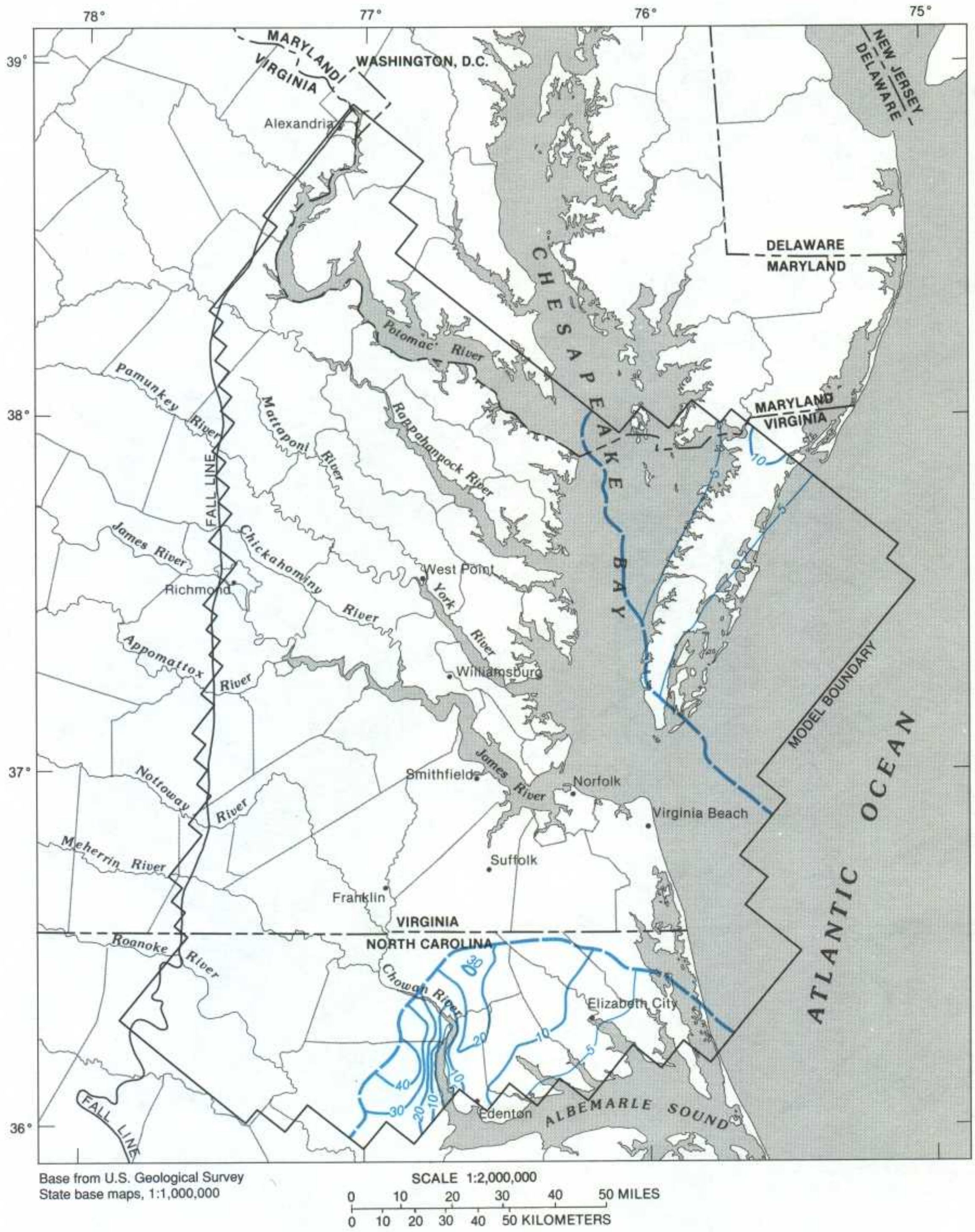
EXPLANATION

—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet. Datum is sea level

— — APPROXIMATE LIMIT OF YORKTOWN-EASTOVER AQUIFER

•3 WELL—Number is measured altitude of water level, in feet above or below sea level

FIGURE 50.—Simulated potentiometric surface of the Yorktown-Eastover aquifer and measured water levels, 1980.

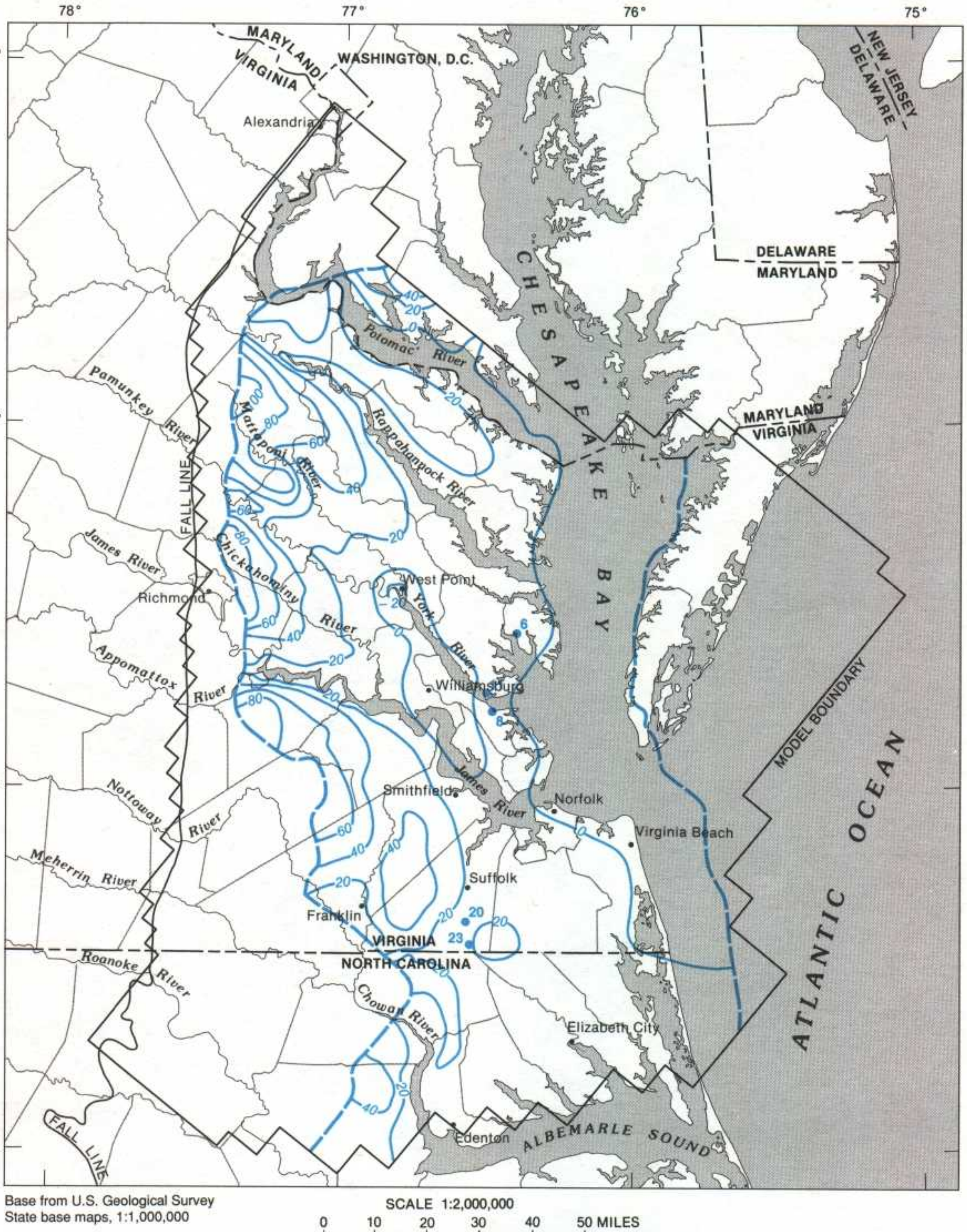


EXPLANATION

—10— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 10 feet with supplemental contour at 5 feet. Datum is sea level

— — APPROXIMATE LIMIT OF ST. MARYS-CHOPTANK AQUIFER

FIGURE 51.—Simulated potentiometric surface of the St. Marys-Choptank aquifer, 1980.



EXPLANATION

—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet. Datum is sea level

— — APPROXIMATE LIMIT OF CHICKAHOMINY-PINEY POINT AQUIFER

•11 WELL—Number is measured altitude of water level, in feet, above sea level

FIGURE 52.—Simulated potentiometric surface of the Chickahominy-Piney Point aquifer and measured water levels, 1980.

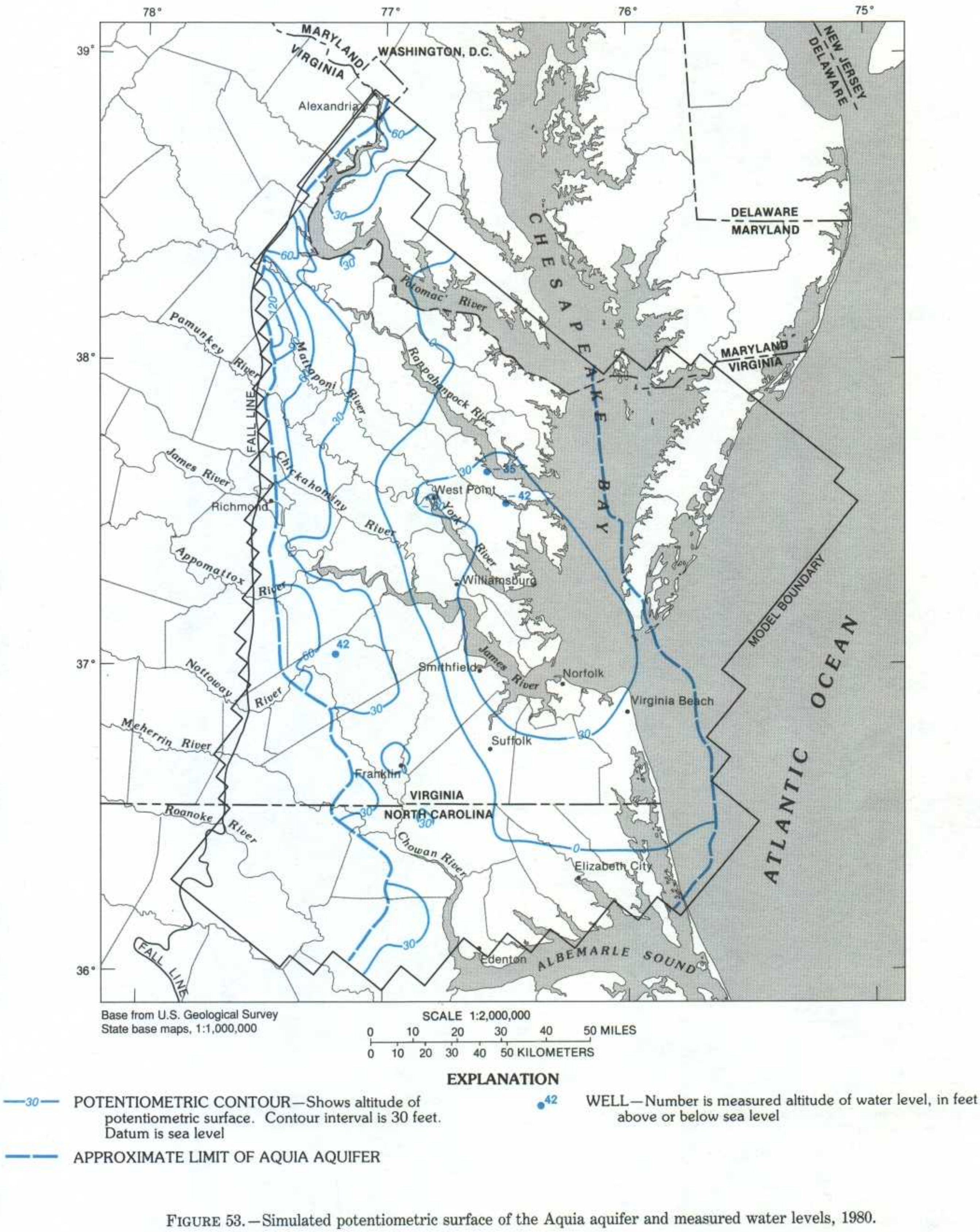
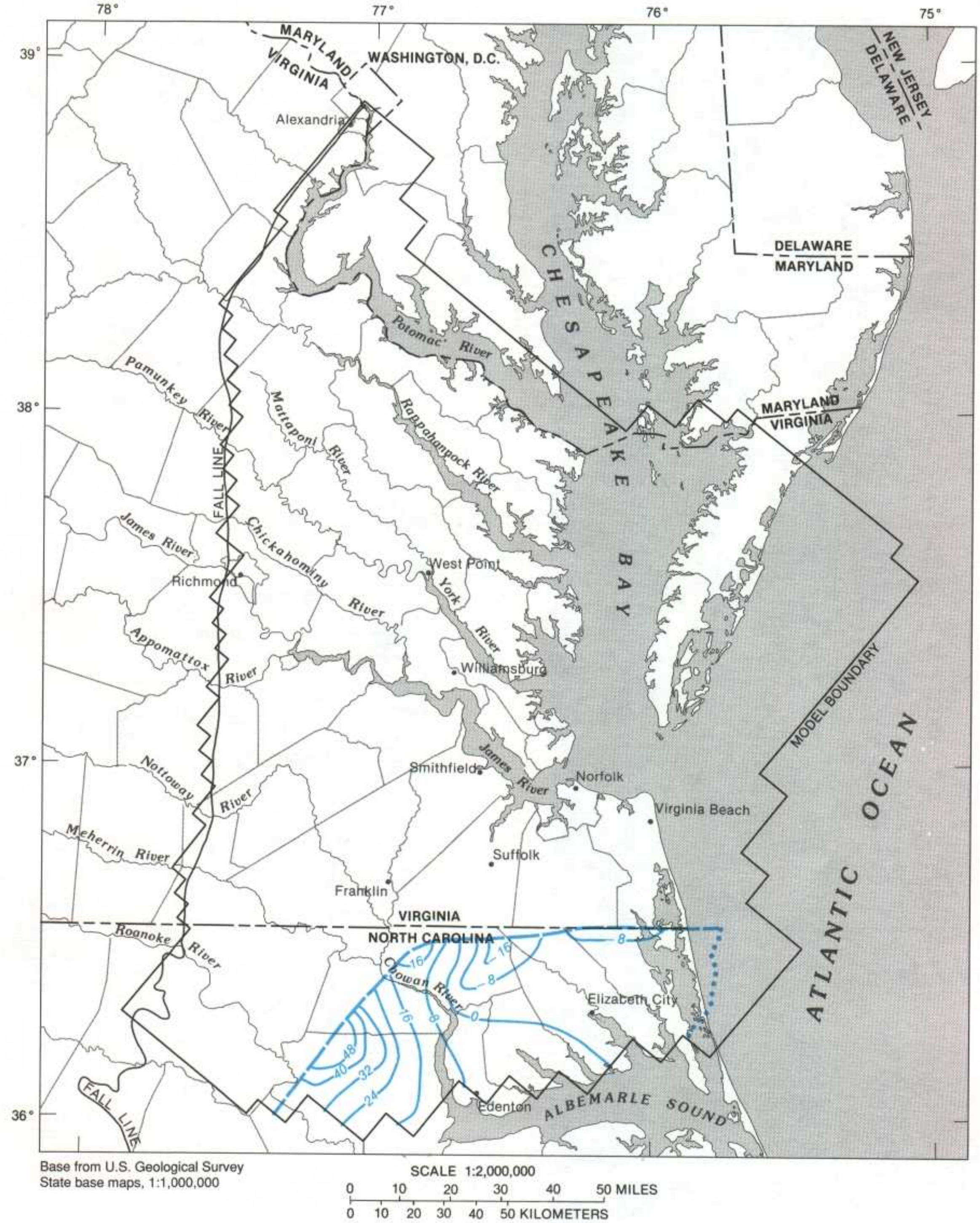


FIGURE 53.—Simulated potentiometric surface of the Aquia aquifer and measured water levels, 1980.



EXPLANATION

—8— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 8 feet. Datum is sea level

— — APPROXIMATE LIMIT OF AQUIFER 4

······· ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

FIGURE 54.—Simulated potentiometric surface of aquifer 4, 1980.

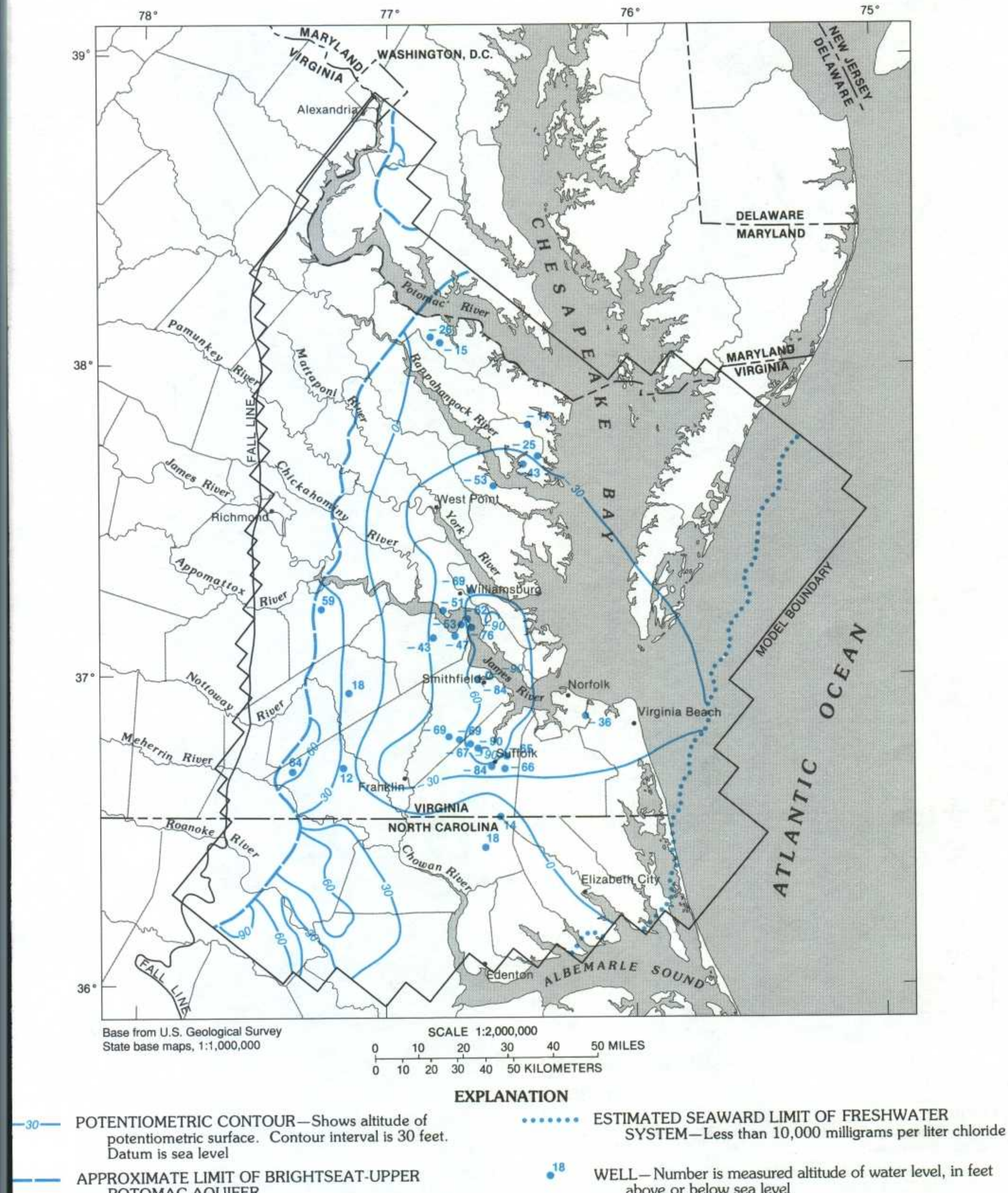


FIGURE 55.—Simulated potentiometric surface of the Brightseat-upper Potomac aquifer and measured water levels, 1980.

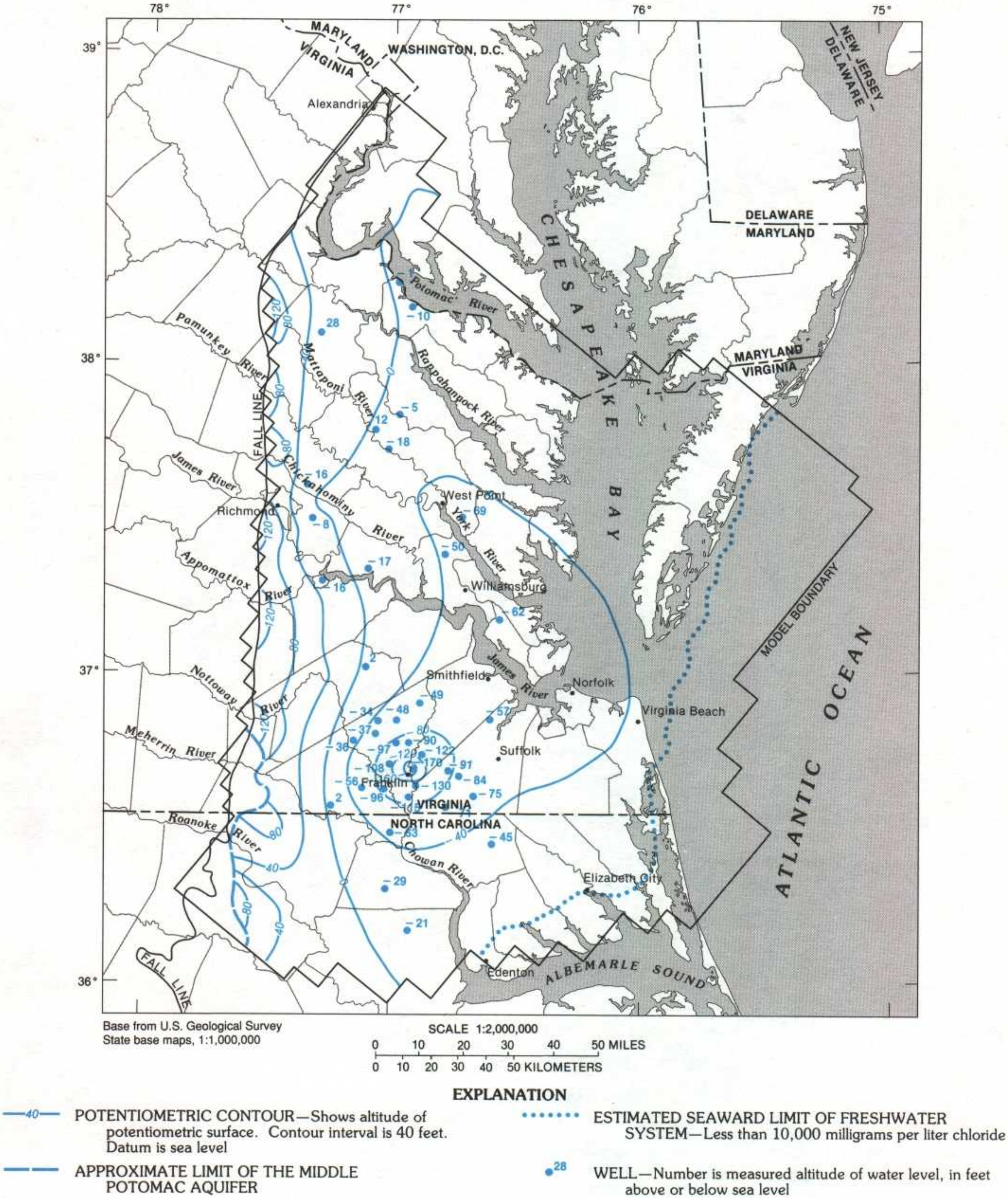
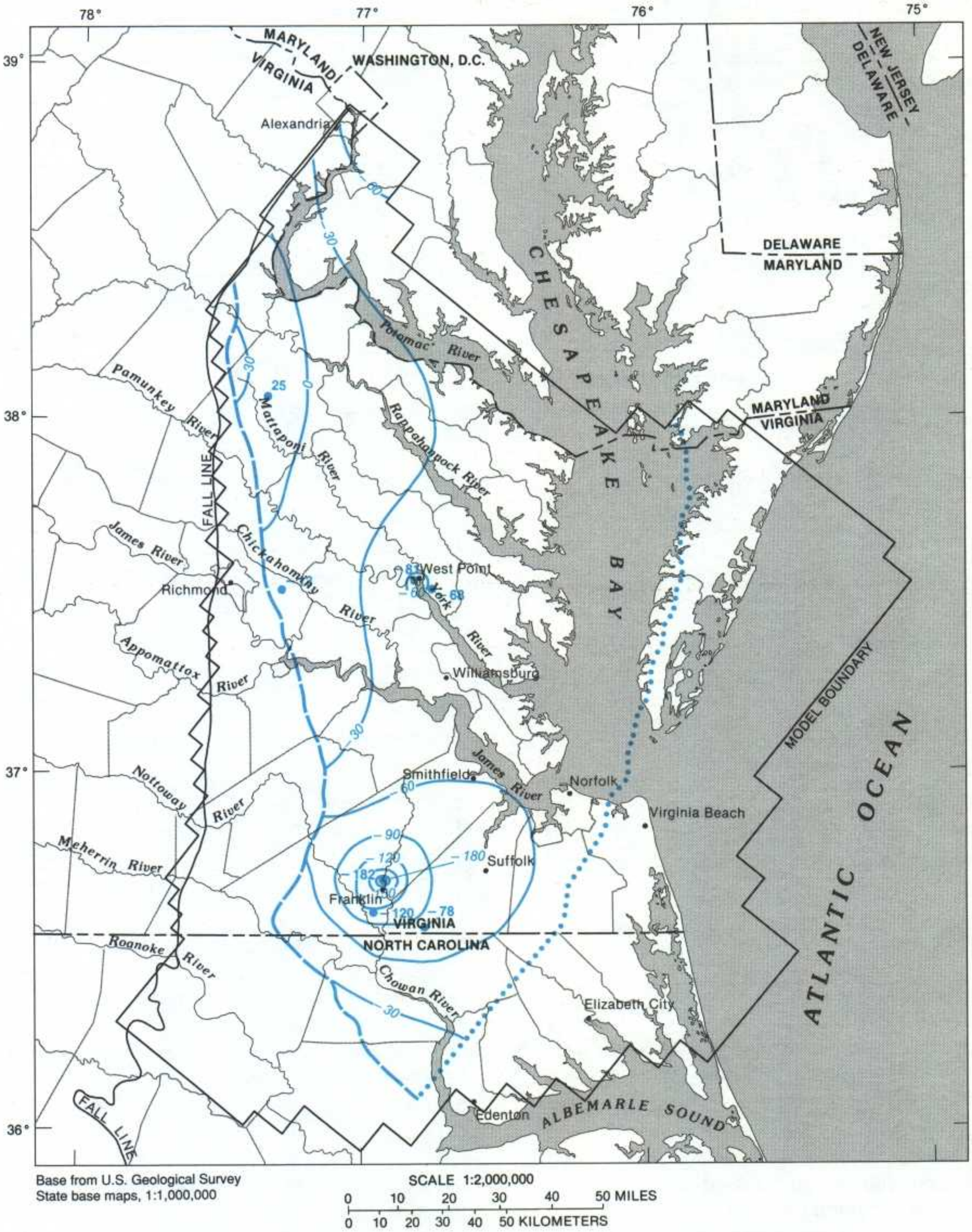


FIGURE 56.—Simulated potentiometric surface of the middle Potomac aquifer and measured water levels, 1980.



EXPLANATION

—30— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 30 feet. Datum is sea level

— — APPROXIMATE LIMIT OF LOWER POTOMAC AQUIFER

•••••• ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride

•25 WELL—Number is measured altitude of water level, in feet above or below sea level

FIGURE 57.—Simulated potentiometric surface of the lower Potomac aquifer, 1980.

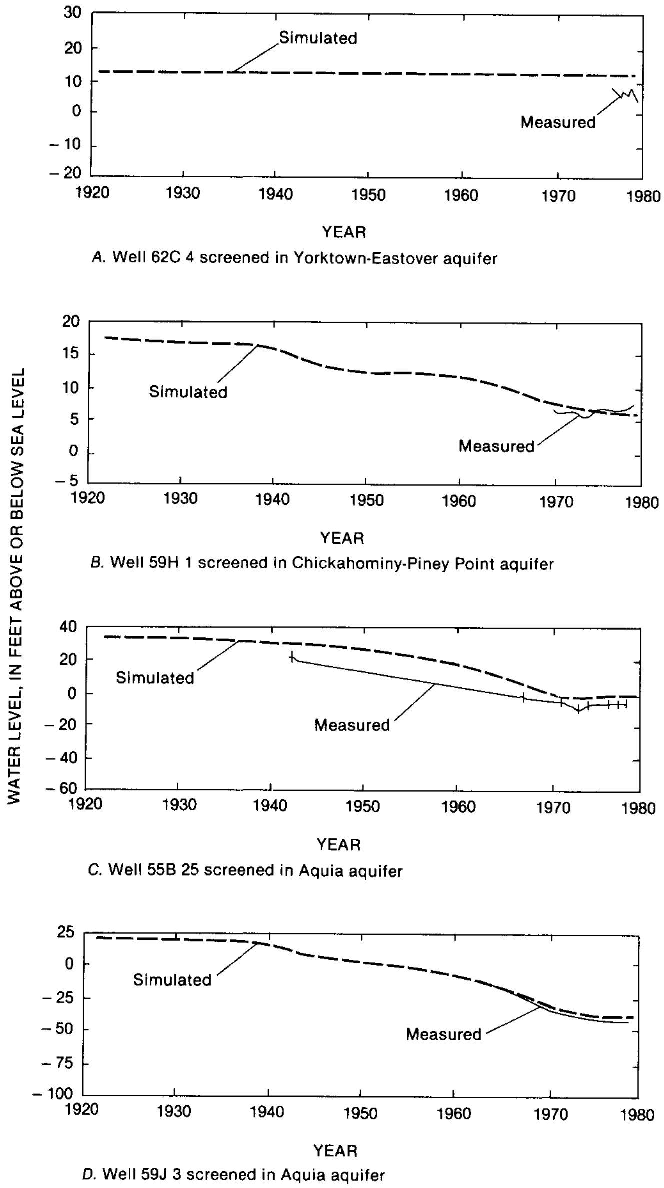


FIGURE 58.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

withdrawal of ground water from the confined aquifers. For example, during prepumping flow conditions the lower Potomac aquifer was recharged over about 25 percent of the total area of the lower Potomac confining unit (fig. 48). In 1980, the lower Potomac aquifer was recharged over about 93 percent of the total area of the lower Potomac confining unit (fig. 70). The remaining 7 percent of the lower Potomac confining unit recharged the middle Potomac aquifer because of large withdrawals from this aquifer near the cities of Williamsburg and Suffolk.

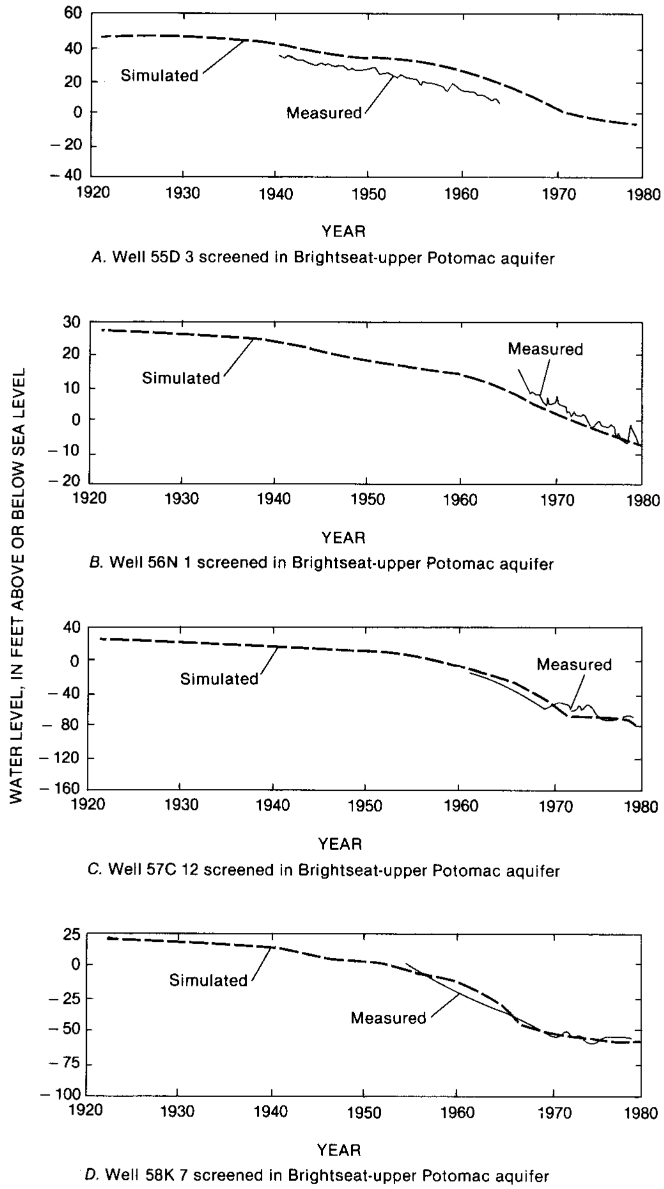


FIGURE 59.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

The development of ground water affected the direction of flow of water between the confined and water-table aquifer systems. Table 10 gives the quantity of water entering and leaving the confined flow system at the end of each pumping period. In 1980, about 177 Mgal/d of water flowed into the confined flow system from the water-table aquifer and about 73 Mgal/d flowed out of the confined flow system into the water-table aquifer. Comparison of the prepumping and final pumping period (1978–80) net leakage values shows an increase of about 110 Mgal/d into the confined flow

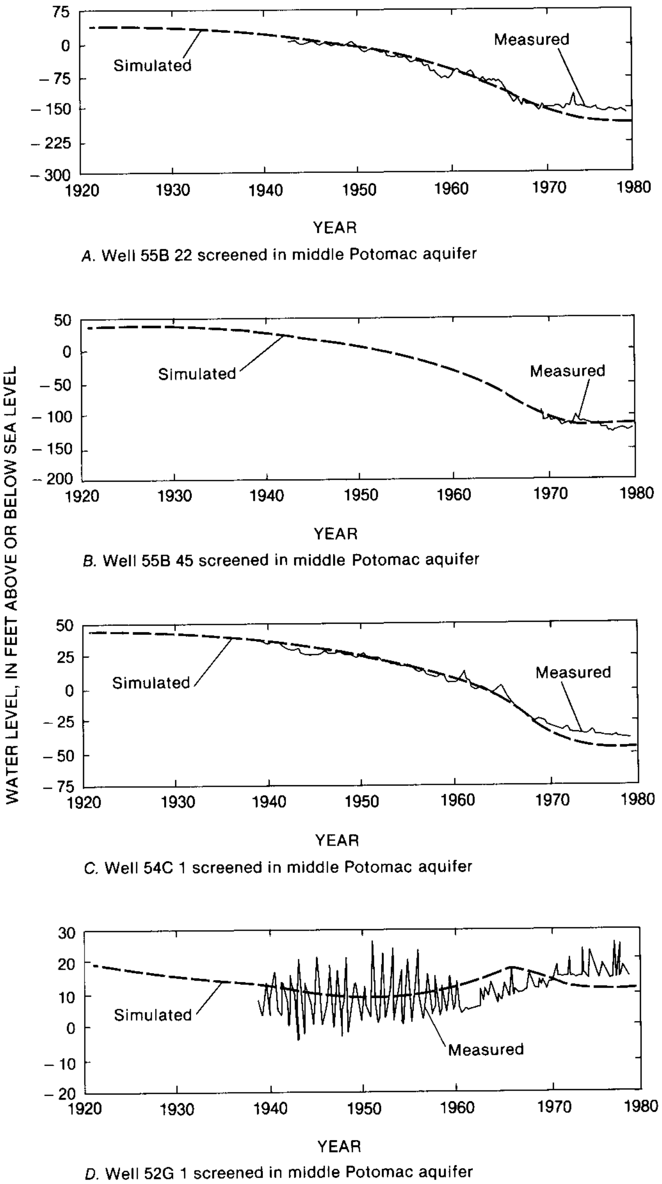


FIGURE 60.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

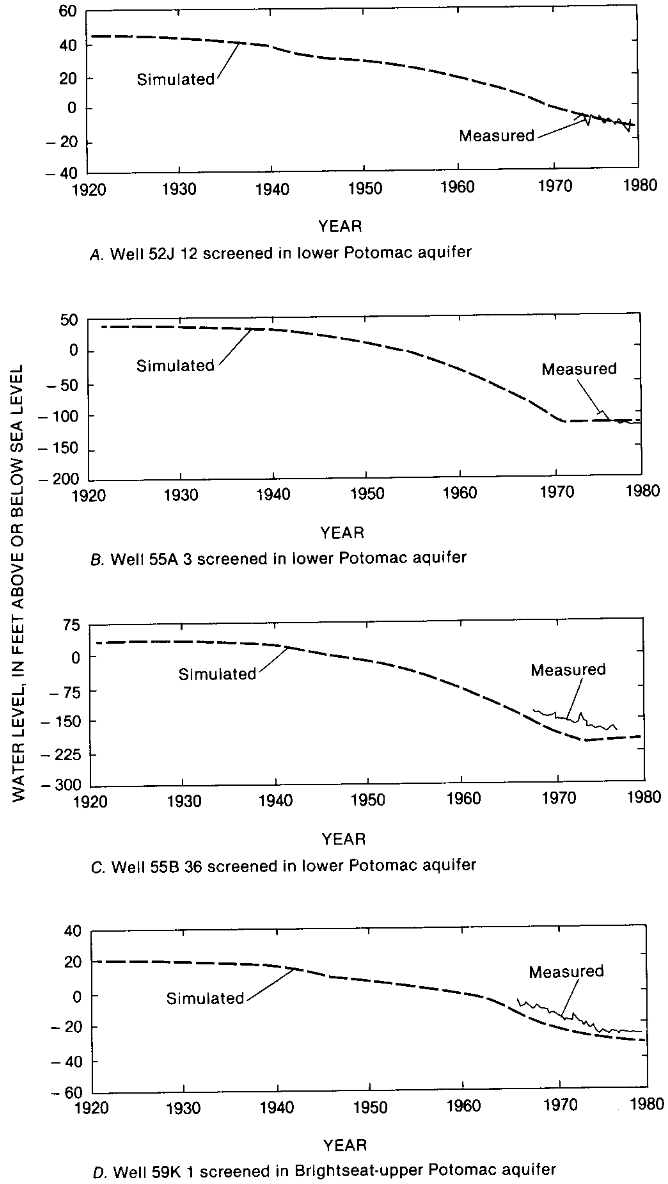


FIGURE 61.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

system over the entire period of simulation. This change in leakage affected the local discharge of ground water to streams and the regional discharge of ground water to coastal water.

The simulated direction of flow between the confined flow system and the water-table aquifer in 1980 is shown in figure 71. Simulated rates of flow entering the confined flow system varied up to about 3.8 in/yr. Simulated rates of flow leaving the confined flow system varied up to about 2.2 in/yr. Comparison of figures 49 and 71 suggests that the withdrawal of ground water from the confined aquifers increased the area of recharge into the confined flow system by about 33 percent. Prior to withdrawal, water in the confined flow system discharged into Chesapeake Bay (fig. 49). Withdrawal from the confined aquifers resulted in the movement of water from Chesapeake Bay into the confined flow system (fig. 71). This movement could affect the water quality of both Chesapeake Bay and the underlying confined flow system.

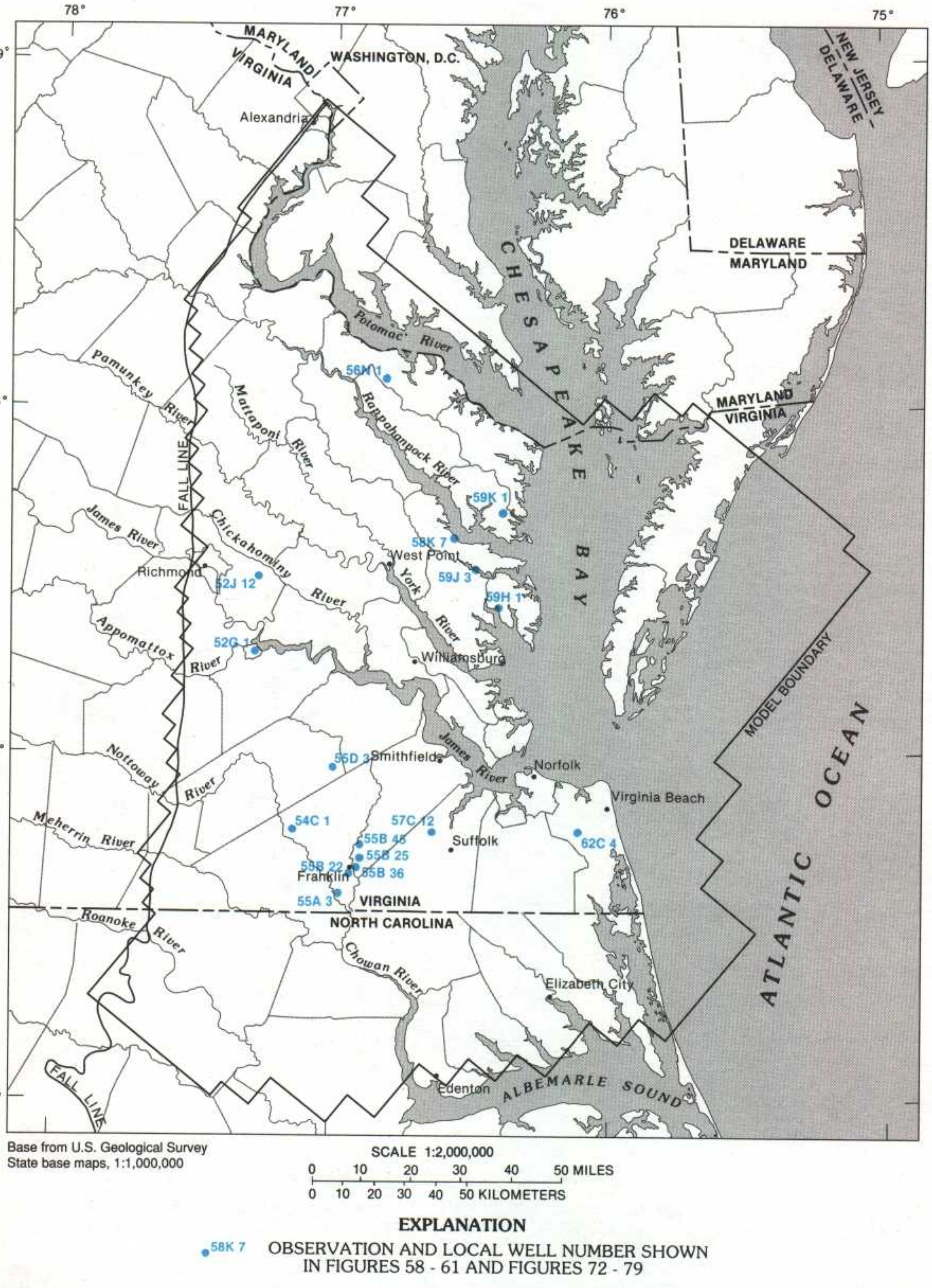


FIGURE 62.—Locations of observation wells used in model calibration for pumping conditions.

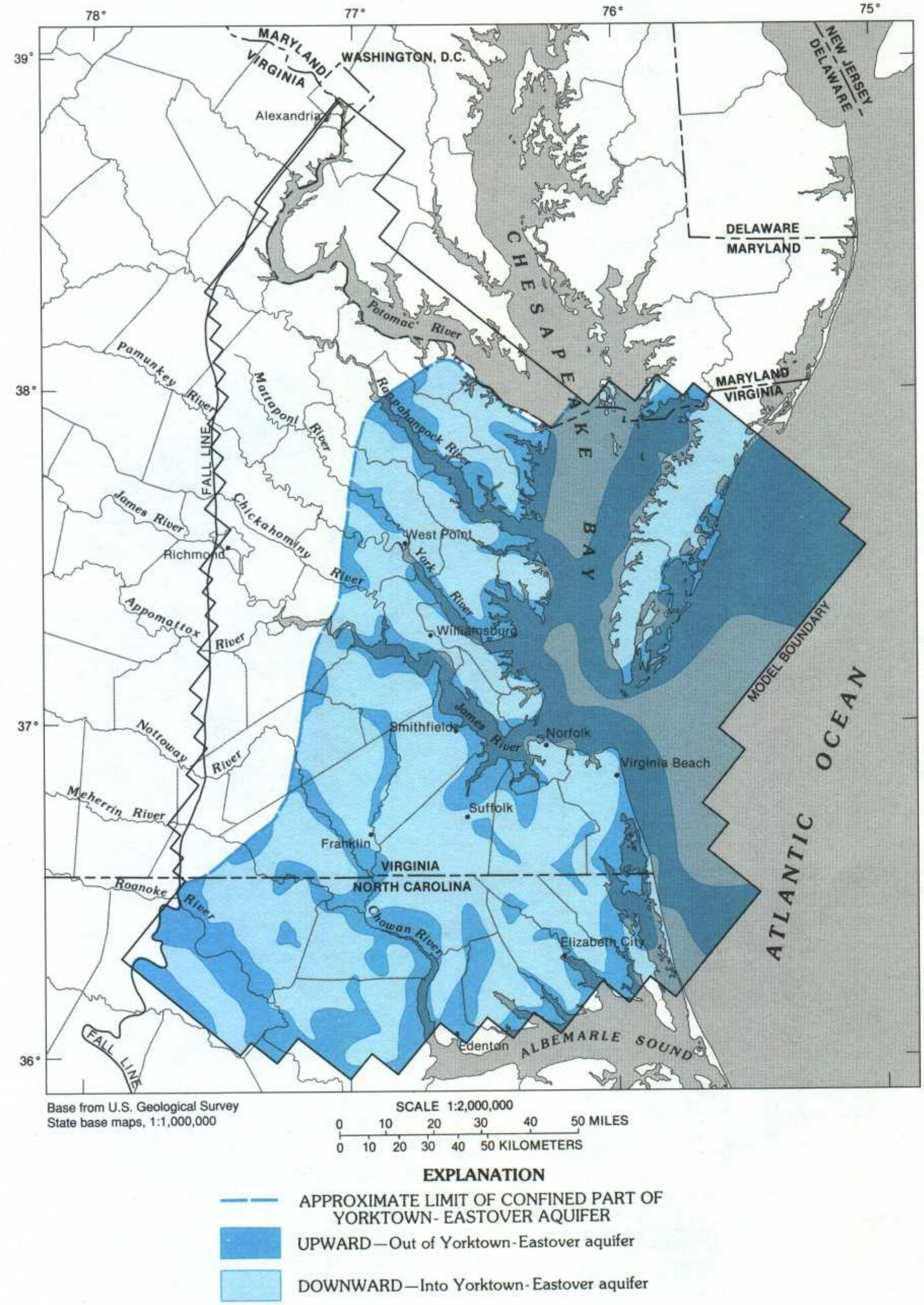


FIGURE 63.—Direction of simulated flow across the Yorktown confining unit, 1980.

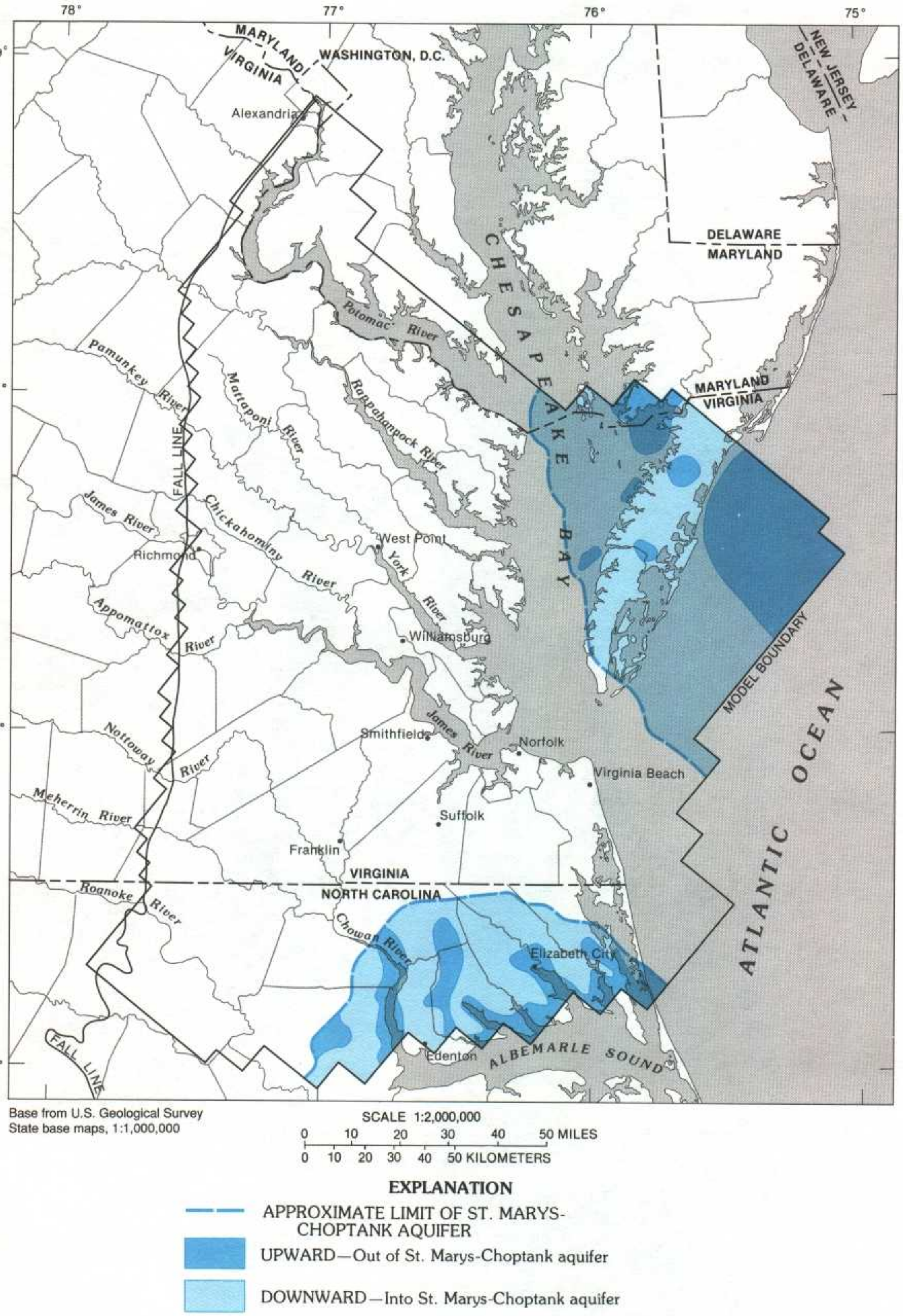


FIGURE 64.—Direction of simulated flow across the St. Marys confining unit, 1980.

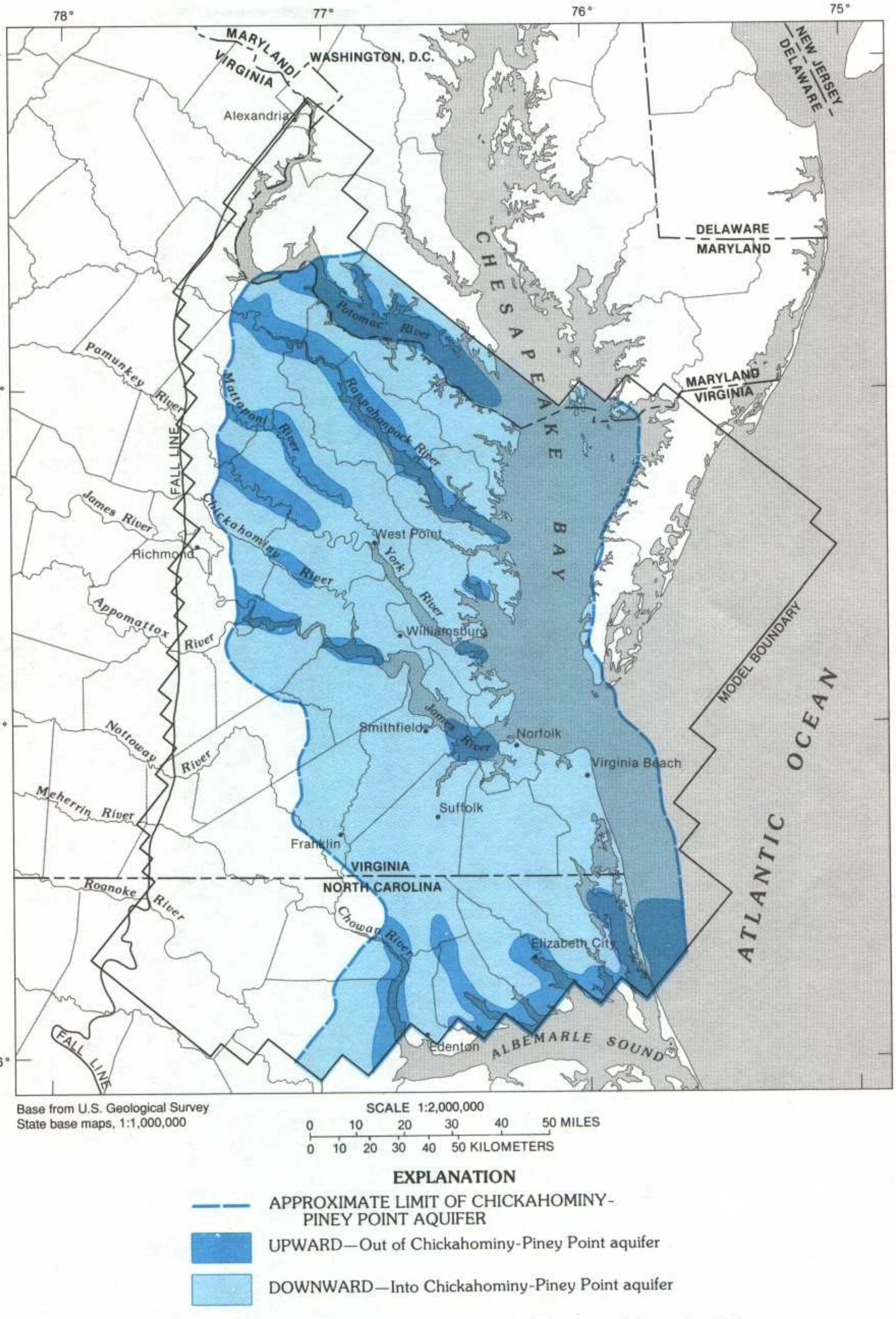
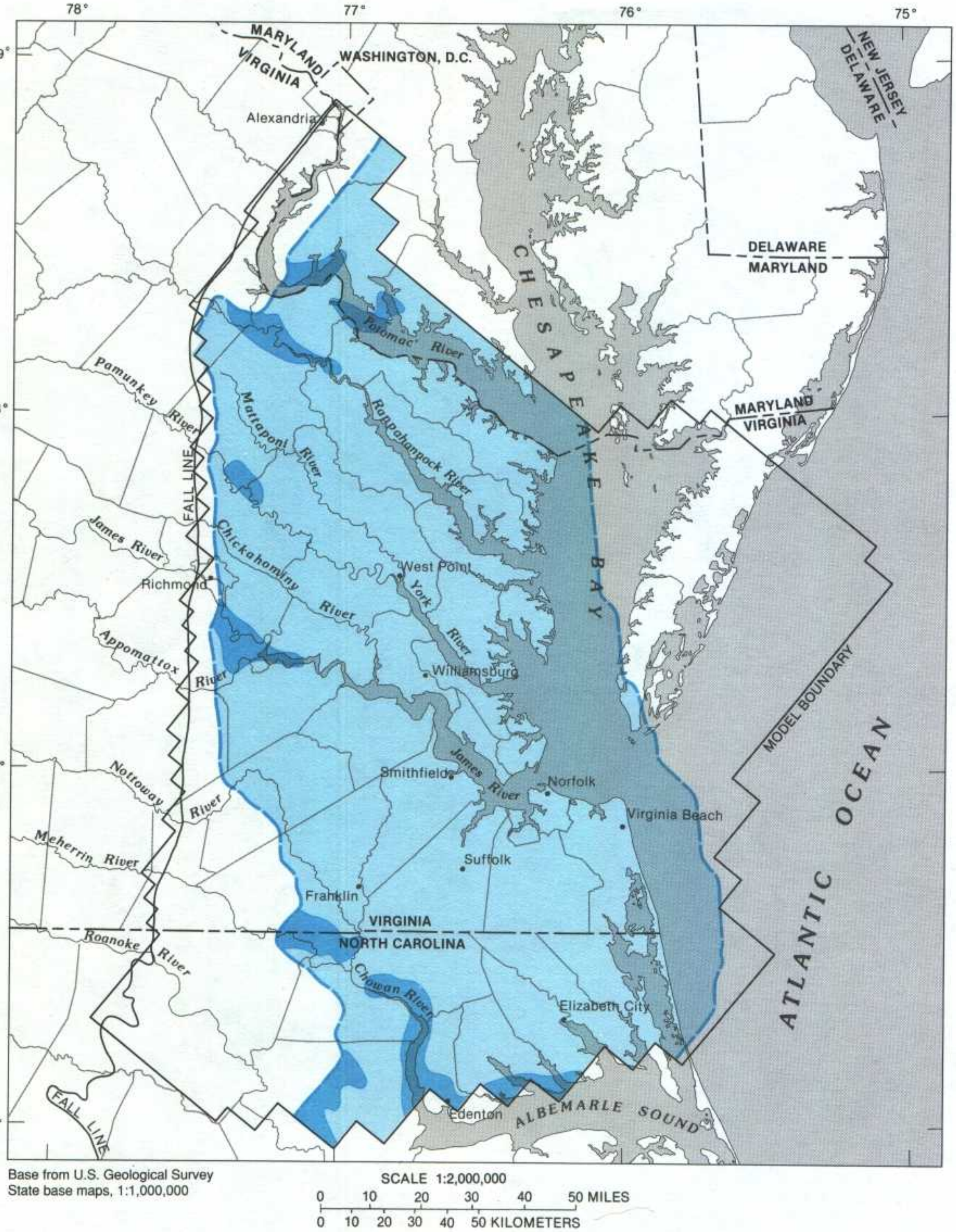


FIGURE 65.—Direction of simulated flow across the Calvert confining unit, 1980.



EXPLANATION

APPROXIMATE LIMIT OF CONFINED PART OF AQUIA AQUIFER

UPWARD—Out of Aquia aquifer

DOWNWARD—Into Aquia aquifer

FIGURE 66.—Direction of simulated flow across the Nanjemoy-Marlboro confining unit, 1980.

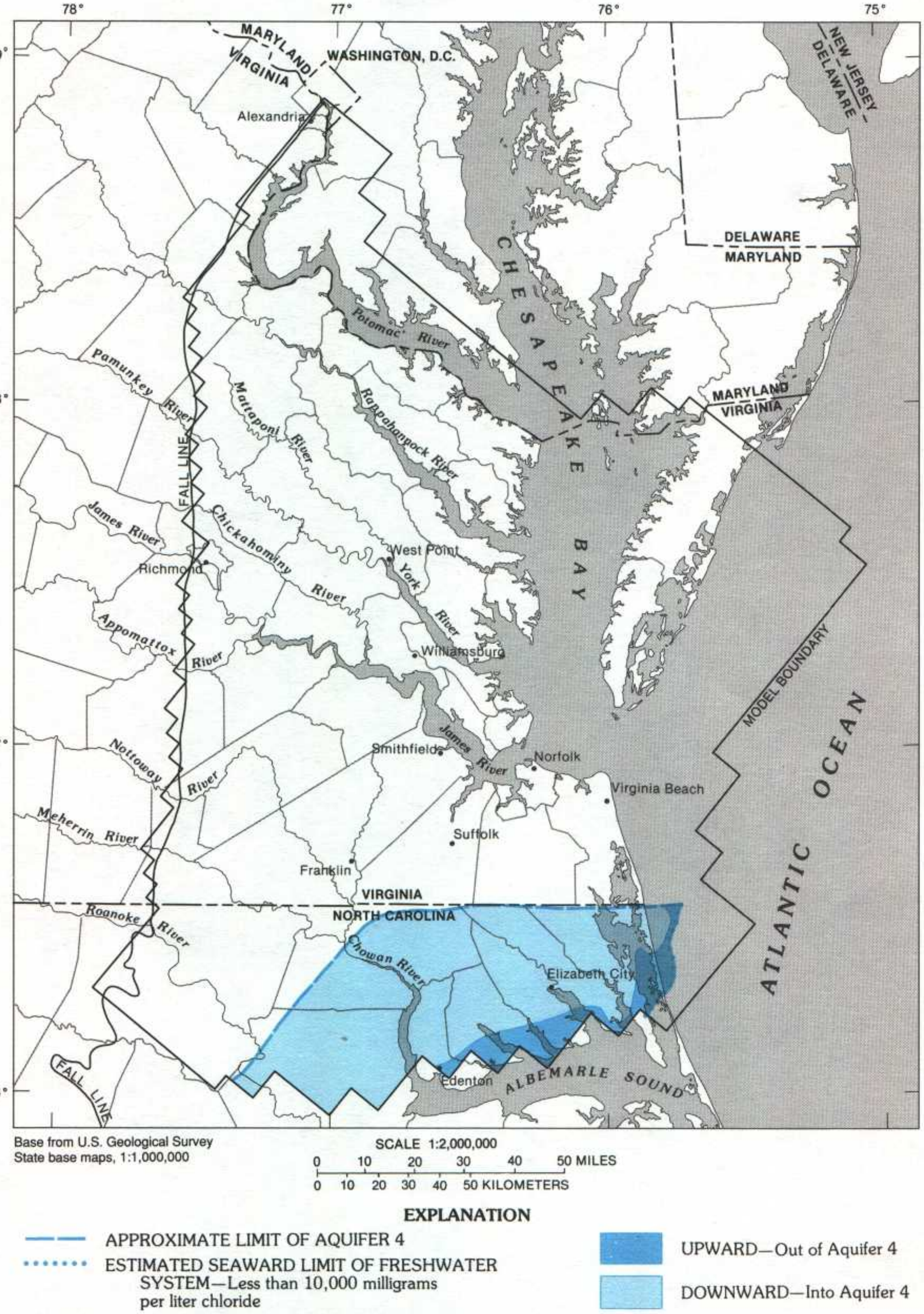


FIGURE 67.—Direction of simulated flow across confining unit 4, 1980.

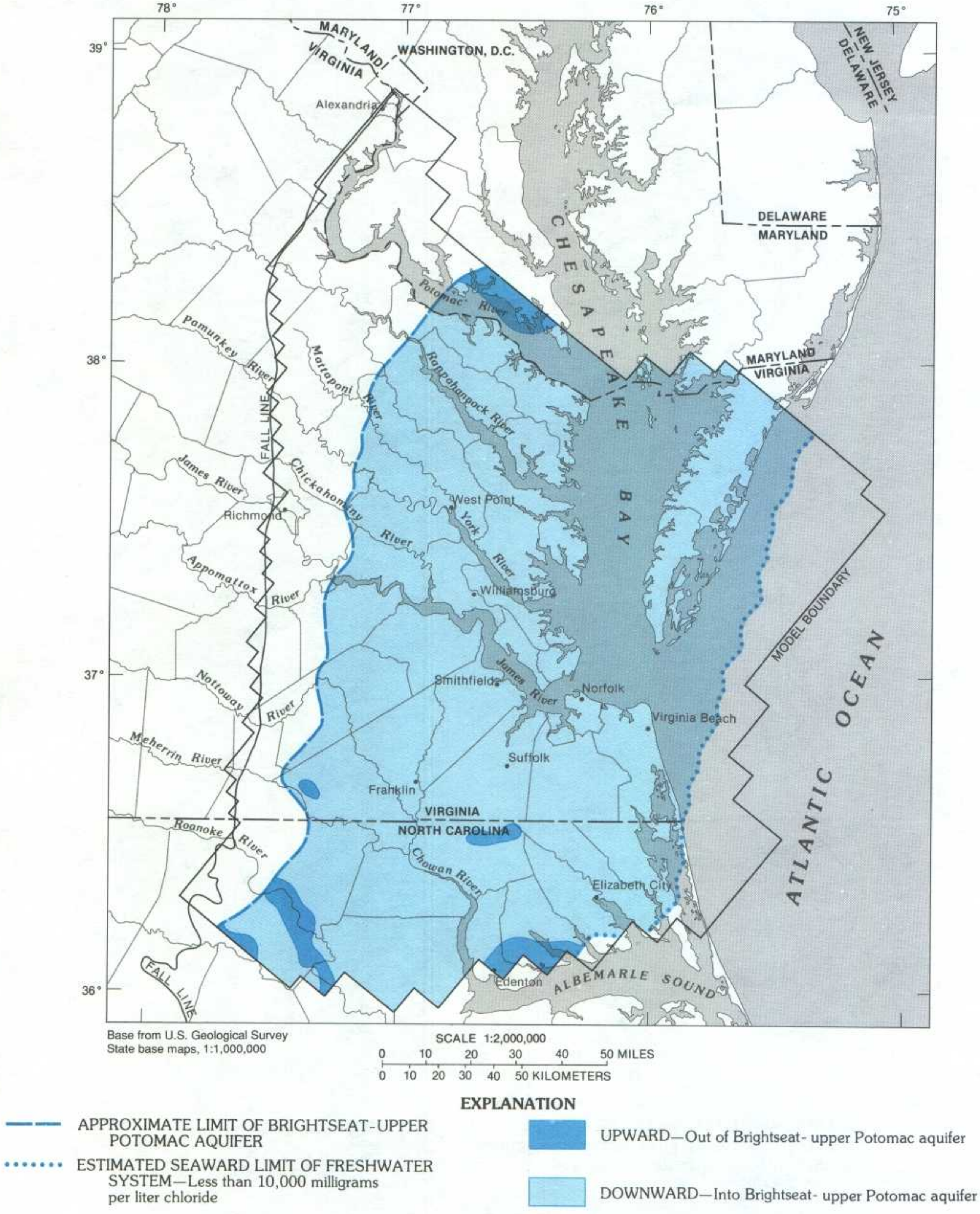


FIGURE 68.—Direction of simulated flow across the Brightseat-upper Potomac confining unit, 1980.

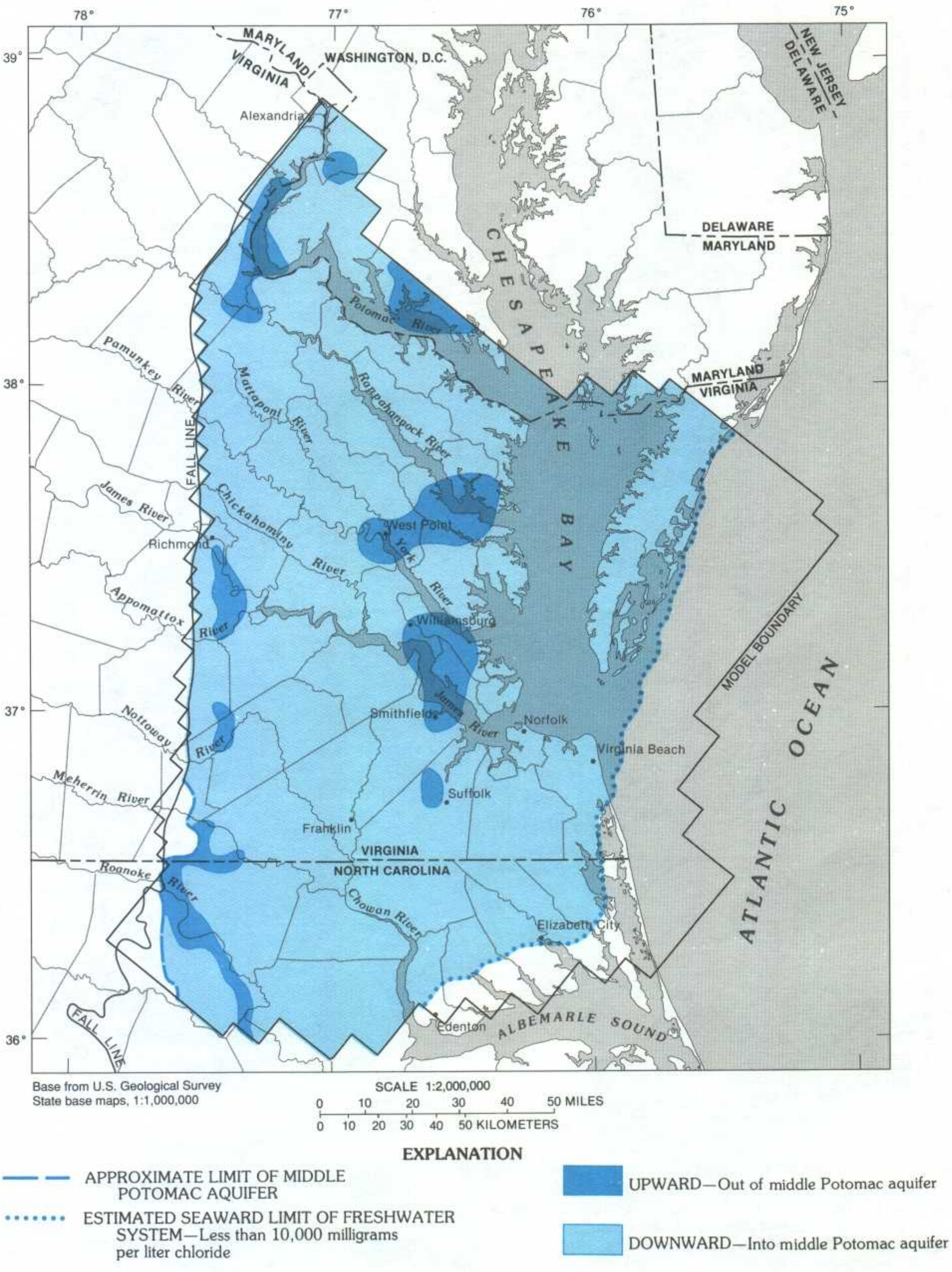
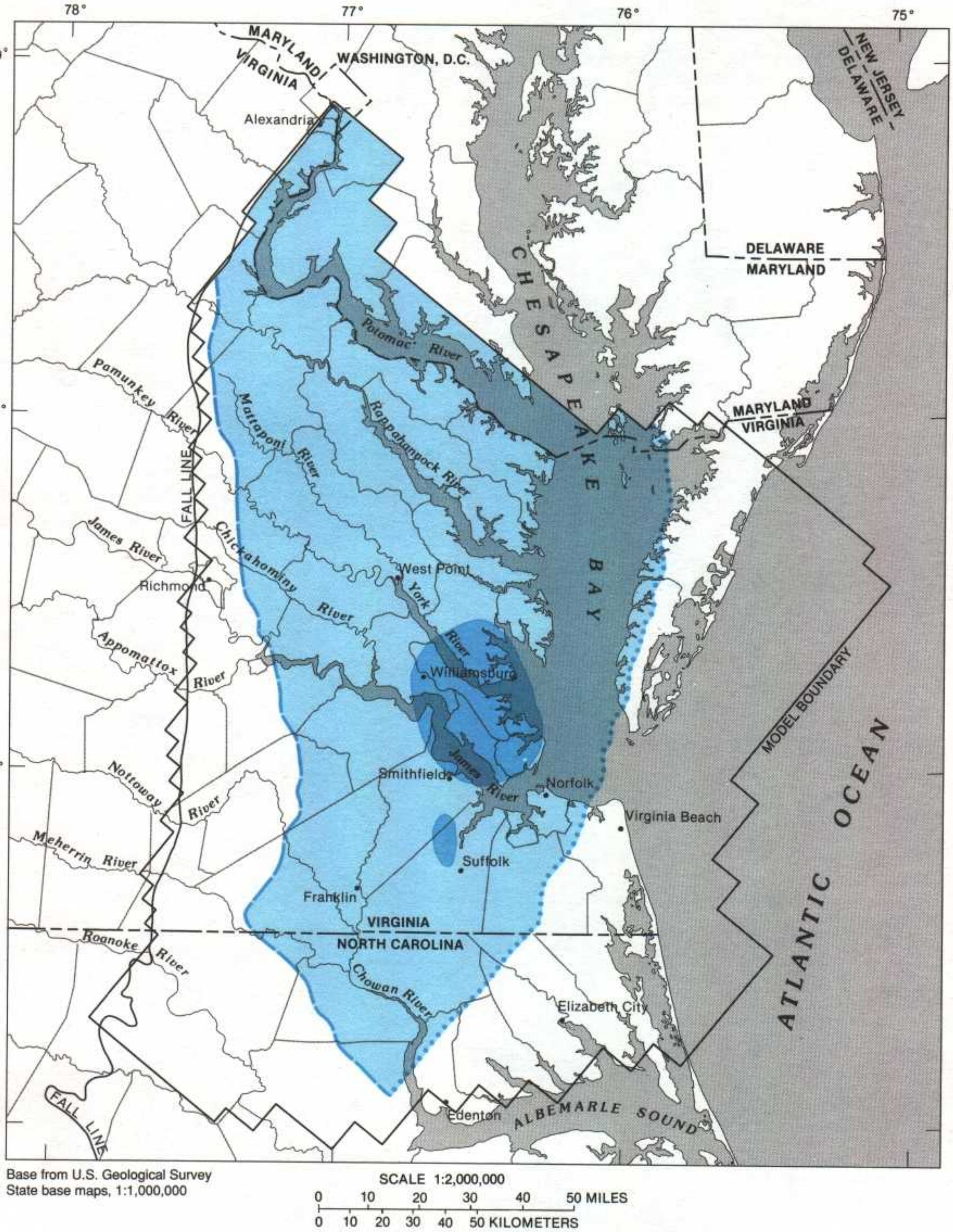


FIGURE 69.—Direction of simulated flow across the middle Potomac confining unit, 1980.



EXPLANATION

- — — APPROXIMATE LIMIT OF LOWER POTOMAC AQUIFER
- ······· ESTIMATED SEAWARD LIMIT OF FRESHWATER SYSTEM—Less than 10,000 milligrams per liter chloride
- UPWARD—Out of lower Potomac aquifer
- DOWNWARD—Into lower Potomac aquifer

FIGURE 70.—Direction of simulated flow across the lower Potomac confining unit, 1980.

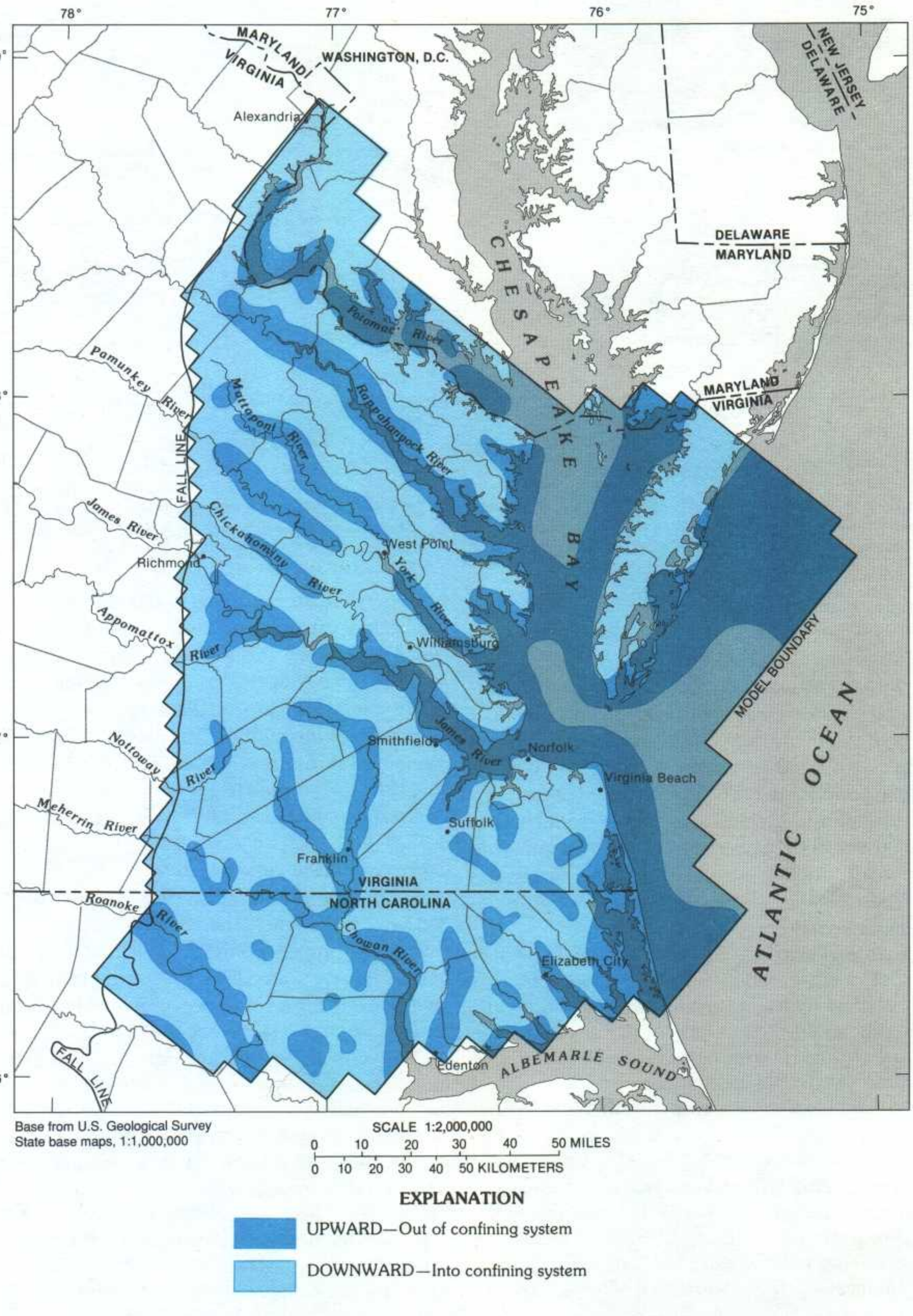


FIGURE 71.—Direction of simulated flow into and out of the confined system, 1980.

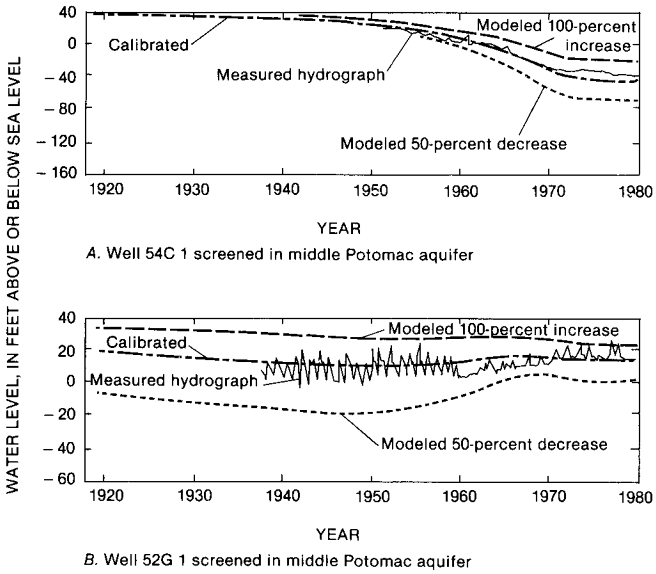


FIGURE 72.—Effects on simulated heads of varying the calibrated value of transmissivity of the middle Potomac aquifer. (Location of wells shown in fig. 62.)

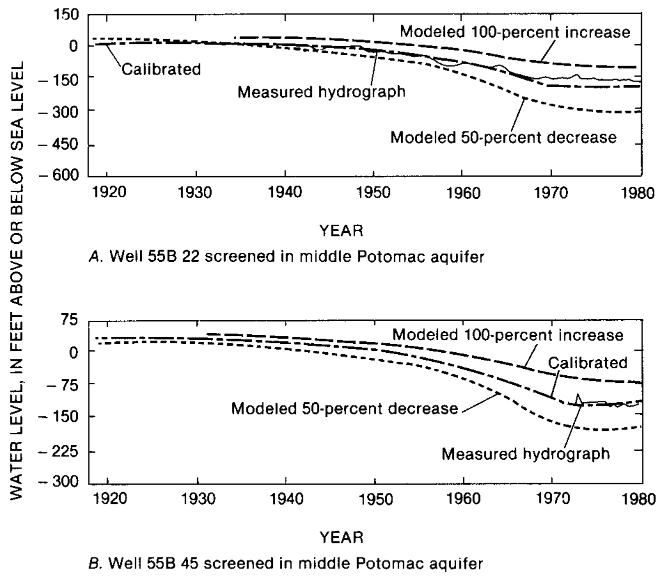


FIGURE 73.—Effects on simulated heads of varying the calibrated value of transmissivity of the middle Potomac aquifer. (Location of wells shown in fig. 62.)

SENSITIVITY ANALYSIS

Sensitivity analysis determines the accuracy of model results in accordance with the degree of uncertainty associated with the simulated value of hydraulic characteristics. In the procedure, the value of an individual calibrated hydraulic characteristic is changed over a specific range, while other values of calibrated characteristics remain unchanged. The magnitude of the change in water levels defines the sensitivity of the model to that hydraulic characteristic and is measured by comparing water-level hydrographs simulated by the calibrated model with those simulated with the changed value of the hydraulic characteristic.

Hydraulic characteristics varied to test model sensitivity were (1) transmissivity of the middle Potomac aquifer, (2) vertical hydraulic conductivity of the middle Potomac confining unit, (3) storage coefficient of the confined aquifers, and (4) specific storage of the confining units. The first two were selected because it was found during calibration that these two hydraulic characteristics had the greatest effect on simulated water levels. The aquifer storage coefficient was tested to evaluate the response of the ground-water flow system to changes in aquifer storage. Storage properties of confining units were tested to determine the significance of neglecting storage in confining units during transient simulations. Table 12 summarizes these sensitivity tests and the results. Lateral flow across model boundaries was not recalculated for any of the sensitivity simulations.

Figures 72 and 73 compare water levels in the middle Potomac aquifer at four observation wells resulting from a 50-percent decrease and a 100-percent increase in the calibrated values of transmissivity. The locations of the wells are shown in figure 62. Water levels within this same aquifer resulting from a 50-percent decrease and a 100-percent increase in the calibrated value of vertical hydraulic conductivity of the overlying confining unit are compared in figures 74 and 75. The sensitivity analysis showed that simulated water levels are much more sensitive to decreases in the selected values of transmissivity and vertical hydraulic conductivity than to increases in the values tested.

Four hydrographs (figs. 76, 77), representing observation wells in the Chickahominy-Piney Point, Brightseat-upper Potomac, and middle Potomac aquifers, compare water levels resulting from an increase of and a decrease of one order of magnitude in the calibrated storage coefficient (1.0×10^{-4}). The locations of these wells are shown in figure 62. The general agreement between hydrographs simulated with the calibrated and the lower value of storage coefficient (1.0×10^{-5}) indicates that the system is near equilibrium at the end of each pumping period and suggests that the calibrated storage coefficient is a reasonable value for simulation. The water levels, which result from an increase in storage coefficient of one order of magnitude, show that the system is sensitive to the higher value (1.0×10^{-3}). The increase in the amount of water released from storage had a significant effect on simulated water levels. The higher value of storage coefficient is not reasonable for confined aquifers in the study area except in a few local areas.

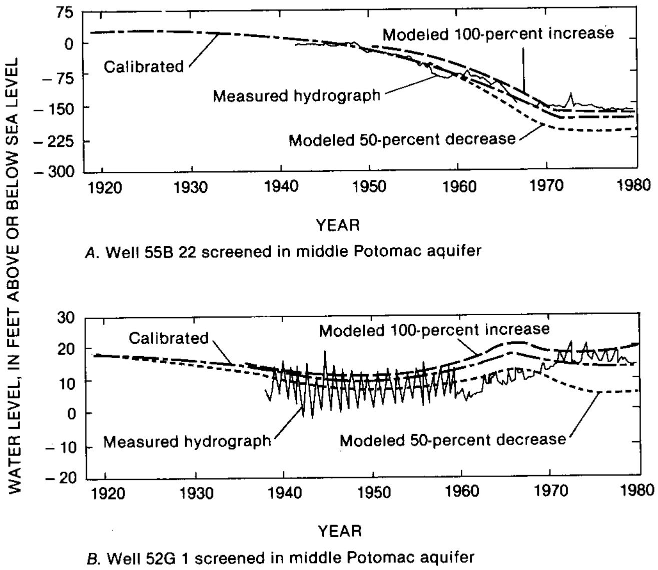


FIGURE 74.—Effects on simulated heads of varying the calibrated value of vertical hydraulic conductivity of the middle Potomac confining unit. (Location of wells shown in fig. 62.)

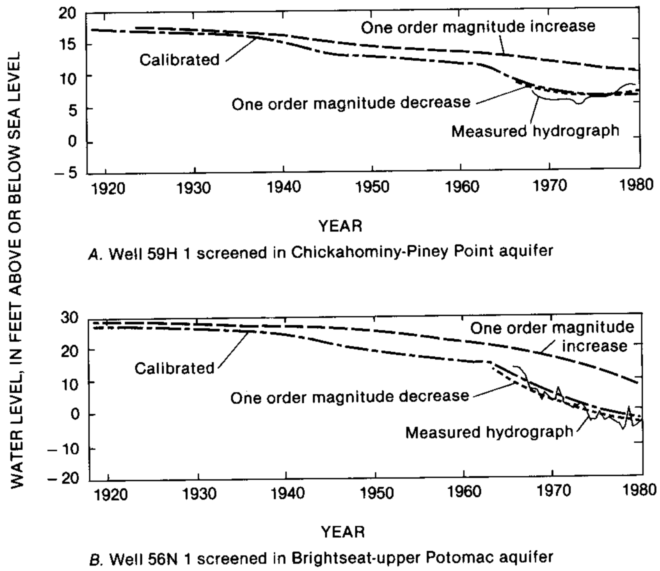


FIGURE 76.—Effects on simulated heads of varying the calibrated value of storage coefficient. (Location of wells shown in fig. 62.)

The calibrated model was developed on the assumption that the effects of storage released from the confining units are negligible over a pumping period. The sensitivity of the model to confining unit storage was tested simulating two values of storage coefficient for each confining unit. One value of storage coefficient was calculated by multiplying the average thickness of each confining unit by a specific storage of 1.0×10^{-6} ft^{-1} (Lohman, 1979). This method assumes that all water released from storage results only from the compressibility of water. The other set of values tested was computed by multiplying the average confining unit thickness by a specific storage of 1.0×10^{-4} ft^{-1}. Storage coefficients tested are shown for each aquifer in table 13.

A specific storage of 1.0×10^{-6} ft^{-1} and the calibrated value, which neglects water released from confining unit storage, resulted in approximately the same water levels (figs. 78, 79). These simulations indicate that the effect of

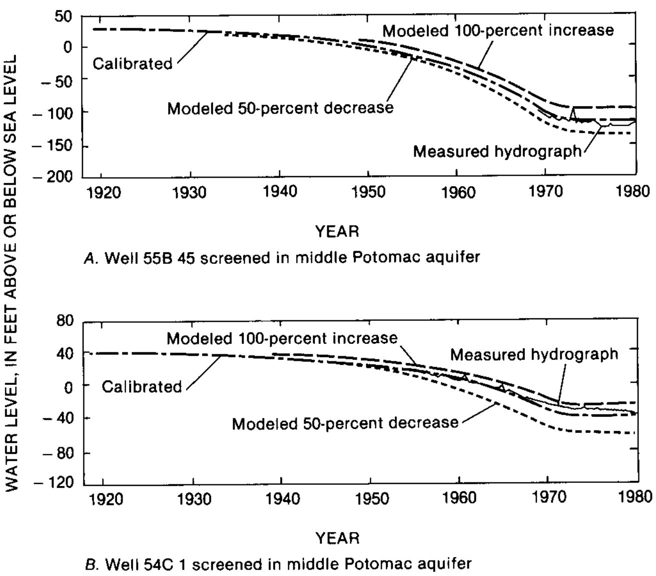


FIGURE 75.—Effects on simulated heads of varying the calibrated value of vertical hydraulic conductivity of the middle Potomac confining unit. (Location of wells shown in fig. 62.)

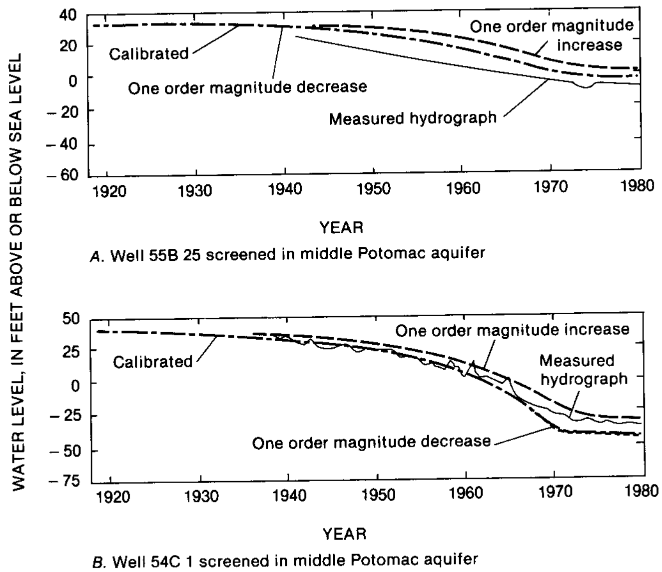


FIGURE 77.—Effects on simulated heads of varying the calibrated value of storage coefficient. (Location of wells shown in fig. 62.)

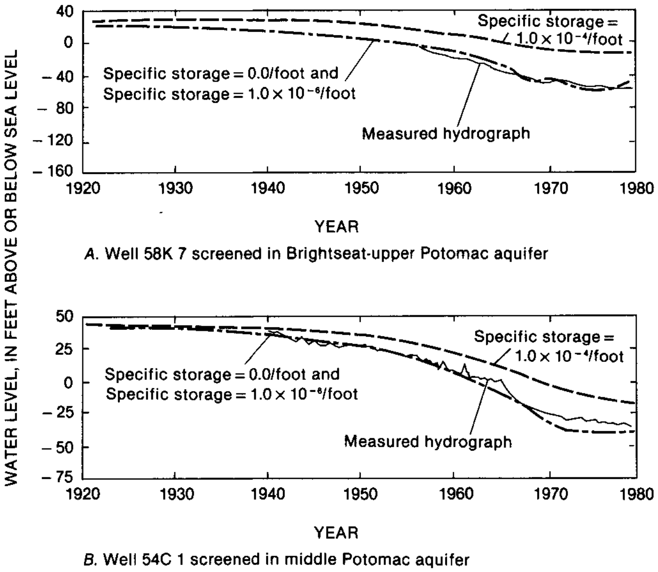


FIGURE 78.—Effects on simulated heads of transient leakage. (Location of wells shown in fig. 62.)

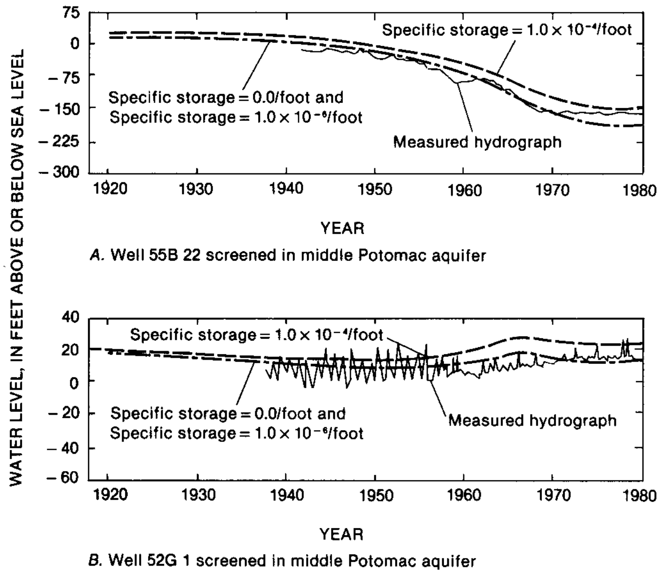


FIGURE 79.—Effects on simulated heads of transient leakage. (Location of wells shown in fig. 62.)

confining unit storage probably is not significant if the water released from confining unit storage is due to the compressibility of water only. Hydrographs generated from confining units having a specific storage of 1.0×10^{-4} ft^{-1} show significantly higher water levels (figs. 78, 79; table 12). The calibrated model does not include confining unit storage because quantitative data defining the storage properties of confining units are not available, and actual storage coefficients probably are closer to the values computed assuming a specific storage of 1.0×10^{-6} ft^{-1}.

LIMITATION AND APPLICATION OF THE FLOW MODEL

The calibrated model is suitable for analyzing the regional flow of ground water in the confined flow system and for evaluating the long-term effects of large-scale withdrawal from the confined aquifers. The model can project the regional impact of proposed large-scale withdrawal scenarios. The large grid scale limits the model's ability to provide detailed analysis of local flow effects. In this study, the accuracy of the model is governed by estimates of hydraulic characteristics, grid spacing (12.25-mi^2 blocks), and time intervals of the 10 pumping periods (3 to 30 yr). Further refinement of the model grid and the values of hydraulic characteristics of aquifers and confining units is needed to analyze local ground-water flow and the short-term effects of ground-water withdrawal and recharge.

The method used to simulate ground-water flow in the water-table aquifer provides an upper boundary condition for the model. The simulation allows water levels to fluctuate in the water-table aquifer; however, it is not intended to provide a detailed analysis of flow in the water-table aquifer or of flow between the water-table aquifer and streams. Additional data defining streambed leakance, stream base flow, and withdrawal from the water-table aquifer are needed to simulate the water-table aquifer more accurately and to quantify flow between the water-table aquifer and streams locally.

More detailed definition of the time-dependent stresses acting on the ground-water flow system and the transient effects of confining unit storage is needed to simulate short-term effects of droughts, seasonal variations in precipitation, and withdrawal. Data needed are storage coefficients of individual confining units and ground-water withdrawal and recharge rates for time intervals smaller than the average annual value.

SUMMARY AND CONCLUSIONS

The unconsolidated sand, silt, and clay of the Coastal Plain aquifer system are an important source of industrial, municipal, domestic, and agricultural water supplies in the Coastal Plain of Virginia. This fresh-ground-water flow system is bounded below and on the west by bedrock, and on the east by salty water. These unconsolidated sediments form a multiaquifer system consisting of a water-table aquifer and an underlying sequence of confined aquifers and intervening confining units that unconformably rest on basement. Near major river channels, aquifers and confining units have been partially or completely eroded and replaced by material more permeable than the confining unit but less permeable than the aquifer.

Use of ground water from confined aquifers began in the Virginia Coastal Plain in the late 1800's and had increased to about 100 Mgal/d in 1980. The continued withdrawal of large quantities of water has resulted in a steady decline of water levels. The decline has changed the direction of ground-water flow toward major pumping centers. These centers are located near the cities of Franklin, Williamsburg, Suffolk, and Alexandria and the towns of West Point and Smithfield. Total withdrawal from these centers is estimated to have been 65 Mgal/d in 1980. The largest center is near Franklin, where withdrawals exceeded 40 Mgal/d in 1980.

A digital flow model was developed to simulate the response of the ground-water flow system to ground-water development. Withdrawal data for each confined aquifer were compiled for the period of simulation, 1891–1980. The middle Potomac aquifer is the most important source of ground water in the Virginia Coastal Plain and supplied an average of about 56 Mgal/d during the period 1978–80. The transmissivity distribution was defined for each aquifer; in general, transmissivity increases from the Fall Line eastward but decreases farther eastward near the freshwater-saltwater interface. The lower and middle Potomac aquifers are the most transmissive aquifers; estimated transmissivity ranges from 410 to 18,145 ft^2/d for the middle Potomac aquifer and from 250 to 12,440 ft^2/d for the lower Potomac aquifer. Vertical leakances simulated the effects of confining units on vertical flow between aquifers.

Maps showing simulated prepumping potentiometric surfaces indicate regional movement of water from the Fall Line toward coastal areas and local movement of ground water from interfluves toward major river valleys. Maps showing simulated flow across confining units indicate that most recharge occurred in narrow bands approximately parallel to the Fall Line and under interfluves and that discharge was toward major river valleys and coastal water. Simulated prepumping rates of recharge into the confined flow system varied up to 3.2 in/yr, and rates of discharge varied up to 2.8 in/yr. The highest rates of simulated recharge are concentrated along the Fall Line.

The simulated potentiometric-surface maps of the major aquifers for 1980 show the lower water levels and the cones of depression that are developing around major pumping centers. The largest simulated decline, about 210 ft, is near Franklin. Water budgets indicate that over the period of simulation (1891–1980) (1) pumpage from the model area increased by about 105 Mgal/d, (2) lateral boundary outflow increased by about 5 Mgal/d, (3) ground-water flow to streams and coastal waters decreased by about 107.5 Mgal/d, (4) lateral boundary inflow increased by about 0.7 Mgal/d, and (5) water released from aquifer storage increased by about 1.6 Mgal/d. Changes in the direction of vertical leakage toward major pumping centers resulted from ground-water withdrawal. The major source of recharge replacing the water pumped from confined aquifers was vertical leakage.

Simulated rates of flow into the confined aquifer system in 1980 varied up to 3.8 in/yr, and rates of flow out of the confined flow system varied up to 2.2 in/yr. Simulations show a net increase of about 110 Mgal/d into the confined from the unconfined flow system over the period of simulation. This change in leakage affected the local discharge of ground water to streams and the regional discharge of ground water to coastal water. The withdrawal of ground water from the confined aquifers increased the area of recharge into the confined flow system by about 33 percent and resulted in the movement of brackish water from Chesapeake Bay into the confined flow system.

Sensitivity analysis shows that simulated water levels are more sensitive to decreases in aquifer transmissivity and confining unit vertical hydraulic conductivity than to increases for the values tested. Lowering the storage coefficient has a negligible effect on simulated water levels; however, increasing the storage coefficient has a significant effect. Sensitivity simulations also indicate that the effect of confining unit storage is not significant if the water released from storage in the confining unit is from the compressibility of water only.

The calibrated model is suitable for analyzing the regional flow of ground water through the confined aquifers. The large grid scale limits the capability of the model to provide a detailed local analysis of the ground-water flow system. The adequacy of the model is governed by estimates of hydraulic characteristics, grid spacing, and time intervals of the 10 pumping periods. The method developed for simulating flow in the water-table aquifer provides an adequate upper-boundary condition for this study. Additional data on streambed leakance, stream base flow, and withdrawal from the water-table aquifer are needed to simulate water levels in the water-table aquifer more accurately and to quantify flow between the water-table aquifer and streams locally. More detailed data are needed to define the time-dependent stresses and the transient effect due to the release of water from storage in the confining units that is neglected in the model developed for this study.

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TABLES 1–13

TABLE 1.—*Relation of stratigraphic formations and hydrogeologic units of the Virginia Coastal Plain*
[Modified from Meng and Harsh, 1988]

Geologic age: Period	Geologic age: Epoch	Stratigraphic formation	Hydrogeologic unit
Quaternary	Holocene	Holocene deposits	Columbia aquifer
	Pleistocene	Undifferentiated deposits	
Tertiary	Pliocene	Yorktown Formation	Yorktown confining unit
			Yorktown-Eastover aquifer
	Miocene	Eastover Formation	
			St. Marys confining unit
		St. Marys Formation	
			St. Marys-Choptank aquifer
		Choptank Formation	
		Calvert Formation	Calvert confining unit
	Oligocene	Old Church Formation	Chickahominy-Piney Point aquifer
	Eocene	Chickahominy Formation	
		Piney Point Formation	
		Nanjemoy Formation	Nanjemoy-Marlboro Clay confining unit
		Marlboro Clay	
	Paleocene	Aquia Formation	Aquia aquifer
		Brightseat Formation	Brightseat-upper Potomac confining unit
Cretaceous	Late Cretaceous	Potomac Formation	Brightseat-upper Potomac aquifer
			Middle Potomac confining unit
			Middle Potomac aquifer
	Early Cretaceous		Lower Potomac confining unit
			Lower Potomac aquifer

TABLE 2.—*Correlation of hydrogeologic units of Maryland, Virginia, and North Carolina and corresponding layers used in the flow model*

[AQ, aquifer; CU, confining unit]

Maryland hydrogeologic unit	Virginia hydrogeologic unit	North Carolina hydrogeologic unit	Flow-model layer
Surficial aquifer	Columbia aquifer	Surficial aquifer	AQ10
Upper Chesapeake confining unit	Yorktown confining unit	Confining unit	CU9
Upper Chesapeake aquifer	Yorktown-Eastover aquifer	Yorktown aquifer	AQ9
St. Marys confining unit	St. Marys confining unit	Confining unit	CU8
Lower Chesapeake aquifer	St. Marys-Choptank aquifer	Pungo River aquifer	AQ8
Lower Chesapeake confining unit	Calvert confining unit	Confining unit	CU7
Piney Point-Nanjemoy aquifer	Chickahominy-Piney Point aquifer	Castle Hayne aquifer	AQ7
Nanjemoy-Marlboro confining unit	Nanjemoy-Marlboro confining unit	Confining unit	CU6
Aquia-Rancocas aquifer	Aquia aquifer	Beaufort aquifer	AQ6
Upper Severn confining unit	Correlative units not present in Virginia Coastal Plain	Confining unit	CU5
Severn aquifer		Peedee aquifer	AQ5
Lower Severn confining unit		Confining unit	CU4
Matawan aquifer		Black Creek aquifer	AQ4
Matawan and Brightseat confining units	Brightseat-upper Potomac confining unit	Confining unit	CU3
Magothy and Brightseat aquifers	Brightseat-upper Potomac aquifer	Upper Cape Fear aquifer	AQ3
Patapsco confining unit	Middle Potomac confining unit	Confining unit	CU2
Patapsco aquifer	Middle Potomac aquifer	Lower Cape Fear aquifer	AQ2
Potomac confining unit	Lower Potomac confining unit	Confining unit	CU1
Patuxent aquifer	Lower Potomac aquifer	Lower Cretaceous aquifer	AQ1

TABLE 3.—*Transmissivities and storage coefficients determined for the lower and middle Potomac aquifers and the Brightseat-upper Potomac aquifer*

[ft^2/d, feet squared per day]

Aquifer names used in previous reports	Aquifer names used in this report	Selected area or test site	Source of data and method of analysis	Transmissivity (ft^2/d) Low	Transmissivity (ft^2/d) High	Transmissivity (ft^2/d) Average	Storage coefficient Low	Storage coefficient High	Storage coefficient Average
Upper Artesian and Principal (Siudyla and others, 1977, Newton and Siudyla, 1979); Mattaponi and Potomac (Cederstrom, 1945, 1957)	Brightseat-upper Potomac aquifer	Franklin (F)	6			1,500			
		Lake Prince (LP)	6			1,500			
		West Point (WP)	10			13,000			5×10^{-4}
		Burton Station (BS)	11	3,800	4,500				
	Middle Potomac aquifer	Franklin (F)	1,2,3, and 4	19,000	55,000		1.1×10^{-3}	1.5×10^{-3}	
			5			19,000	1.0×10^{-4}	6.0×10^{-4}	
			6			12,000			
			8			19,000			
			9	6,000	24,000				
		Lake Prince (LP)	2	20,000	27,000				1.5×10^{-3}
			5			19,000	1.0×10^{-4}	6.0×10^{-4}	
			6	8,000	12,000				
			7	20,000	23,000				7.8×10^{-4}
		Washington's Birthplace (WB)	12			2,000			2.0×10^{-4}
		West Point (WP)	10			15,000			5.0×10^{-4}
		Ferry Slip (FS)	11	2,600	4,200				
	Lower Potomac aquifer	Franklin (F)	1,2,3, and 4	19,000	55,000		1.1×10^{-3}	1.5×10^{-3}	
			5			19,000	1.0×10^{-4}	6.0×10^{-4}	
			6			12,000			
			8			19,000			
			9	6,000	24,000				
		Lake Prince (LP)	2	20,000	27,000				1.5×10^{-3}
			5			19,000	1.0×10^{-4}	6.0×10^{-4}	
			6	8,000	12,000				
			7	20,000	23,000				7.8×10^{-4}
		West Point (WP)	10			15,000			5.0×10^{-4}

Explanation:

1. Aquifer test recovery data Sinnott (1968), Cooper and Jacob (1946).
2. Aquifer test drawdown data Sinnott (1968), Cooper and Jacob (1946).
3. Aquifer test recovery data Sinnott (1968), Theis (1935).
4. Aquifer test drawdown data Sinnott (1968), Theis (1935).
5. Cosner (1975), model calibration.
6. Layne-Western (1983), analog model.
7. Aquifer test drawdown data Geraghty and Miller (1967), Hantush (1960).
8. Cosner (1975), circumference method.
9. Cosner (1975), potentiometric-slope method.
10. Aquifer test drawdown data Leggette and others (1966), Cooper and Jacob (1946).
11. Aquifer test drawdown data Geraghty and Miller (1979b), Cooper and Jacob (1946).
12. Aquifer test drawdown data Lichtler (1974), Cooper and Jacob (1946).

Letters in parentheses appear on location map of test sites, figure 3.

TABLE 4.—*Vertical hydraulic conductivities of confining units determined by laboratory methods*
[ft, feet; ft/d, foot per day]

City or County	Name of confining unit	U.S. Geological Survey No.	Depth of sample below land surface (ft)	Hydraulic conductivity (ft/d)
Suffolk	Lower Potomac	[1]25-3	978.5-979.5	1.9×10^{-6}
Norfolk	Middle Potomac	[1]24-2	1034-1035	3.4×10^{-6}
Accomac	Nanjemoy-Marlboro	[1]55-10	949-951	1.6×10^{-5}
Northumberland	Nanjemoy-Marlboro	[1]59-12	485-486	2.2×10^{-6}
Gloucester	Nanjemoy-Marlboro	[1]58H4	609	2.0×10^{-5}
Isle of Wight	Calvert	[1]26-5	267-268	9.2×10^{-6}
Norfolk	St. Marys	[1]24-1	538.5-540	2.8×10^{-6}
Gloucester	St. Marys	[2]58H4	248	2.0×10^{-5}
James City	Middle Potomac	[3]56H20	523	2.3×10^{-5}
Suffolk	Yorktown	[3]58B260	42-44.5	3.9×10^{-3}
Suffolk	Yorktown	[3]58B259	60-62	5.9×10^{-4}

[1]Analysis performed by Corps of Engineers, Cincinnati, Ohio. Samples remolded and tests conducted at a series of overburden pressures, with highest pressure equal to or greater than in situ pressure.

[2]Analysis performed by Core Laboratories, Inc., Dallas, Texas.

[3]Analysis performed by Corps of Engineers, Cincinnati, Ohio.

TABLE 5.—*Major withdrawals by aquifer, 1980*

[Mgal/d, million gallons per day; do., ditto. Locations of water users shown in fig. 8]

Water user number	Geographic location	Aquifer	1980 withdrawal (Mgal/d)
020	Franklin	Lower Potomac	10.29
025	West Point	do.	3.79
020	Franklin	Middle Potomac	25.21
023	Williamsburg	do.	1.95
025	West Point	do.	6.57
038	Franklin	do.	1.44
039	Franklin	do.	3.66
045	Tidewater	do.	4.96
048	Tidewater	do.	2.29
068	Henrico County	do.	1.96
071	Alexandria	do.	1.12
016	Smithfield	Brightseat-upper Potomac	1.12
018	Smithfield	do.	1.38
023	Williamsburg	do.	1.33
025	West Point	do.	2.61
028	Urbanna	do.	1.65
045	Tidewater	do.	2.71
054	Williamsburg	do.	1.70
025	West Point	Aquia	.71
434	Southern Maryland	do.	.39
445	Southern Maryland	do.	.21
024	James City	Chickahominy-Piney Point	.35
025	West Point	do.	2.37
309	Edenton	do.	.68
006	Delmarva Peninsula	Yorktown-Eastover	1.55
031	Delmarva Peninsula	do.	.78
300	Elizabeth City	do.	1.30

TABLE 6.—*Average estimated and model-calibrated values of lateral and vertical hydraulic conductivity for aquifers and confining units, respectively*

[In feet per day]

		Average lateral hydraulic conductivity of aquifers	
Model layer	Aquifer name	Initial estimated value	Model-calibrated value
AQ1	Lower Potomac	25.0	41.4
AQ2	Middle Potomac	25.0	51.8
AQ3	Brightseat-upper Potomac	25.0	32.8
AQ4	Aquifer 4	15.0	25.9
AQ5	Aquifer 5	15.0	23.3
AQ6	Aquia	40.0	26.9
AQ7	Chickahominy-Piney Point	35.0	25.1
AQ8	St. Marys-Choptank	10.0	14.7
AQ9	Yorktown-Eastover	20.0	14.7
AQ10	Columbia	15.0	18.1

		Average vertical hydraulic conductivity of confining units	
Model layer	Confining unit name	Initial estimated value	Model-calibrated value
CU1	Lower Potomac	8.50×10^{-4}	3.28×10^{-5}
CU2	Middle Potomac	8.50×10^{-4}	4.06×10^{-5}
CU3	Brightseat-upper Potomac	1.30×10^{-4}	4.41×10^{-5}
CU4	Confining unit 4	1.12×10^{-6}	3.46×10^{-5}
CU5	Confining unit 5	8.64×10^{-6}	7.78×10^{-5}
CU6	Nanjemoy-Marlboro	8.64×10^{-5}	5.36×10^{-5}
CU7	Calvert	8.64×10^{-5}	1.12×10^{-4}
CU8	St. Marys	4.32×10^{-3}	4.15×10^{-4}
CU9	Yorktown	3.46×10^{-3}	8.64×10^{-4}

TABLE 7.—*Minimum and maximum values of transmissivity for aquifers and vertical leakance values for confining units derived by model calibration*

[ft²/d, feet squared per day; 1/d, inverse day]

Model layer	Aquifer name	Transmissivity (ft^2/d) Minimum	Maximum
AQ1	Lower Potomac	250	12,440
AQ2	Middle Potomac	410	18,145
AQ3	Brightseat-upper Potomac	330	4,175
AQ4	Aquifer 4	210	3,320
AQ5	Aquifer 5	300	1,240
AQ6	Aquia	100	3,830
AQ7	Chickhominy-Piney Point	65	7,640
AQ8	St. Marys-Choptank	210	2,600
AQ9	Yorktown-Eastover	10	4,650
AQ10	Columbia	15	3,000

Model layer	Confining unit name	Vertical leakance ($^1/d$) Minimum	Maximum
CU1	Lower Potomac	$1.01x10^{-7}$	$1.64x10^{-5}$
CU2	Middle Potomac	$2.54x10^{-7}$	$4.06x10^{-3}$
CU3	Brightseat-upper Potomac	$3.90x10^{-7}$	$4.41x10^{-3}$
CU4	Confining unit 4	$1.30x10^{-7}$	$3.84x10^{-6}$
CU5	Confining unit 5	$4.89x10^{-7}$	$7.78x10^{-6}$
CU6	Nanjemoy-Marlboro	$8.25x10^{-8}$	$2.68x10^{-3}$
CU7	Calvert	$2.67x10^{-7}$	$5.60x10^{-3}$
CU8	St. Marys	$1.14x10^{-6}$	$3.19x10^{-3}$
CU9	Yorktown	$4.80x10^{-6}$	$1.08x10^{-3}$

TABLE 8.—*Average withdrawal from each aquifer used in the calibrated model, by pumping period from 1891 to 1980*
[In million gallons per day]

Model layer	Aquifer	Pumping period 1 1891-1920	2 1921-1939	3 1940-1945	4 1946-1952	5 1953-1957	6 1958-1964	7 1965-1967	8 1968-1972	9 1973-1977	10 1978-1980
1	Lower Potomac	0.01	0.29	2.14	3.69	6.13	9.19	11.55	14.56	14.91	14.22
2	Middle Potomac	5.34	8.38	12.73	15.30	20.34	31.06	38.78	51.09	54.48	55.91
3	Brightseat-upper Potomac	5.46	6.06	11.43	11.99	10.59	13.14	17.28	20.76	19.26	19.42
4	Aquifer 4	.01	.25	.26	.26	.25	.24	.22	.56	.20	.20
5	Aquifer 5	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
6	Aquia	.06	.28	1.39	1.70	1.61	1.51	2.05	2.52	2.85	2.82
7	Chickahominy-Piney Point	.16	.90	1.91	2.28	3.01	3.52	4.44	4.15	3.84	4.19
8	St. Marys-Choptank	.00	.00	.00	.00	.00	.00	.00	.00	.02	.16
9	Yorktown-Eastover	.03	.32	.50	.93	1.16	1.54	2.59	5.81	8.46	8.25
10	Columbia	.00	.00	.00	.00	.00	.01	.02	.02	.03	.05
	Totals	11.07	16.48	30.36	36.15	43.09	60.21	76.93	99.47	104.05	105.22

TABLE 9.—*Computed lateral boundary fluxes*

[Values, in million gallons per day, are not intended to imply accuracy to the precision shown. do., ditto]

Simulated conditions	Lower Potomac aquifer			Middle Potomac aquifer			Brightseat-upper Potomac aquifer			Aquifer 4			Aquifer 5		
	Flux			Flux			Flux			Flux			Flux		
	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
Prepumping	0.36	0.04	0.32	0.17	1.21	-1.14	0.27	0.30	-0.12	0.05	0.24	-0.19	0.00	0.08	-0.08
Pumping period 1 1891-1920	.36	.04	.32	.17	1.21	-1.14	.27	.39	-.12	.05	.24	-.19	.00	.08	-.08
do. 2 1921-1939	.00	1.32	-1.32	.21	.91	-.70	.27	.38	-.11	.06	.22	-.16	.00	.08	-.08
do. 3 1940-1945	.00	2.97	-2.97	.26	.81	-.55	.28	.39	-.11	.14	.21	-.07	.00	.08	-.08
do. 4 1946-1952	.00	4.82	-4.82	.44	.55	-.11	.28	.35	-.07	.14	.20	-.06	.00	.07	-.07
do. 5 1953-1957	.00	3.17	-3.17	.44	.63	-.19	.26	.38	-.12	.14	.20	-.66	.00	.07	-.07
do. 6 1958-1964	.00	2.70	-2.70	.50	.71	-.21	.23	.44	-.21	.12	.21	-.09	.00	.07	-.07
do. 7 1965-1967	.00	2.28	-2.28	.75	.75	-.00	.22	.55	-.33	.10	.20	-.10	.00	.06	-.06
do. 8 1968-1972	.00	2.83	-2.83	1.00	.69	.31	.22	.63	-.41	.08	.21	-.13	.00	.05	-.05
do. 9 1973-1977	.00	3.85	-3.85	1.36	.94	.42	.20	.75	-.55	.09	.23	-.14	.00	.05	-.05
do. 10 1978-1980	.00	4.27	-4.27	1.37	1.17	.20	.19	.86	-.67	.09	.26	-.17	.00	.04	-.04

Simulated conditions	Aquia aquifer			Chickahominy-Piney Point aquifer			St. Marys-Choptank aquifer			Yorktown-Eastover aquifer			Columbia Aquifer		
	Flux			Flux			Flux			Flux			Flux		
	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
Prepumping	0.15	0.78	-0.63	0.20	1.60	-1.40	0.14	0.39	-0.25	0.33	0.90	-0.67	0.08	0.67	-0.59
Pumping period 1 1891-1920	.15	.78	-.63	.20	1.60	-1.40	.14	.39	-.25	.33	.90	-.57	.08	.67	-.59
do. 2 1921-1939	.15	.76	-.61	.20	1.57	-1.37	.14	.38	-.24	.33	.91	-.58	.08	.67	-.59
do. 3 1940-1945	.15	.73	-.58	.20	1.54	-1.34	.15	.39	-.24	.32	.90	-.58	.08	.67	-.59
do. 4 1946-1952	.12	.75	-.63	.17	1.55	-1.38	.15	.39	-.24	.32	.90	-.58	.08	.67	-.59
do. 5 1953-1957	.12	.75	-.63	.16	1.55	-1.39	.15	.39	-.24	.32	.90	-.58	.08	.67	-.59
do. 6 1958-1964	.10	.80	-.70	.15	1.60	-1.45	.15	.38	-.23	.32	.90	-.58	.08	.67	-.59
do. 7 1965-1967	.07	1.00	-.93	.13	1.62	-1.47	.16	.38	-.22	.32	.90	-.58	.08	.66	-.58
do. 8 1968-1972	.05	.90	-.85	.12	1.60	-1.48	.17	.37	-.20	.32	.89	-.57	.08	.66	-.58
do. 9 1973-1977	.05	1.03	-.98	.11	1.63	-1.52	.19	.37	-.18	.40	.88	-.48	.08	.67	-.59
do. 10 1978-1980	.04	1.02	-.98	.11	1.61	-1.50	.20	.37	-.17	.38	.88	-.50	.08	.67	-.59

TABLE 10.—*Computed leakage rates across confining units into and out of the confined flow system*
[Values, in million gallons per day, are not intended to imply accuracy to the precision shown. do., ditto]

Simulated Conditions		Lower Potomac confining-unit			Middle Potomac confining-unit			Brightseat-upper Potomac confining-unit			Confining unit 4			Confining unit 5		
		Volumetric leakage rate			Volumetric leakage rate			Volumetric leakage rate			Volumetric leakage rate			Volumetric leakage rate		
		Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
		Lower Potomac aquifer			Middle Potomac aquifer			Brightseat-upper Potomac aquifer			Aquifer 4			Aquifer 5		
Prepumping		1.96	1.71	-0.25	31.38	30.56	0.82	15.65	19.31	-3.66	1.55	3.40	-1.85	0.00	0.06	-0.06
Pumping Period 1	1891-1920	1.96	2.45	-.49	33.48	27.76	5.72	18.34	15.21	3.13	1.65	2.97	-1.32	.00	.05	-.05
do. 2	1921-1939	2.91	1.50	1.41	35.43	25.12	10.31	19.94	13.79	6.15	1.80	2.64	-.84	.00	.05	-.05
do. 3	1940-1945	5.65	.95	4.68	40.18	22.76	17.42	25.54	11.39	14.15	2.20	1.92	.28	.00	.04	-.04
do. 4	1946-1952	8.77	.54	8.23	43.58	20.45	23.13	27.93	10.62	17.31	2.01	1.98	.03	.00	.04	-.04
do. 5	1953-1957	9.36	.23	9.13	47.96	18.63	29.33	31.28	9.77	21.51	2.20	1.65	.55	.00	.03	-.03
do. 6	1958-1964	11.81	.21	11.60	58.56	15.97	42.59	41.24	8.51	32.73	2.88	1.03	1.85	.01	.02	-.01
do. 7	1965-1967	13.30	.39	12.91	66.39	15.87	50.12	49.50	7.97	41.53	3.48	.77	2.71	.01	.02	-.01
do. 8	1968-1972	17.08	.42	16.56	80.02	13.50	66.52	63.43	7.24	56.19	5.16	.40	4.76	.03	.00	.03
do. 9	1973-1977	18.65	.25	18.40	83.80	11.71	72.09	66.14	6.99	59.15	5.17	.42	4.75	.02	.00	.02
do. 10	1978-1980	18.59	.20	18.39	84.89	10.85	74.04	66.89	6.46	60.43	5.33	.39	4.94	.02	.00	.02

Simulated Conditions		Nanjemoy-Marlboro confining unit			Calvert confining unit			St. Marys confining unit			Yorktown confining unit					
		Volumetric leakage rate			Volumetric leakage rate			Volumetric leakage rate			Volumetric leakage rate			Volumetric leakage rate		
		Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
		Aquia aquifer			Chickahominy-Piney Point aquifer			St. Marys-Choptank aquifer			Yorktown-Eastover aquifer			Confined system		
Prepumping		21.30	34.52	-13.22	29.61	35.21	-5.60	8.12	9.40	-1.28	92.23	109.71	-17.48	118.73	124.03	-5.30
Pumping Period 1	1891-1920	24.10	28.68	-4.58	31.90	31.28	.62	8.37	8.93	-.56	96.66	103.68	-7.02	123.30	117.68	5.62
do. 2	1921-1939	26.00	26.15	.15	33.47	29.36	4.11	8.66	8.65	.01	99.12	100.55	-1.43	126.37	113.80	12.57
do. 3	1940-1945	32.06	21.88	10.17	37.55	25.28	12.27	8.92	8.14	.78	103.56	92.93	10.63	132.08	104.85	27.23
do. 4	1946-1952	34.80	19.74	15.06	39.23	23.62	15.61	9.06	7.88	1.17	107.31	90.71	16.61	136.66	101.38	35.28
do. 5	1953-1957	37.37	18.74	18.63	41.06	22.37	18.69	9.22	7.62	1.60	108.64	88.14	20.50	138.38	98.77	39.61
do. 6	1958-1964	45.43	15.85	29.58	45.75	19.49	26.26	9.83	6.84	2.99	117.65	82.46	36.19	149.45	91.10	58.35
do. 7	1965-1967	50.60	17.08	33.53	52.97	14.22	38.75	10.27	6.45	3.82	121.74	77.06	44.68	154.74	84.83	69.91
do. 8	1968-1972	66.44	11.45	54.99	58.99	14.57	44.42	11.22	5.91	5.31	136.96	69.54	37.42	171.50	76.24	95.26
do. 9	1973-1977	69.90	10.68	59.22	60.81	13.63	47.18	11.61	5.80	5.81	140.22	68.33	71.89	175.48	74.48	101.00
do. 10	1978-1980	70.31	10.38	59.93	61.15	13.42	47.73	11.83	5.69	6.14	140.77	67.15	73.62	177.02	72.74	104.28

TABLE 11.—*Model-computed ground-water budgets*

[Values, in million gallons per day, are not intended to imply accuracy to the precision shown]

Sources	MODEL-COMPUTED VOLUMETRIC FLOW RATES FOR PREPUMPING SIMULATION
Recharge from precipitation	9,237.81
Lateral boundary inflow	1.76
Ground-water flow from streams and coastal water bodies	.00
Discharges	
Lateral boundary outflow	6.31
Ground-water flow into streams and coastal-water bodies	9,233.93

MODEL-COMPUTED VOLUMETRIC FLOW RATES FOR PUMPING SIMULATION

	Pumping Period									
	1 (10957.2 days) 1891-1920	2 (6939.8 days) 1921-1939	3 (2191.0 days) 1940-1945	4 (2556.7 days) 1946-1952	5 (1826.4 days) 1953-1957	6 (2556.7 days) 1958-1964	7 (1095.7 days) 1965-1967	8 (1826.4 days) 1968-1972	9 (1826.4 days) 1973-1977	10 (1095.7 days) 1978-1980
Sources										
Water released from aquifer storage	0.00	0.09	2.92	1.39	1.82	2.62	7.28	6.57	2.80	1.60
Lateral boundary inflow	1.76	1.45	1.58	1.71	1.67	1.67	1.85	2.05	2.49	2.46
Recharge from precipitation	9,237.81	9,237.81	9,237.81	9,237.81	9,237.81	9,237.81	9,237.81	9,237.81	9,237.91	9,237.91
Ground-water flow from streams and coastal water bodies	.00	.00	.00	.00	.00	.00	.07	.26	.48	.53
Discharges										
Water entering aquifer storage	.00	.00	.02	.00	.03	.00	.00	.00	.10	.11
Lateral boundary outflow	6.30	7.22	8.69	10.23	8.72	8.48	8.45	8.86	10.41	11.50
Ground-water withdrawal from wells	10.88	16.49	29.94	35.05	42.52	60.23	76.75	99.42	104.02	105.13
Ground-water flow into streams and coastal water bodies	9,224.24	9,217.13	9,204.85	9,197.09	9,191.28	9,174.47	9,162.84	9,139.57	9,129.88	9,127.29

Note: The difference between total sources and discharges is due to numerical truncation errors in the digital simulation.

TABLE 12.—*Summary of sensitivity tests*
[ft/d, foot per day; ft, foot]

Hydraulic characteristic	Range of change	Actual value	Change in water levels, in feet: Range in deviation in hydrographs of middle Potomac aquifer from calibrated hydrographs in 1980	Change in water levels, in feet: Hydrographs of selected confined aquifers shown in figures 76-79; range in deviation from calibrated hydrographs in 1980
Transmissivity of middle Potomac aquifer	Increase 100% Decrease 50%	Variable	+20 to +75 -15 to -125	Not applicable
Vertical hydraulic conductivity of middle Potomac confining unit	Increase 100% Decrease 50%	$8.12x10^{-5}$ ft/d $2.03x10^{-5}$ ft/d	+10 to +30 -30 to -60	Not applicable
Storage coefficient of all confined aquifers	Increase 1 order of magnitude Decrease 1 order of magnitude	$1.0x10^{-3}$ $1.0x10^{-5}$	Not applicable	+5 to +15 Less than 5
Specific storage coefficient of all confining units		$1.0x10^{-4}$/ft $1.0x10^{-6}$/ft	Not applicable	+15 to +40 Less than 5[1]

[1]Hydrographs for calibrated model which neglected water released from storage in the confining units during transient simulations (specific storage = 0/ft) and the assumed specific storage of the confining unit ($1.0x10^{-6}$/ft) are shown as same line in figures 78 and 79.

TABLE 13.—*Specific storage and computed storage coefficients of confining units used for sensitivity tests*

Model layer	Confining unit	Estimated average confining unit thickness (feet)	Computed storage coefficient (dimensionless): Specific storage $1.0x10^{-4}$ ft^{-1}	Computed storage coefficient (dimensionless): Specific storage $1.0x10^{-6}$ ft^{-1}
CU1	Lower Potomac	25	$2.50x10^{-3}$	$2.50x10^{-5}$
CU2	Middle Potomac	40	$4.00x10^{-3}$	$4.00x10^{-5}$
CU3	Brightseat-upper Potomac	35	$3.50x10^{-3}$	$3.50x10^{-5}$
CU4	Confining unit 4	25	$2.50x10^{-3}$	$2.50x10^{-5}$
CU5	Confining unit 5	25	$2.50x10^{-3}$	$2.50x10^{-5}$
CU6	Nanjemoy-Marlboro	100	$1.00x10^{-2}$	$1.00x10^{-4}$
CU7	Calvert	125	$1.25x10^{-2}$	$1.25x10^{-4}$
CU8	St. Marys	90	$9.00x10^{-3}$	$9.00x10^{-5}$
CU9	Yorktown	50	$5.00x10^{-3}$	$5.00x10^{-5}$