HYDROGEOLOGY AND ANALYSIS OF THE GROUND-WATER FLOW SYSTEM IN THE COASTAL PLAIN OF SOUTHEASTERN VIRGINIA

By Pixie A. Hamilton and Jerry D. Larson

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CONVERSION FACTORS

Inch-pound units of measurement in this report may be converted to metric (International System) units using the following conversion factors:

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
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)
square foot per day (ft^2/d)	0.09294	square meter per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per mile (ft/mi)	0.06308	meter per kilometer (m/km)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
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)

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 "Mean Sea Level of 1929."

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ABSTRACT

Hydrogeology and the ground-water flow system in the Coastal Plain physiographic province of southeastern Virginia were analyzed, and the continued reliability of ground water as a resource was assessed. Since the early 1900's, steadily increasing pumpage has resulted in declining water levels, extensive cones of depression that expand from supply wells in industrial and population centers, and the potential for water-quality degradation as a result of saltwater encroachment. The study primarily focused on hydrogeologic characteristics of the multiaquifer system, development and refinement of a digital, ground-water flow model, and analysis of future hydrologic conditions resulting from potential injection or increased pumpage.

The Coastal Plain physiographic province of southeastern Virginia is underlain by unconsolidated sediments consisting primarily of sand, clay, silt, and gravel with variable amounts of shell material. These sediments dip and thicken eastward and lie directly upon granitic basement. On the basis of lithologic and hydrologic analysis of the sediments, a hydrogeologic framework consisting of a water-table aquifer and seven confined aquifers and intervening confining units was identified. Values for transmissivity, vertical leakance, and storage which describe the ability of sediments to transmit, store, or release water were defined. The three lowermost aquifers (lower, middle, and upper Potomac) are the thickest, most transmissive, and most productive aquifers in the framework.

The ground-water flow system is bounded by granitic basement, the Fall Line to the west, and the freshwater-saltwater interface to the east. Ground-water flow under prepumping and pumping conditions was conceptualized from known hydrogeologic information and from water-level observations that began in the late 1800's. Under prepumping conditions, which were assumed to have existed prior to 1891, water presumably moved regionally from the Fall Line to Chesapeake Bay and the Atlantic Ocean and locally to streams, swamps, and bays. A hydraulic equilibrium prevailed, with recharge to the ground-water system approximating discharge to surface water. Under pumping conditions, pumpage from the confined system lowered water levels and resulted in extensive cones of depression and flow toward major pumping centers.

To provide a more detailed analysis of water-level decline and ground-water flow, a three-dimensional, digital, ground-water flow model, which incorporated hydrogeologic characteristics of the aquifers and confining units, was developed to simulate prepumping and pumping conditions. The model area extended beyond southeastern Virginia into the York-James Peninsula and northern part of North Carolina to include ground-water users affecting

flow in southeastern Virginia. Pumping conditions were simulated from 1891, when estimated pumpage from the model area was less than 10 Mgal/d (million gallons per day), through 1983, when estimated pumpage was approximately 87 Mgal/d. The model was used to assess net effects of historic pumpage and potential injection or increased pumpage on regional water levels, ground-water flow, water budgets, and surface-water/ground-water relations.

Model results for prepumping conditions were consistent with known water-level data and the previously conceptualized ground-water flow pattern. Model results for pumping conditions also were consistent with known water-level data, including a significant decline greater than 250 feet that occurred in the lower and middle Potomac aquifers in the Franklin area. The model also described changes in ground-water flow from prepumping conditions, primarily in the vicinity of production wells.

In the simulated prepumping water budget, recharge to the ground-water system approximated discharge to surface water. Under pumping conditions, discharge to surface water was reduced because of increased movement from the water-table aquifer into the confined system to replace pumpage from the deeper aquifers. In some areas, surface water recharged the ground-water system. The reduced discharge to surface water and induced recharge from surface water accounted for approximately 86 percent of the water pumped from the model area in the last pumping period analyzed (1981-83). The remaining pumpage was accounted for by a decrease in lateral outflow and an increase in lateral inflow across model boundaries and by water released from storage. In this period, water released from storage was minimal, suggesting that steady-state conditions were being approached.

The model was used to project the response of the ground-water flow system to potential injection or increased pumpage in southeastern Virginia. Seven scenarios were run, each representing an increase in pumpage or injection above average pumpage conditions simulated in the final pumping period (1981-83). The first scenario involved increased pumpage of 54.4 Mgal/d (141.0 Mgal/d total) resulting from continuous use of 18 emergency-supply wells, generally used in times of drought. The second scenario involved increased pumpage of 19.8 Mgal/d (106.4 Mgal/d total) resulting from continuous use of selected industrial wells at respective permitted limits. Both scenarios were run using a steady-state solution to the ground-water flow equation. Water-level decline from simulated 1983 water levels would be substantial in both scenarios; however, water levels would remain well above the top of aquifers throughout most of the model area. The major consequences would be considerable well interference among ground-water users and potential degradation of water quality.

Scenarios 3 through 7 involved injection into or pumpage from 5 Virginia Beach emergency-supply wells located in the city of Suffolk, Isle of Wight County, and Southampton County. These wells which primarily penetrate the middle Potomac aquifer were designed to be pumped during dry periods, allowing for water-level recovery during wetter periods. On the basis of this original well design, scenario 3 involved increased pumpage at a rate of 4 Mgal/d from each of the wells during July, August, and September for 5 years. Scenarios 4 through 7 presented other potential uses for the wells. Modeled water levels in the vicinity of the wells in the middle Potomac aquifer were projected for a 5-year period (1984-88) and used to assess benefits derived from injection and impacts from increased pumpage. Increased pumpage during 3 months at design capacity (4 Mgal/d) from each well followed by 9 months with no increased pumpage would result in a maximum 35.5-foot water-level decline during the 5-year period. The water level would rise during the 9-month recovery period following maximum decline to within about 6 feet of the simulated 1983 water level. Improvement in water-level recovery resulting from injection during wetter periods (at a rate of 1 Mgal/d into each well during January, February, March, and April) would be minimal. Injection would increase water levels during the month of maximum decline by only about 3.4 feet. Maximum water-level decline resulting from year-round pumpage at a rate of 1 Mgal/d for 5 years would be approximately 12 feet. The water levels would generally be lower throughout the 5-year period (maximum 7 feet) than those resulting from pumping an equivalent volume of water during 3 months of the year at a higher rate of 4 Mgal/d. However, water levels would be approximately 24 feet higher in September each year--the time corresponding to the end of 3-month pumpage. Year-round pumpage at a lower rate would, therefore, prevent periods of extreme water-level decline. Water levels would decline by approximately 58.8 feet after 5 years if the wells were pumped year-round at design capacity (4 Mgal/d). The water levels would be significantly lower throughout the 5-year period than those resulting from pumping only during dry periods at design capacity. A 9-month recovery period would, therefore, play an important role in restoring water levels in the area.

INTRODUCTION

Ground water is an important resource in southeastern Virginia, supplying approximately 55 Mgal/d (million gallons per day) for industrial, municipal, and commercial use in 1983. Since the early 1900's, steadily increasing pumpage has resulted in water-level decline, extensive cones of depression that expand from industrial and population centers, and potential contamination by saltwater encroachment. As a measure to protect the ground-water resource, approximately 3,000 mi^2 (square miles) of southeastern Virginia were designated a Ground Water Management Area in February 1976 under the Groundwater Act of 1973. The area includes the five counties of Surry, Sussex, Isle of Wight, Prince George, and Southampton, and the cities of Virginia Beach, Suffolk, Chesapeake, Portsmouth, Norfolk, Hopewell, and Franklin. Under the management-area designation, industrial, municipal, or commercial use of ground water exceeding 300,000 gallons per month requires a permit.

Continued population growth, combined with increasing industrial and agricultural demand, will inevitably result in continued water-level decline, greater well interference, and diminished water quality. The reliability of ground water as a viable resource to meet future water needs in southeastern Virginia is therefore in question. The Virginia Water Control Board (VWCB) is concerned about the effects that population growth and development and increased pumpage will have on an already sensitive ground-water system. In July 1984, the VWCB and the U.S. Geological Survey began a cooperative investigation of the area to (1) better understand the hydrogeology and ground-water flow system and (2) develop a tool that would aid in assessing ground-water resources and future hydrologic conditions resulting from potential injection or increased pumpage.

Purpose and Scope

The purpose of this report is to describe the hydrogeology and ground-water flow system in southeastern Virginia. The report provides a technical discussion of (1) hydrogeologic characteristics of aquifers and confining units, (2) development and refinement of a three-dimensional, digital, ground-water flow model, and (3) analysis of future hydrologic conditions resulting from potential injection or increased pumpage. The report is intended for the scientifically informed public and, specifically, for Federal, State and local officials who may use the results to formulate water-supply decisions.

Hydrogeologic characteristics were defined for a water-table aquifer and seven confined aquifers and intervening confining units in southeastern Virginia. These hydrogeologic characteristics were incorporated into a digital, ground-water flow model that was used to simulate existing water-level data for prepumping (prior to 1891) and pumping conditions (1891-1983), and to describe water-level decline, direction and magnitude of ground-water flow, and surface-water/ground-water relations. The model also was used to project the response of the ground-water flow system to seven potential scenarios involving injection or increased pumpage in southeastern Virginia. The scenarios provide examples of the ability of the model to assess the continued reliability of ground water as a resource in southeastern Virginia. Historic and projected pumpage is primarily from the confined aquifers and, therefore, the primary focus of the study was on the seven confined aquifers, without a detailed analysis of the water-table aquifer. Because of the size of the study area (approximately 3,800 mi^2), all model analyses in the study were regional, with results calculated for 3-square-mile units.

The model area was extended beyond the northern and southern limits of the study area to incorporate pumpage that could affect ground-water flow in southeastern Virginia. The southern model boundary extended across the Virginia State line into North Carolina. Available geologic and hydrologic data were obtained from North Carolina agencies and incorporated to maintain continuity across the State border; however, analysis and description of the ground-water flow system in northeastern North Carolina were not within the scope of this study.

Description of Study and Model Areas

The study area (fig. 1) comprises approximately 3,800 mi^2 within the Coastal Plain physiographic province of southeastern Virginia. It is bounded on the north by the James River, on the east by the Atlantic Ocean, on the south by the Virginia-North Carolina border, and on the west by the Fall Line, which separates the Coastal Plain physiographic province from the Piedmont physiographic province. The model area (fig. 1) extends beyond the northern limit of the study area to the York River, and beyond the southern limit of the study area to Albemarle Sound in northeastern North Carolina to incorporate pumpage that may affect ground-water flow in southeastern Virginia. It covers approximately 9,200 mi^2.

Previous Studies

A literature search was conducted for all previous studies associated with water use, water levels, hydrogeology, and ground-water resources in southeastern Virginia. A major contribution to the literature on water use in the Virginia Coastal Plain is Kull and Laczniak (1987). Meng and Harsh (1984) describe the hydrogeologic framework in the Virginia Coastal Plain. Harsh and Laczniak (1986) describe the conceptualization of ground-water flow in the multiaquifer system and provide a regional model of the Virginia Coastal Plain. Sanford (1913), Cederstrom (1945), Virginia Water Control Board (1974), and Geraghty and Miller (1978b) describe the geology and ground-water resources throughout southeastern Virginia. Geraghty and Miller (1967), Sinnot (1967), Brown and Cosner (1974), and Cosner (1975) describe ground-water resources in and near Franklin, Virginia. Geraghty and Miller (1978a; 1979a; 1979b), Converse and others (1981), and Faust and others (1981) describe ground-water resources for the city of Virginia Beach. Siudyla and others (1981) describe a comprehensive study of ground-water resources for the Four Cities area (Norfolk, Virginia Beach, Portsmouth, and Chesapeake). Meisler (1986) documents the occurrence and distribution of salty ground water in the northern Atlantic Coastal Plain aquifer system. Larson (1981) describes the occurrence of saline ground water in the Coastal Plain aquifers of Virginia. Cosner (1975), Bal (1978), and Layne-Western Company (1983) describe ground-water movement in selected areas in the Virginia Coastal Plain using digital or analog models.

Methods of Investigation

The basis for the hydrogeologic framework was provided by Meng and Harsh (1984). Additional hydrogeologic data were obtained during the study to

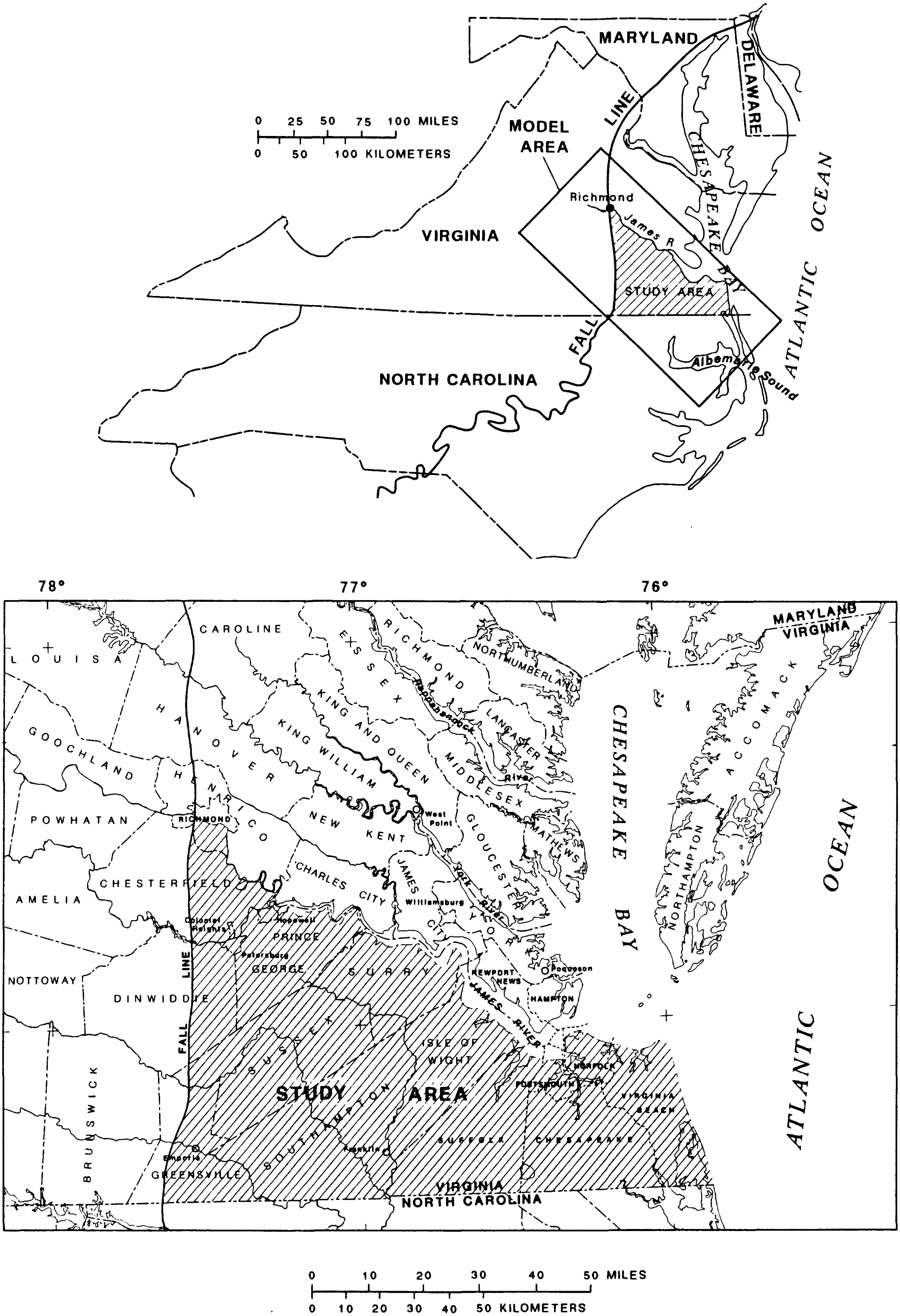

Figure 1.--Location and extent of study and model areas.

refine the framework. Geophysical logs provided by local well drillers and the VWCB and water-level and water-quality data were analyzed to revise the extent and thickness of each hydrogeologic unit. Three research stations were drilled and developed by VWCB. Each station consists of five or six wells that penetrate different aquifers. Geologic and geophysical data were gathered during drilling. Continuous water-level data were collected at the research stations for approximately 6 months to assess vertical variations of water levels within the multiaquifer system.

Synoptic water-level data were collected quarterly at approximately 60 wells located throughout the study area. Historic water-level data through 1983 for approximately 150 wells were reviewed for errors and entered into the U.S. Geological Survey data base. Hydrographs of these data were used in model calibration. The U.S. Geological Survey water-use data base, containing pumpage records for large industrial and municipal water-supply and small commercial and public-supply systems in the Coastal Plain physiographic province of Virginia, was updated to 1983. Aquifer-test data collected by VWCB and local well drillers were analyzed to revise values for transmissivity and storage coefficient.

A three-dimensional, digital, ground-water flow model was developed and calibrated to simulate water levels and ground-water flow for prepumping (prior to 1891) and pumping conditions (1891-1983). The model was then used to project effects of injection or increased pumpage on water levels and the direction and magnitude of ground-water flow under seven proposed pumping scenarios. Conceptualization of ground-water flow used in model development was provided by Harsh and Laczniak (1986) who describe a regional model of the entire Virginia Coastal Plain.

Acknowledgments

Special thanks are given to the VWCB for providing hydrologic information, drilling services, and assistance throughout the project and to Andrew A. Meng for revising the hydrogeologic framework maps for southeastern Virginia. The authors also would like to thank local well drillers for providing access to geophysical logs and well-construction data and to the North Carolina Department of Natural and Economic Resources for providing hydrologic information on research stations.

HYDROGEOLOGY

This section of the report describes the hydrogeology of the multiaquifer system in southeastern Virginia. It includes a discussion of the geologic history of sediment deposition; stratigraphy and areal extent of aquifers and confining units; hydraulic characteristics of aquifers; and occurrence, movement, and use of ground water.

Geologic History of Sediment Deposition

The Coastal Plain physiographic province of southeastern Virginia is underlain by unconsolidated sediments ranging from early Cretaceous to Holocene age. The sediments, dipping and thickening eastward, consist primarily of sand, clay, silt, and gravel with variable amounts of shell material. The sediments lie directly upon Precambrian granitic and metamorphic or Mesozoic sedimentary rock, commonly referred to as "basement." The westernmost extent of Coastal Plain sediments is at the Fall Line, beyond which the igneous and metamorphic rocks of the Piedmont physiographic province occur. Sediment thickness in southeastern Virginia ranges from near zero feet at the Fall Line to 2,472 feet at Moore's Bridge Treatment Plant near the city of Norfolk. Thickness may exceed 3,500 feet in the Back Bay area of the city of Virginia Beach.

The depositional patterns of the Coastal Plain sediments are complex and are presented in detail by Meng and Harsh (1984). About 70 percent of the sediments are early Cretaceous age, generally consisting of interbedded arkosic quartz sand and clay. These deposits are of continental origin and consist of alternating channel sand deposits and interchannel clayey sediments. Weathered material was transported by high-gradient streams from the highlands and deposited in the lowlands in stream beds, along the shore, and in shallow bays. Sediments accumulated eastward and large delta lobes formed. Within the deltas, fluvial conditions produced a variety of interfingering continental material ranging from clay and silty clay to sand and gravel. Because of the fluvial-deltaic manner of deposition, the Cretaceous sediments vary laterally, and may thicken, thin, or pinch out over short distances. Upper Cretaceous sediments are of marine origin, resulting from inundations of the seas over the deltas.

Tertiary sediments, deposited in seas that extended inland at least as far as the Fall Line, generally consist of a layered sequence of sand, clay, marl, and some shells. Because of the relatively constant and widespread condition of the transgressing seas, these sediments are more homogeneous and uniform throughout the Coastal Plain than are Cretaceous sediments.

Pleistocene sediments were deposited as channel fills and fluvial-marine terraces during periods of variable sea level. Changes in sea level occurred repeatedly in the last few million years as a result of glacial formation and melting associated with climatic changes. During drops in sea level, Coastal Plain sediments were eroded and incised by streams. During rises, the deeply incised stream valleys were flooded and headlands were eroded. This process produced drowned river valleys and broad terrace landforms. Peat, silty clay, and sand were deposited in stream valleys, and gravel, sand, and clay were deposited on the terraces. Marly strata were deposited on easternmost terraces.

A thin layer of Holocene deposits overlie Pleistocene sediments in the eastern part of the Coastal Plain. The Holocene sediments were deposited in lagoons, beaches, tidal flats, and barrier islands during rising sea levels since the Pleistocene. These deposits are considered hydrogeologically part of the Pleistocene sediments in this report.

A major feature affecting the study area is the Chesapeake Bay estuary formed by flooding of the lower Susquehanna River when sea level rose during the retreat of the last ice age. Lower areas of the James and York Rivers in the model area also flooded at this time. The flooding allowed finer-grained material to settle out, thereby covering older deposits of sand and gravel with sandy silt (Hack, 1957).

Stratigraphy and Areal Extent of Aquifers and Confining Units

The hydrogeologic framework for the study area is a series of aquifers and intervening confining units defined on the basis of lithologic and hydrologic properties of the unconsolidated Coastal Plain sediments. One water-table and seven confined aquifers, separated by intervening confining units, were identified for the study area. One other confined aquifer (Peedee) and intervening confining unit (Peedee confining unit) located in northeastern North Carolina, as well as a confining unit (St. Marys confining unit) located north of the James River, were included in the model framework for hydrologic analysis. Table 1 summarizes relations between the hydrogeologic units and geologic formations and ages and corresponding hydrogeologic names used in previous investigations. Lower Cretaceous sediments include the lower and middle Potomac aquifers and confining units; Upper Cretaceous sediments include the upper Potomac, Virginia Beach, and Peedee aquifers and confining units; Tertiary sediments include the Aquia, Chickahominy-Piney Point, and Yorktown-Eastover aquifers, and Nanjemoy-Marlboro, Calvert, St. Marys, and Yorktown confining units; and Quaternary sediments comprise the Columbia aquifer.

A brief discussion of the nine aquifers and intervening confining units used in model analysis is presented. The reader is referred to Meng and Harsh (1984) for a more detailed description of age, lithologic characteristics, and stratigraphy of each aquifer and confining unit. This report follows the basic framework outlined by Meng and Harsh; however, the areal extent and thickness of several aquifers and confining units were revised after analyzing geophysical logs and water-level data collected during this study (A.A. Meng, U.S. Geological Survey, written commun., 1986). Figure 2 shows locations of wells used in the hydrogeologic framework analysis. Figures 3 through 10 illustrate tops of each aquifer relative to sea level and areal extent, and figures 11 through 19 illustrate thickness and areal extent of confining units. Figure 20 illustrates general depth of aquifers, confining units, and basement from the Fall Line through southeastern Virginia. Table 2 describes general hydrogeologic characteristics and well yields for individual aquifers in the model area.

The lower Potomac aquifer in the lower part of the Potomac Formation is the lowermost confined aquifer in the hydrogeologic framework and lies entirely on basement. This aquifer is thinnest along its western limit near the Fall Line and thickens seaward. Thickness in the study area ranges from near zero at the Fall Line to 882 feet at well 61C1 in the city of Norfolk. The aquifer predominantly consists of thick interbedded sequences of medium- to very coarse-grained sand, clayey sand, and clay with interbedded gravel. It is capable of supplying large quantities of water but generally lies too deep to be affordable for all but large industrial users. Elevated chloride concentrations in the east restrict its use as a potable source of water. The lower Potomac aquifer is overlain by the lower Potomac confining unit throughout its extent. The confining unit is composed of sequences of brown, gray, or dark-green carbonaceous clay, interbedded with thin, sandy clay. The clay beds are not continuous or areally extensive but, instead, are a series of interlensing clayey deposits. Because of this depositional pattern, the confining unit varies considerably in thickness, ranging from a thin edge in the western part of the study area to approximately 80 feet in the city of

Table 1.--Hydrogeologic column showing aquifers and confining units in model area

Period	Epoch	Stratigraphic formation	Hydrogeologic units: This report	Cederstrom 1945	Geraghty and Miller 1979 a & b	Siudyla and others 1981	Harsh and Laczniak 1986
Quaternary	Holocene Pleistocene	Undifferentiated sediments	Columbia aquifer	Sands of Recent deposits and the Columbia group	Water-table aquifer	Water-table aquifer	Columbia aquifer
Tertiary	Pliocene	Yorktown Formation	Yorktown confining unit	Sands and shells of the Yorktown Formation	Upper artesian aquifer system	Yorktown aquifer	Yorktown confining unit
			Yorktown-Eastover aquifer				Yorktown-Eastover aquifer
	Miocene	Eastover Formation					
		St. Marys Formation	St. Marys confining unit				St. Marys confining unit
		Choptank Formation	Not present in model area				St. Marys-Choptank aquifer
		Calvert Formation	Calvert confining unit				Calvert confining unit
	Oligocene	Old Church Formation	Chickahominy-Piney Point aquifer				Chickahominy-Piney Point aquifer
	Eocene	Chickahominy Formation		Glauconitic sands of the Pamunkey coup		Eocene-Upper Cretaceous aquifer	
		Piney Point Formation					
		Nanjemoy Formation	Nanjemoy-Marlboro confining unit				Nanjemoy-Marlboro confining unit
		Marlboro Clay					
	Paleocene	Aquia Formation	Aquia aquifer				Aquia aquifer
		Brightseat Formation	Not present in model area				Not present in Virginia
Cretaceous	Late Cretaceous	Peedee Formation (of North Carolina)	Peedee confining unit[1]			Eocene-Cretaceous aquifer	
			Peedee aquifer[1]				
		Unnamed deposits (Black Creek Formation equivalent) in Virginia	Virginia Beach confining unit	Sands of Late Cretaceous age	Lower artesian aquifer system		
			Virginia Beach aquifer				
		Potomac Formation	Upper Potomac confining unit	Sands of the Potomac Group			Upper Potomac confining unit
			Upper Potomac aquifer				Upper Potomac aquifer
	Early Cretaceous		Middle Potomac confining unit			Lower Cretaceous aquifer	Middle Potomac confining unit
			Middle Potomac aquifer				Middle Potomac aquifer
			Lower Potomac confining unit				Lower Potomac confining unit
			Lower Potomac aquifer				Lower Potomac aquifer

[1]Not present in study area but used in model simulations of ground-water flow

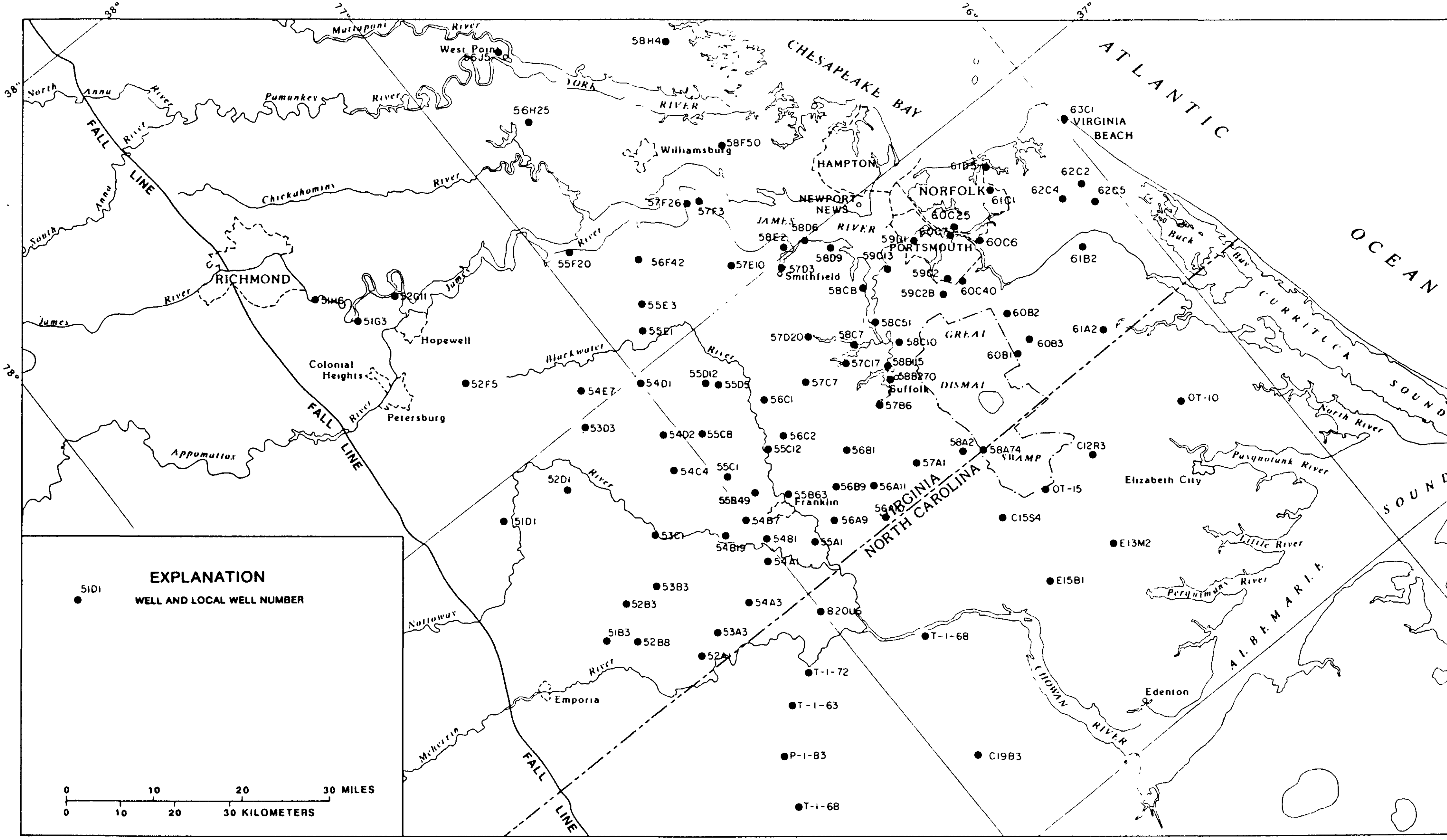

Figure 2.--Location of wells used in hydrogeologic framework analysis.

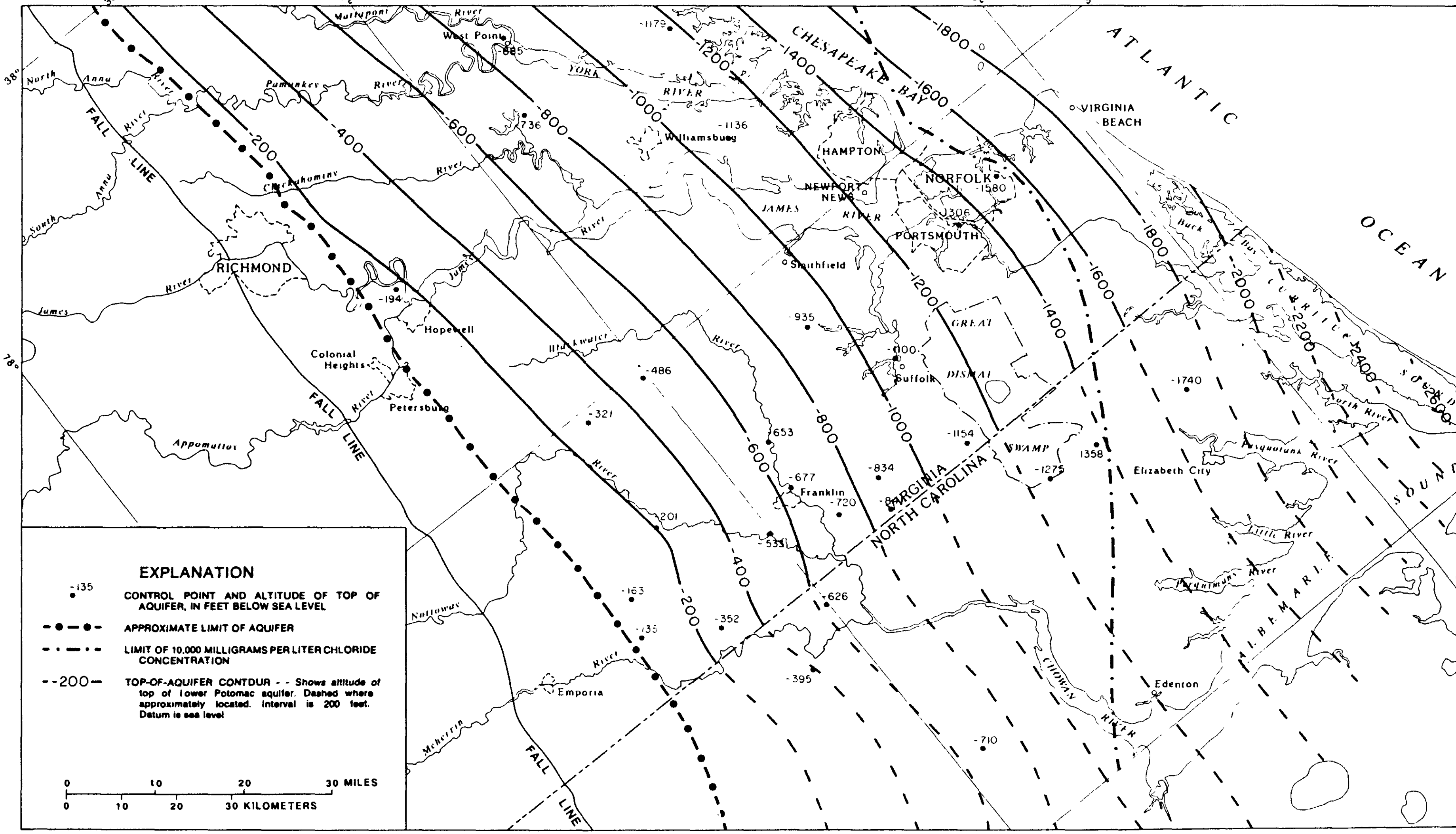

Figure 3.--Altitude of top and areal extent of lower Potomac aquifer.

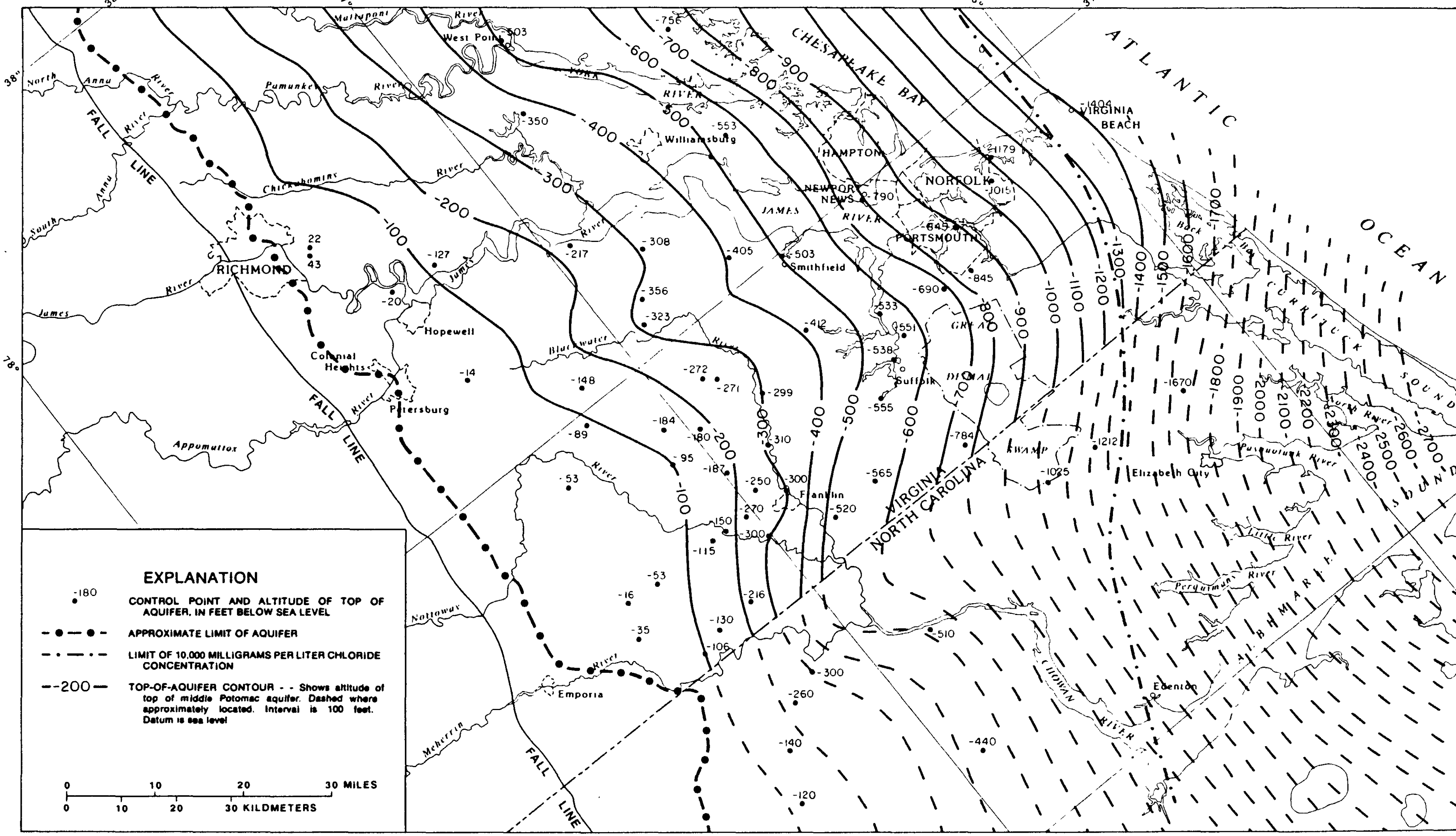

Figure 4.--Altitude of top and areal extent of middle Potomac aquifer.

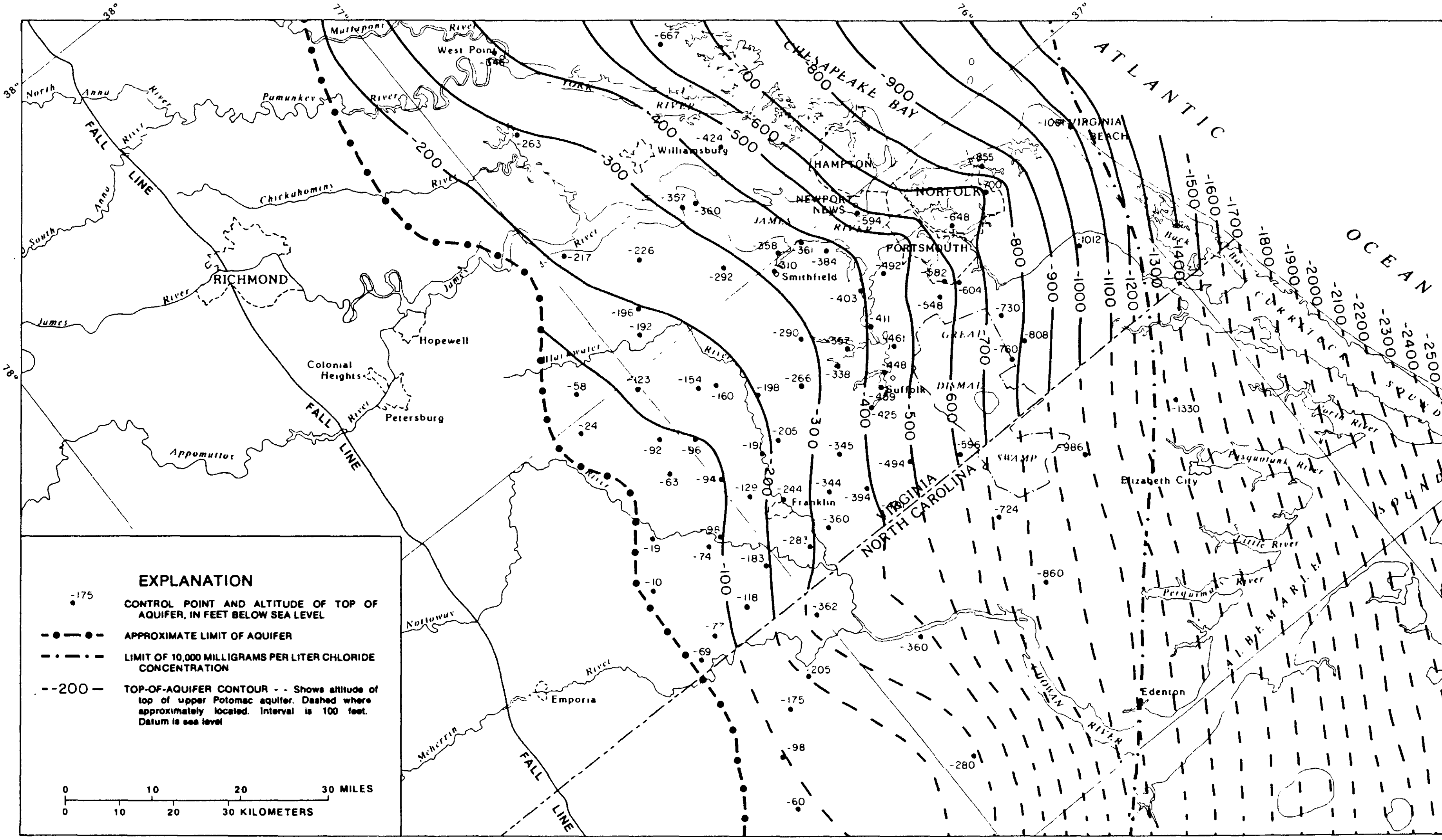

Figure 5.--Altitude of top and areal extent of upper Potomac aquifer.

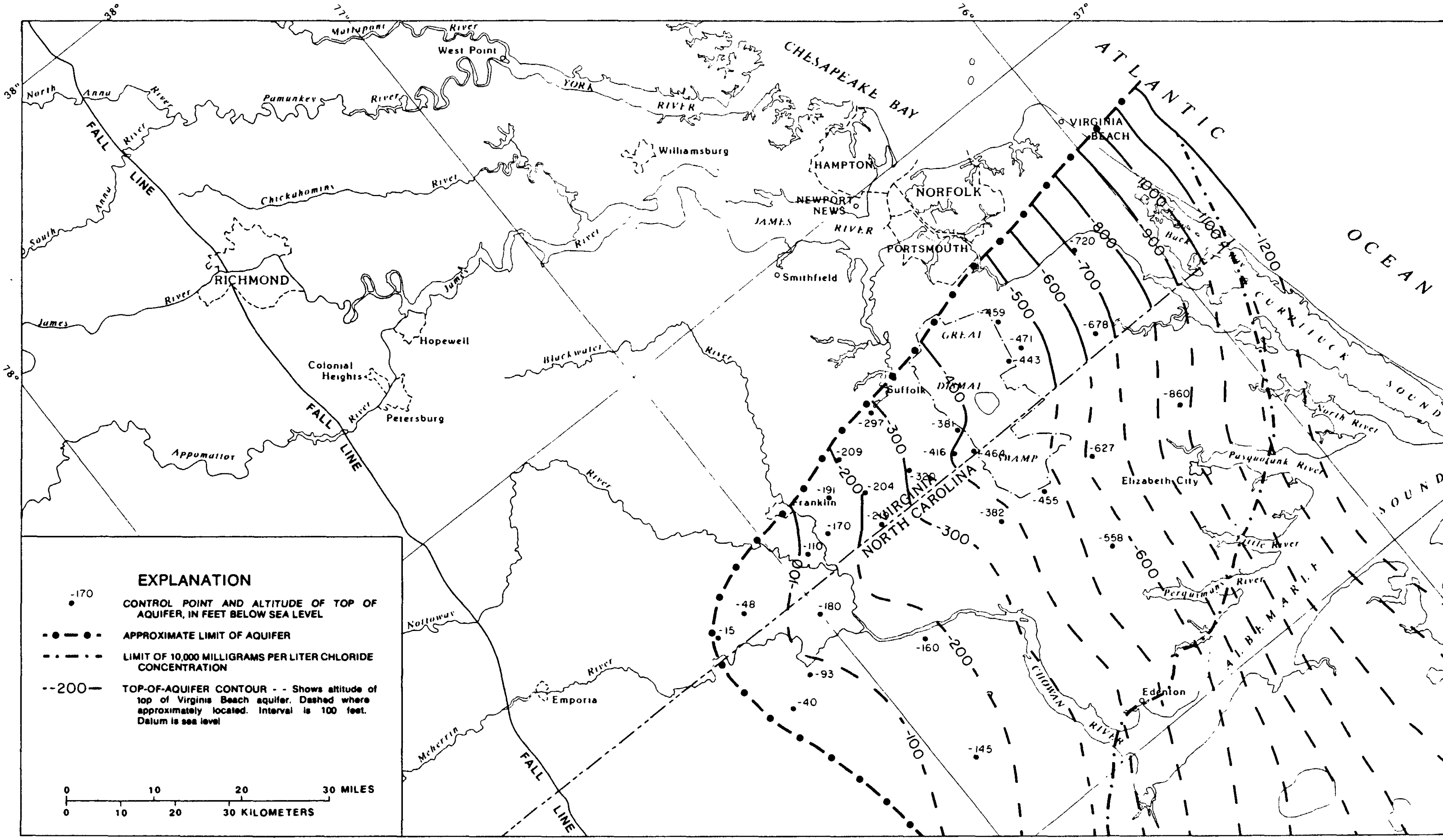

Figure 6.--Altitude of top and areal extent of Virginia Beach aquifer.

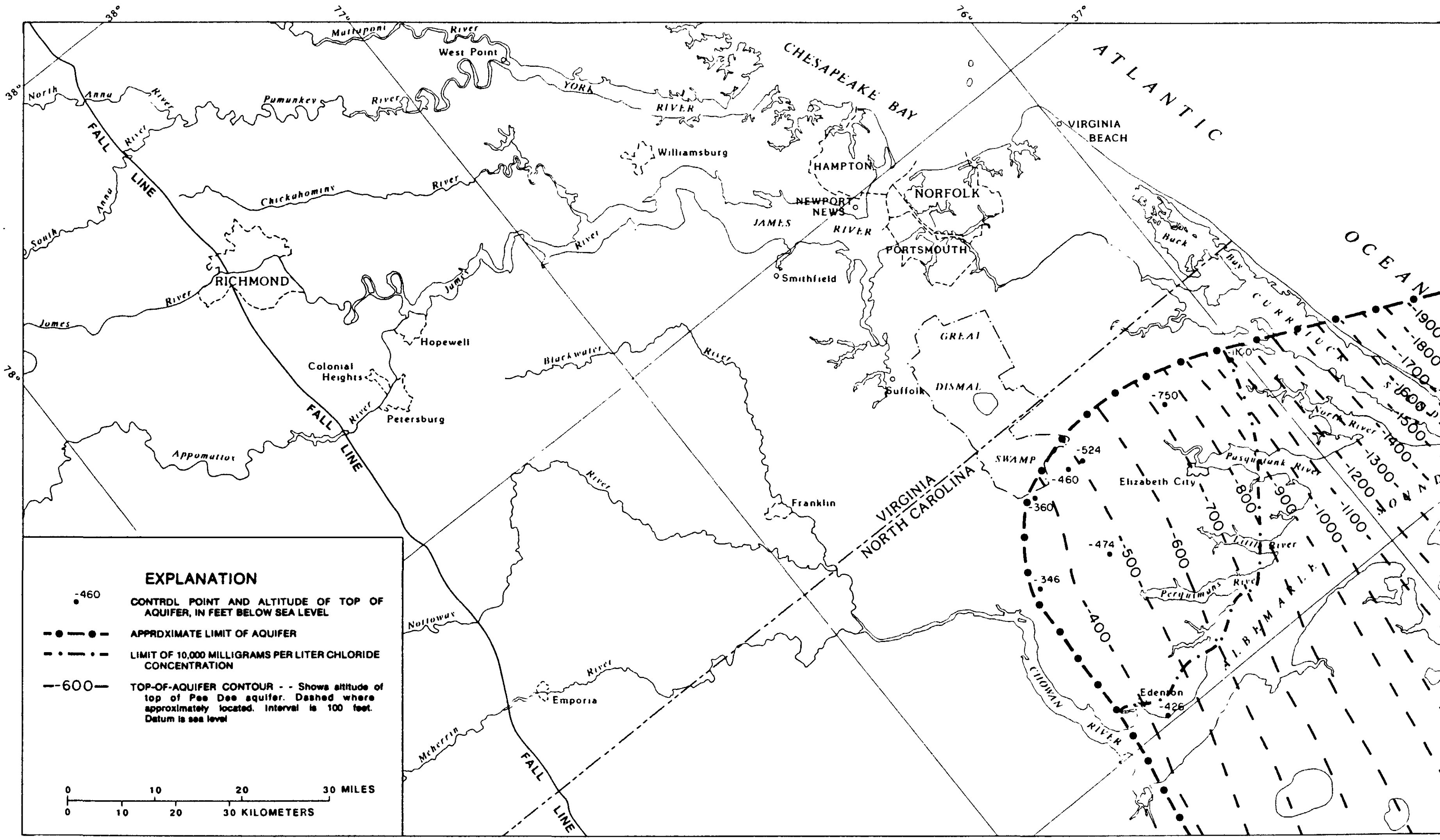

Figure 7.--Altitude of top and areal extent of Peedee aquifer.

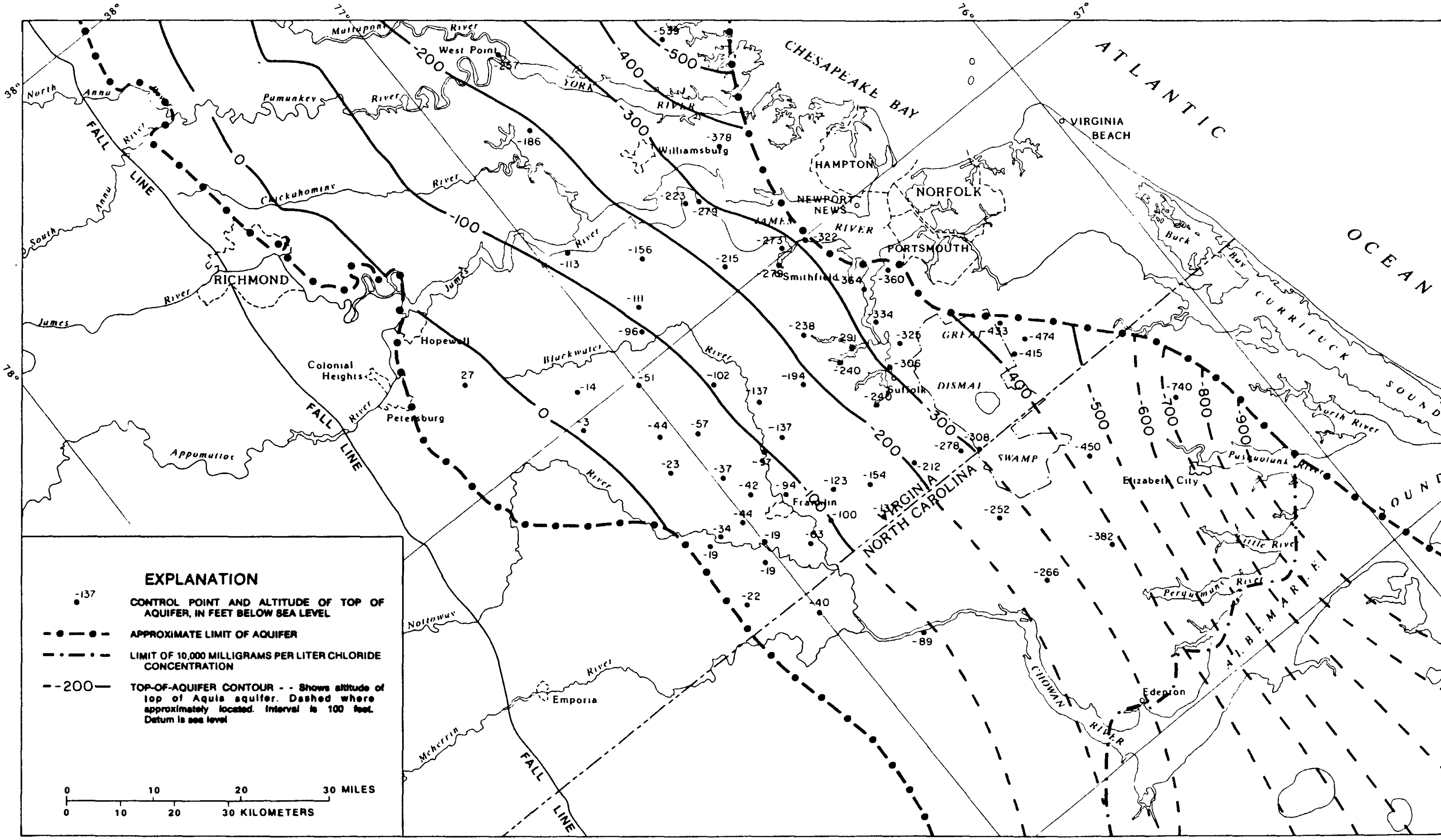

Figure 8.--Altitude of top and areal extent of Aquia aquifer.

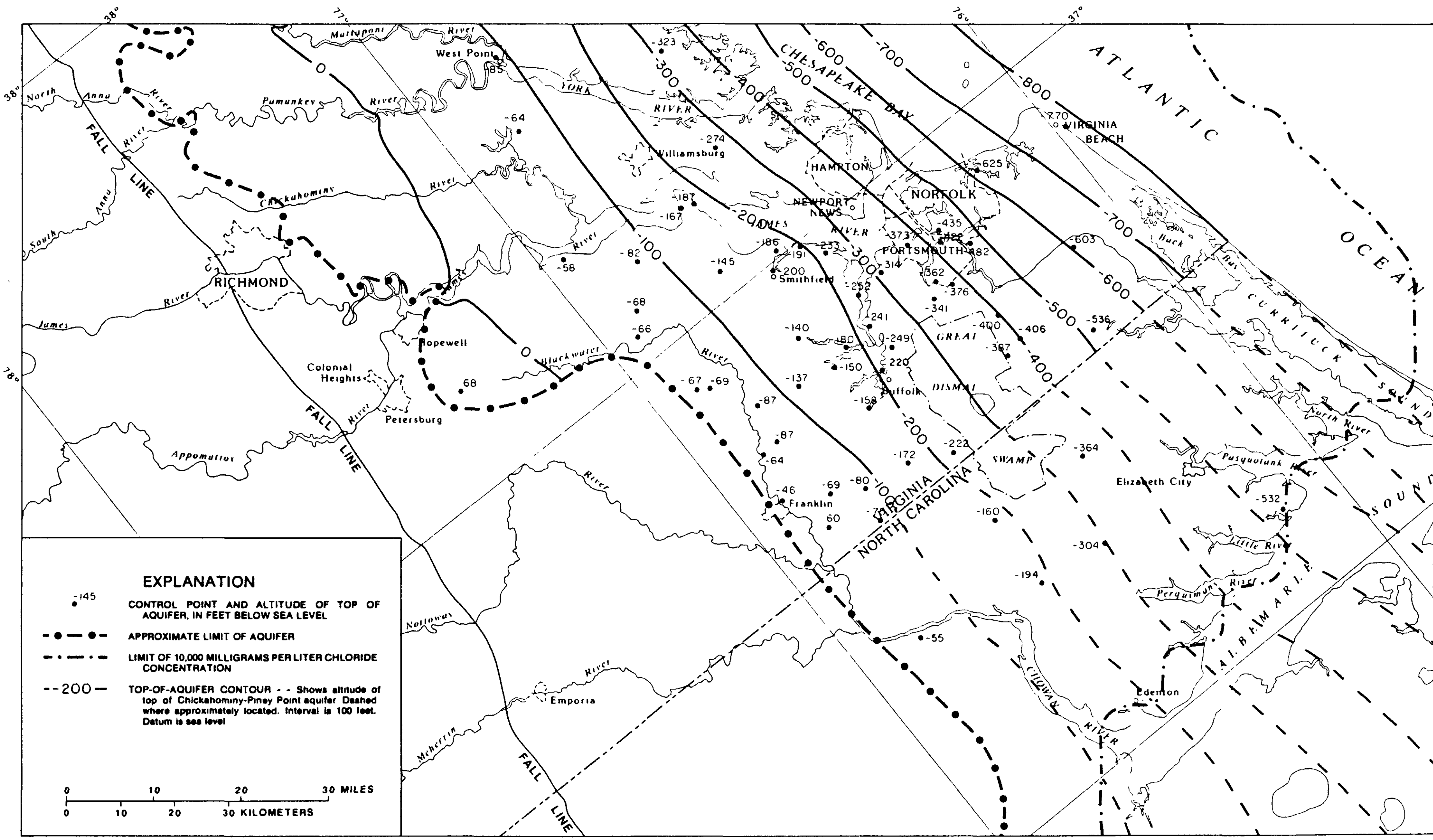

Figure 9.--Altitude of top and areal extent of Chickahominy-Piney Point aquifer.

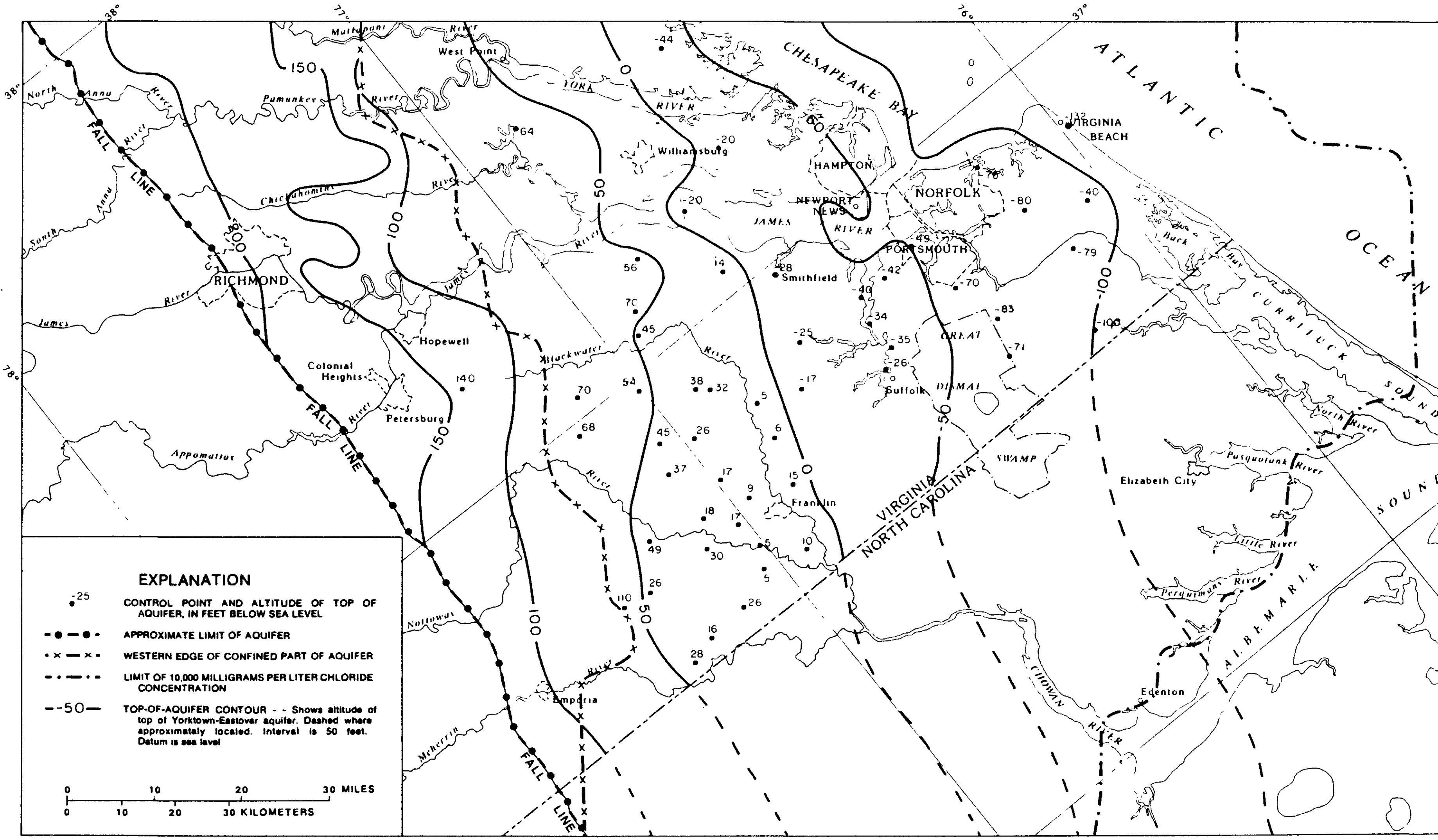

Figure 10.--Altitude of top and areal extent of Yorktown-Eastover aquifer.

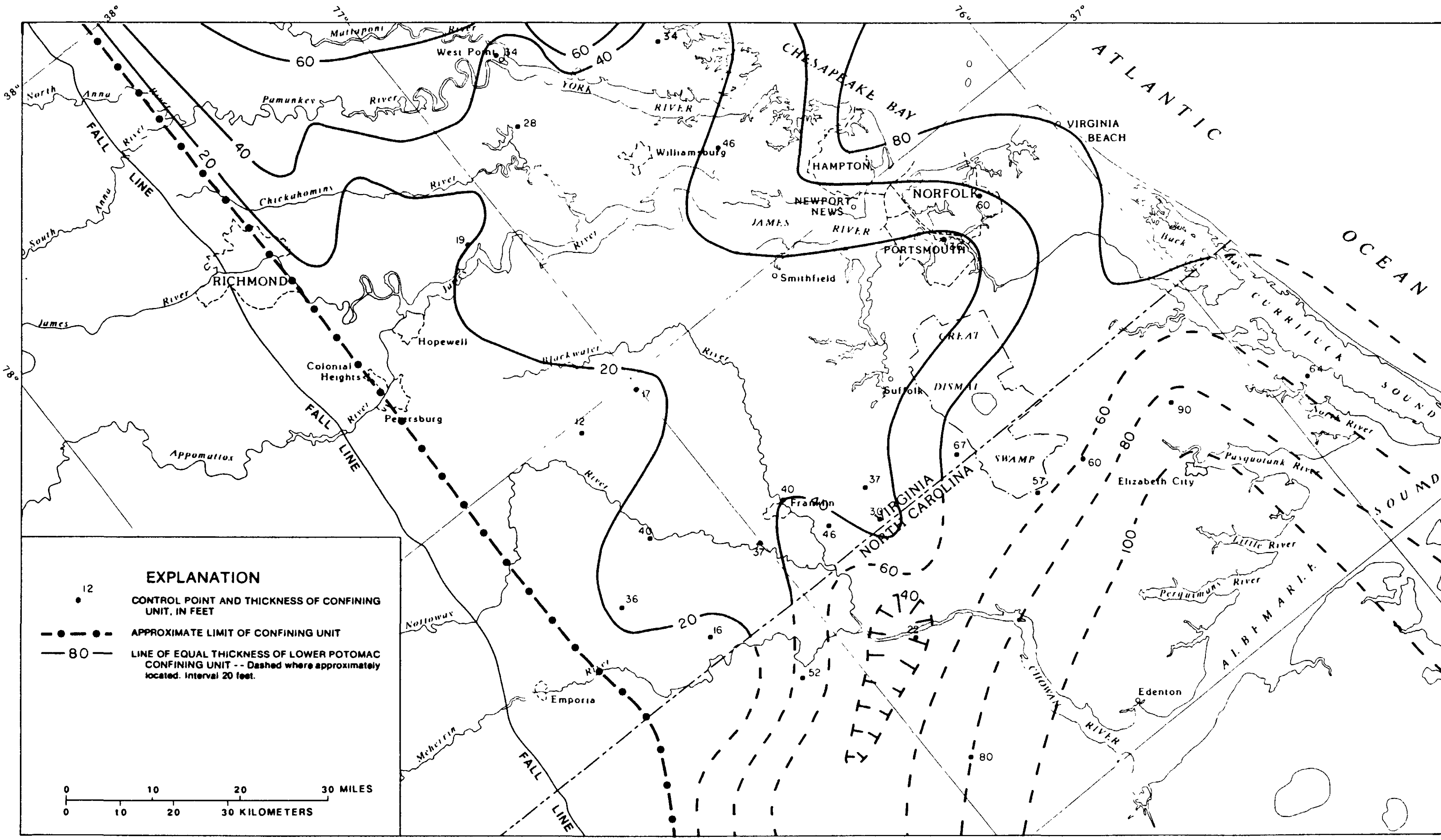

Figure 11.--Thickness and areal extent of lower Potomac confining unit.

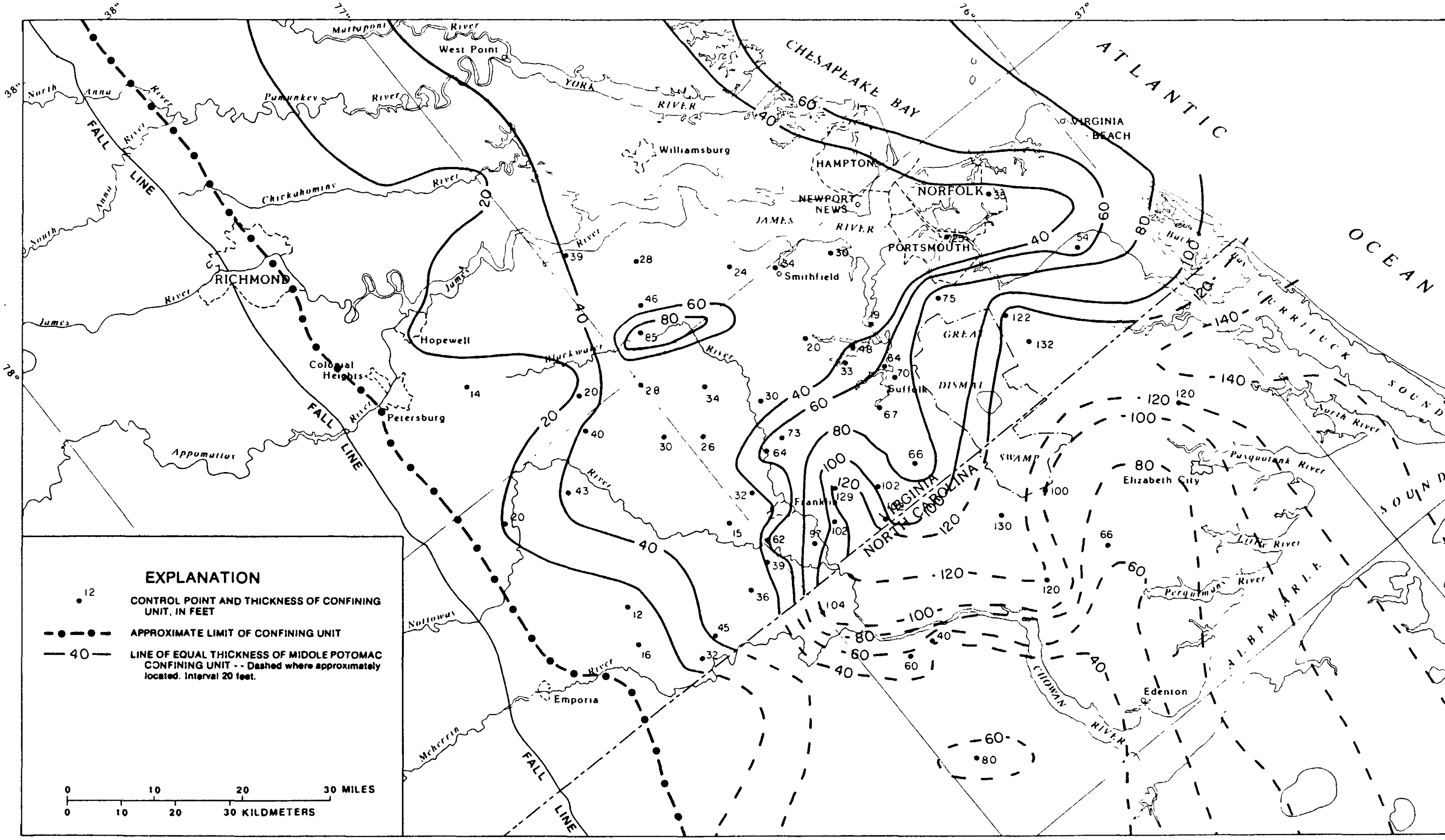

Figure 12.--Thickness and areal extent of middle Potomac confining unit.

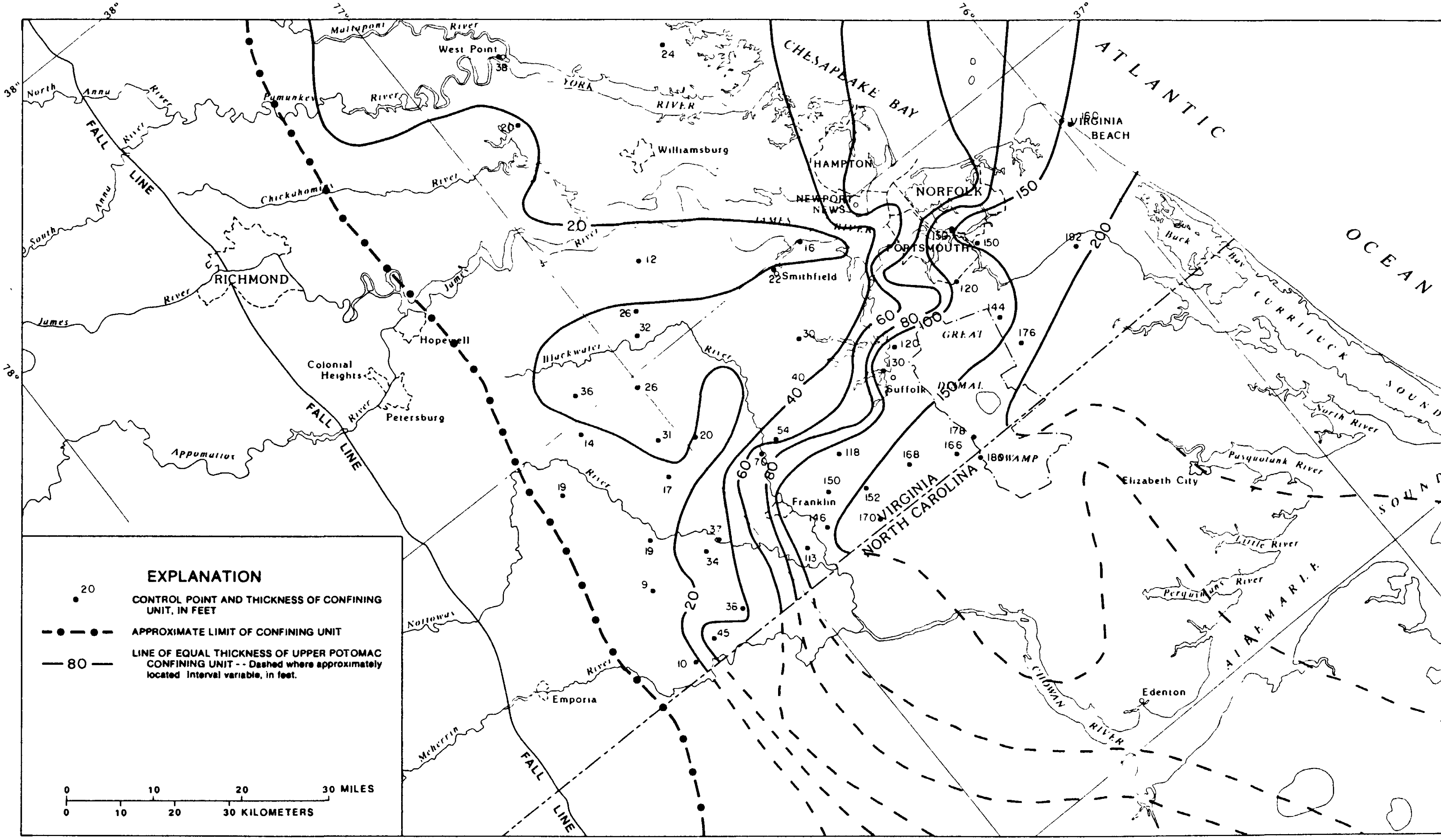

Figure 13.--Thickness and areal extent of upper Potomac confining unit.

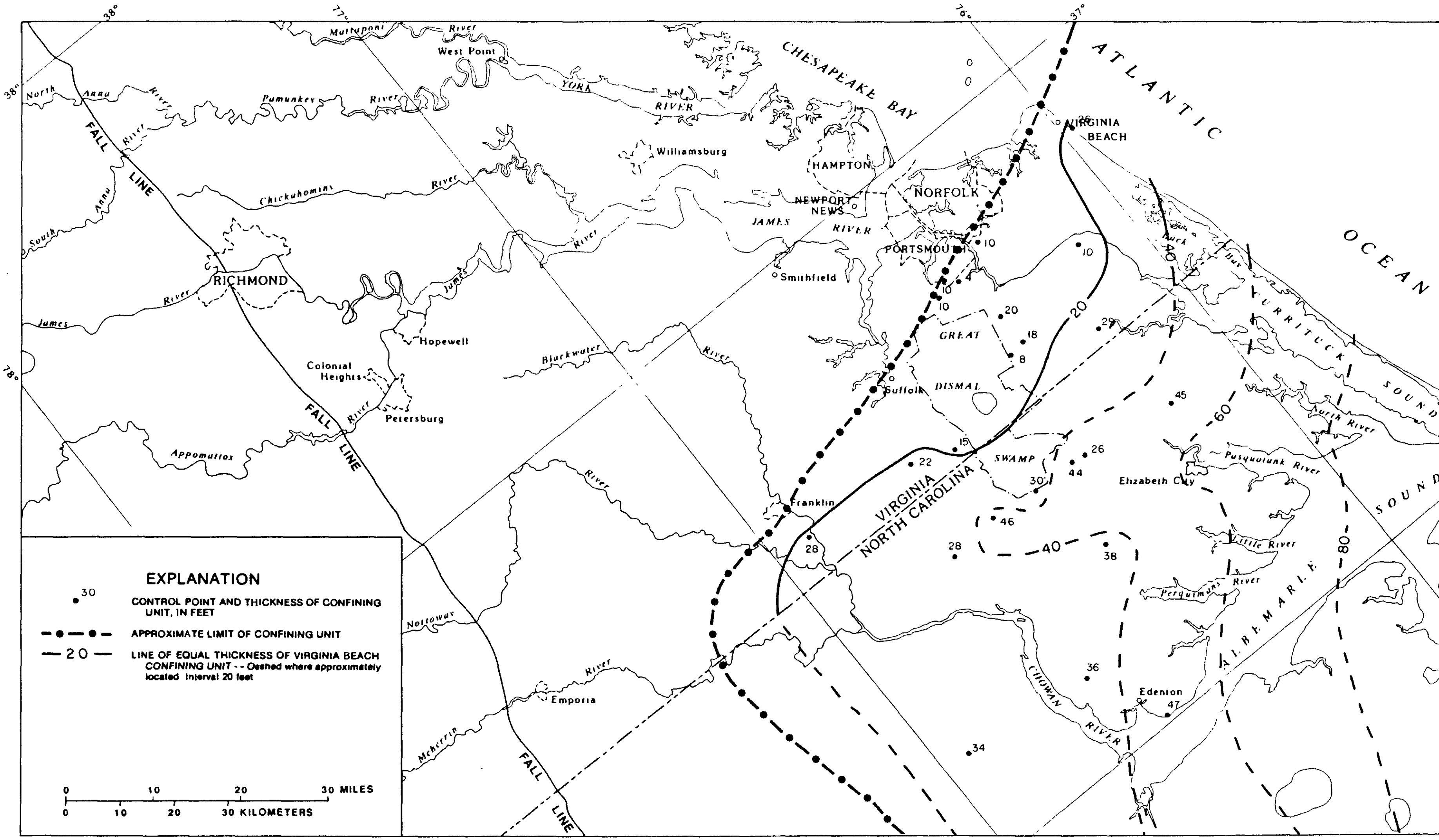

Figure 14.--Thickness and areal extent of Virginia Beach confining unit.

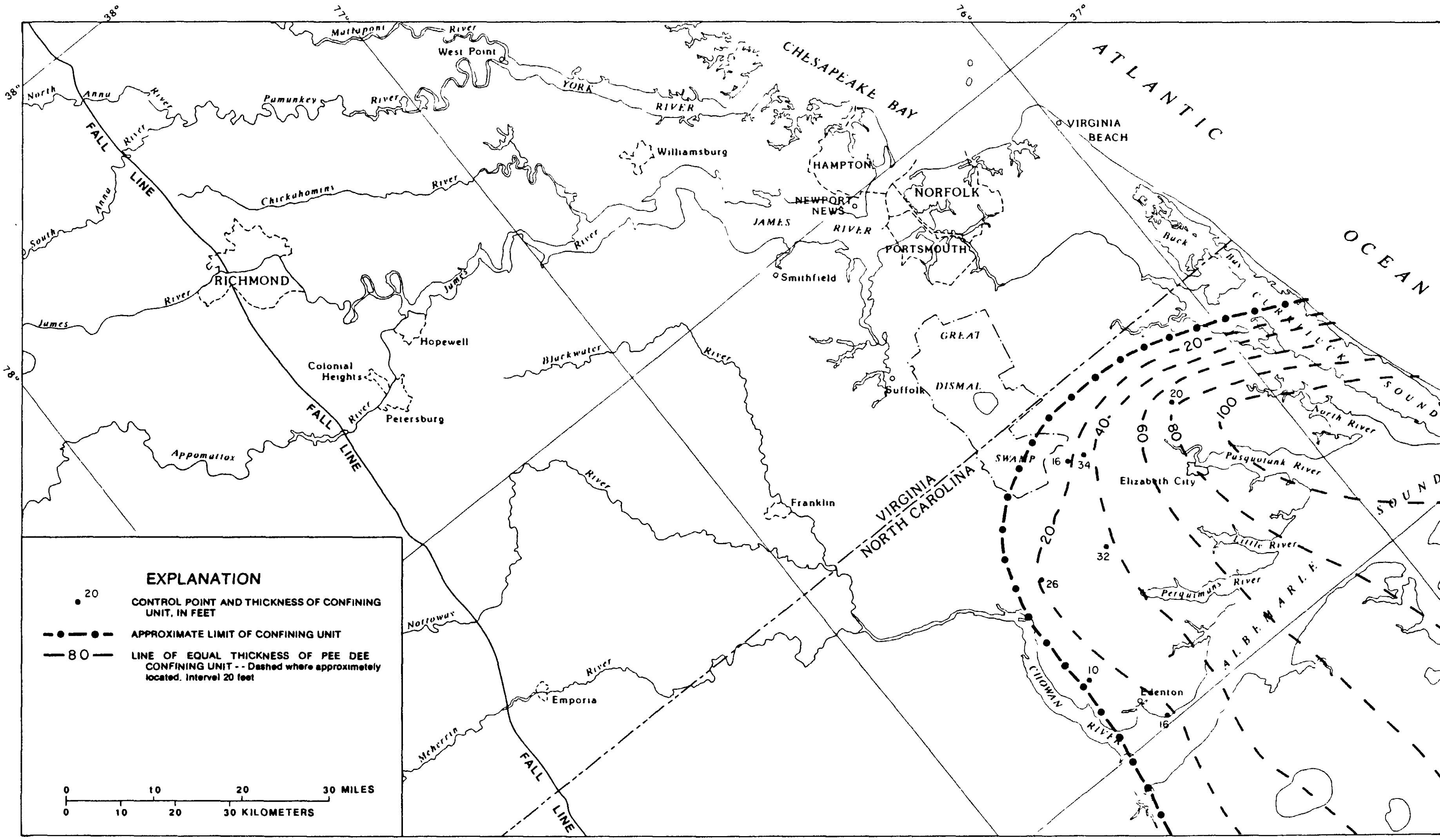

Figure 15.--Thickness and areal extent of Peedee confining unit.

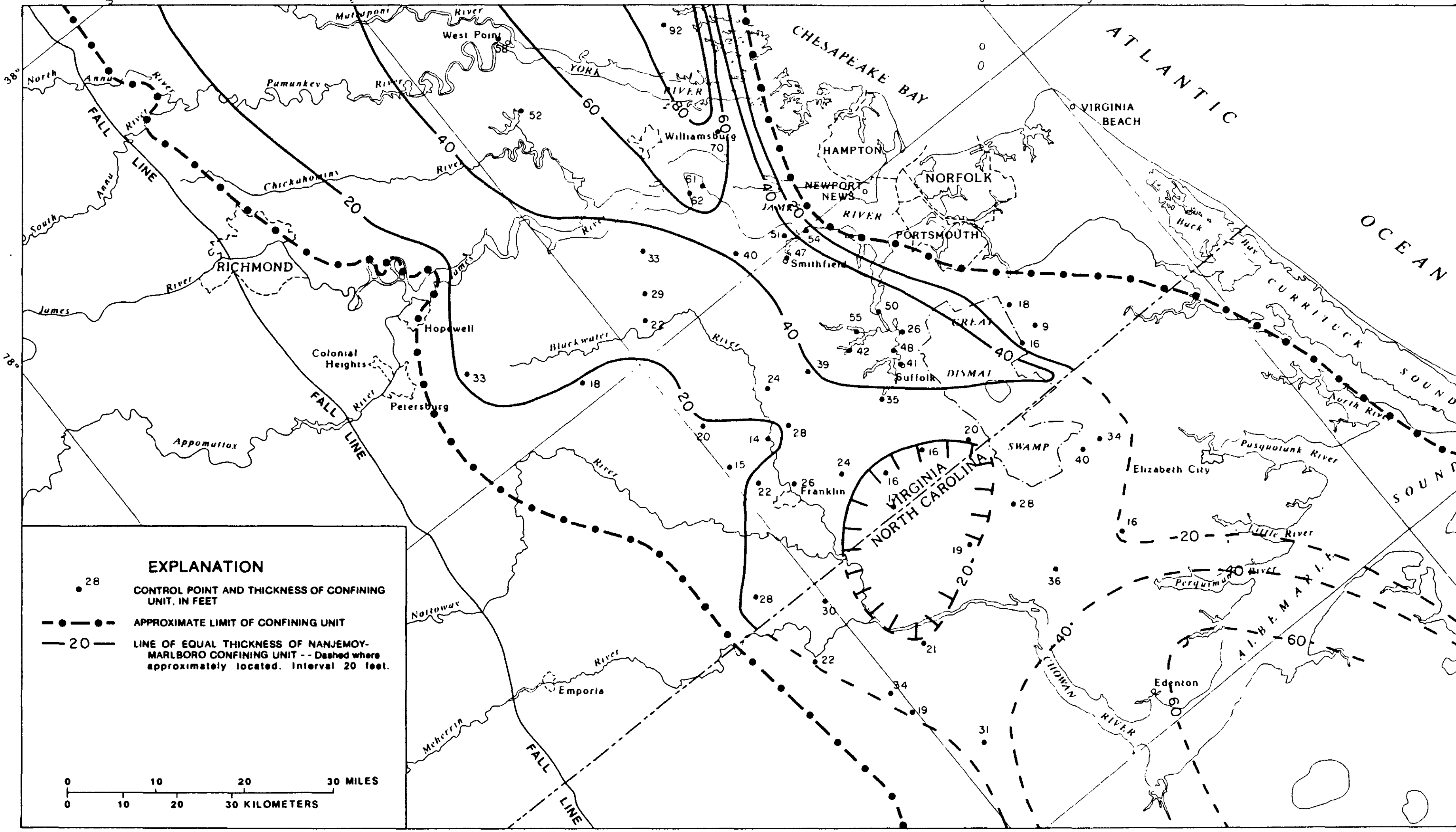

Figure 16.--Thickness and areal extent of Nanjemoy-Marlboro confining unit.

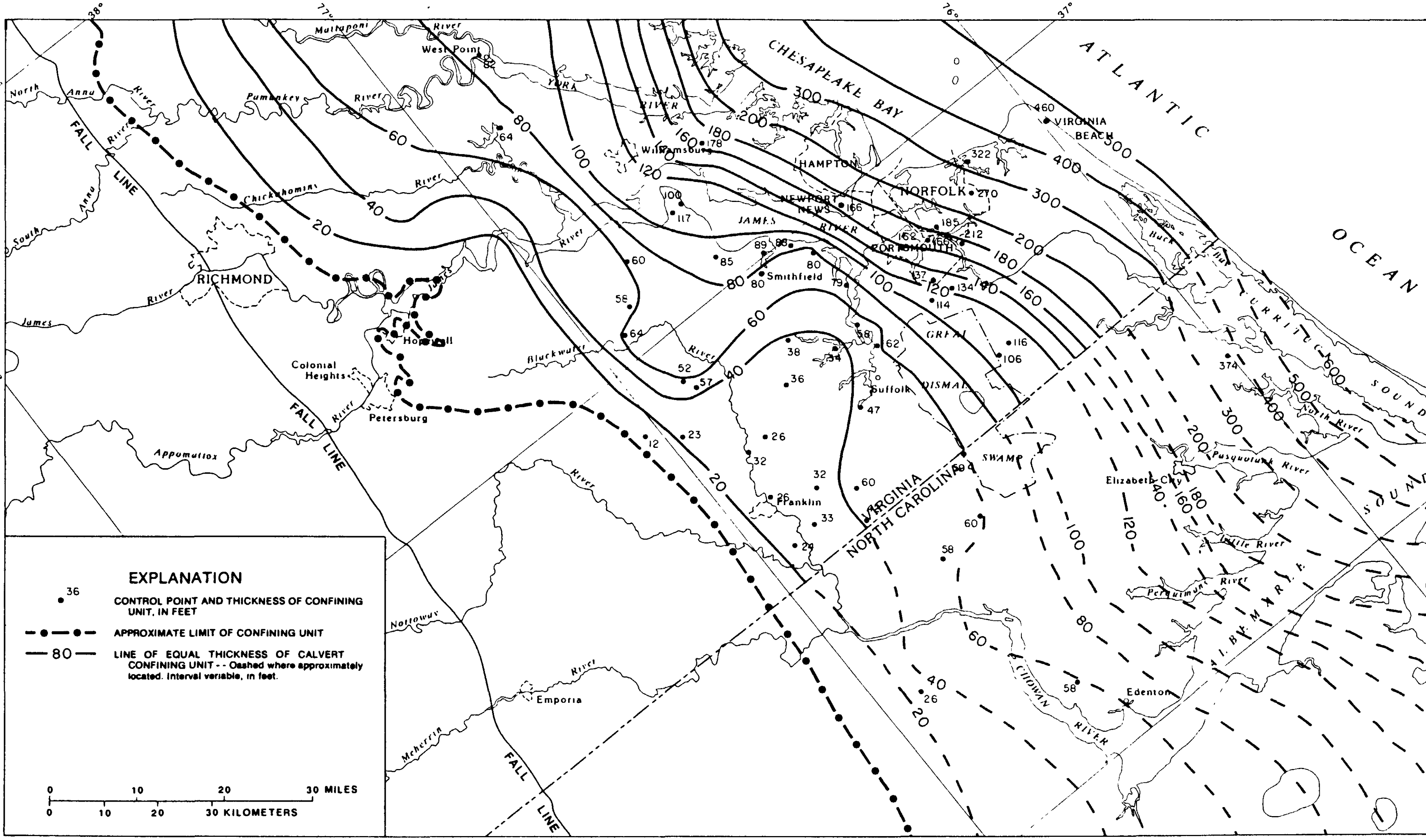

Figure 17.--Thickness and areal extent of Calvert confining unit.

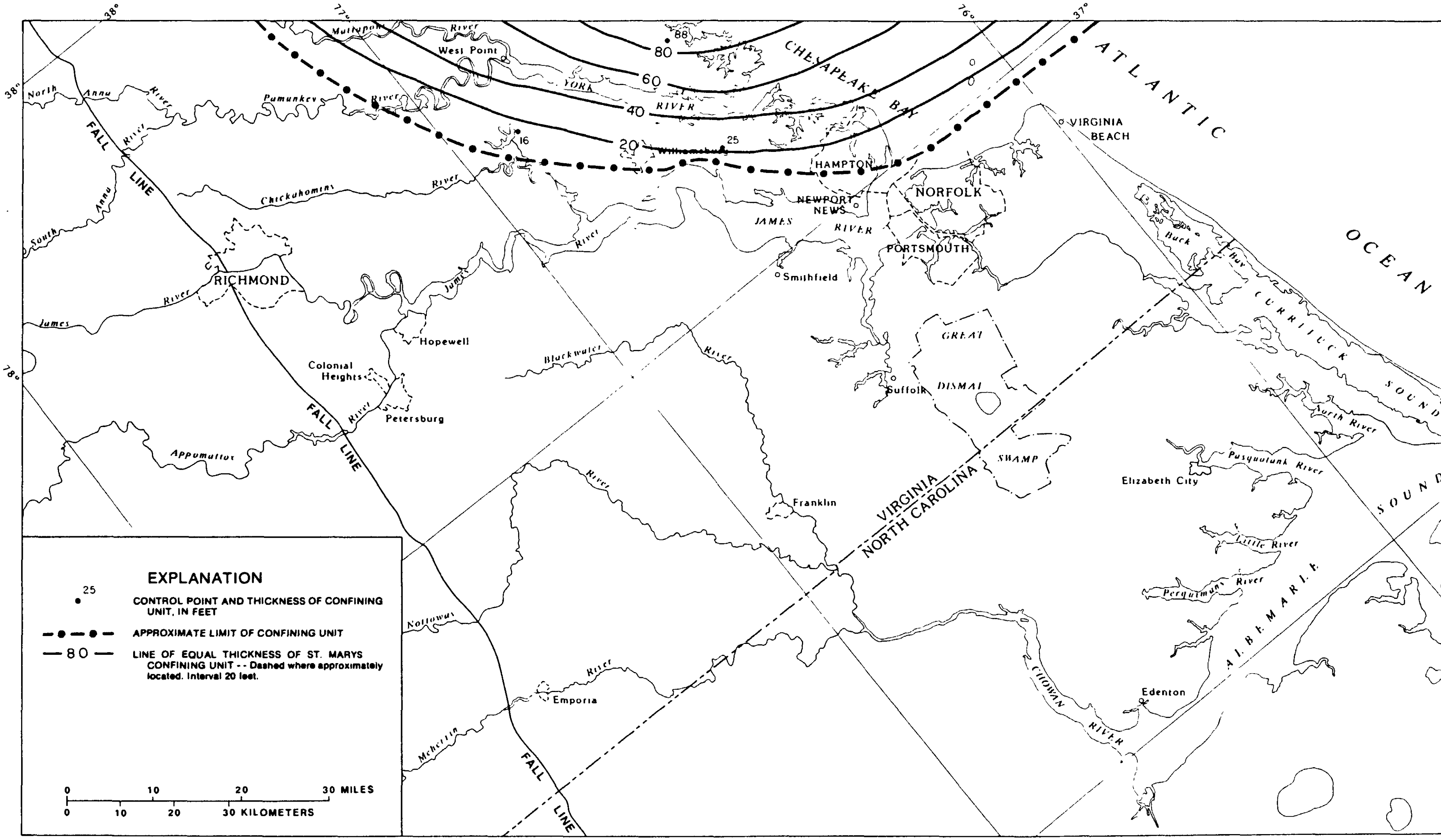

Figure 18.--Thickness and areal extent of St. Marys confining unit.

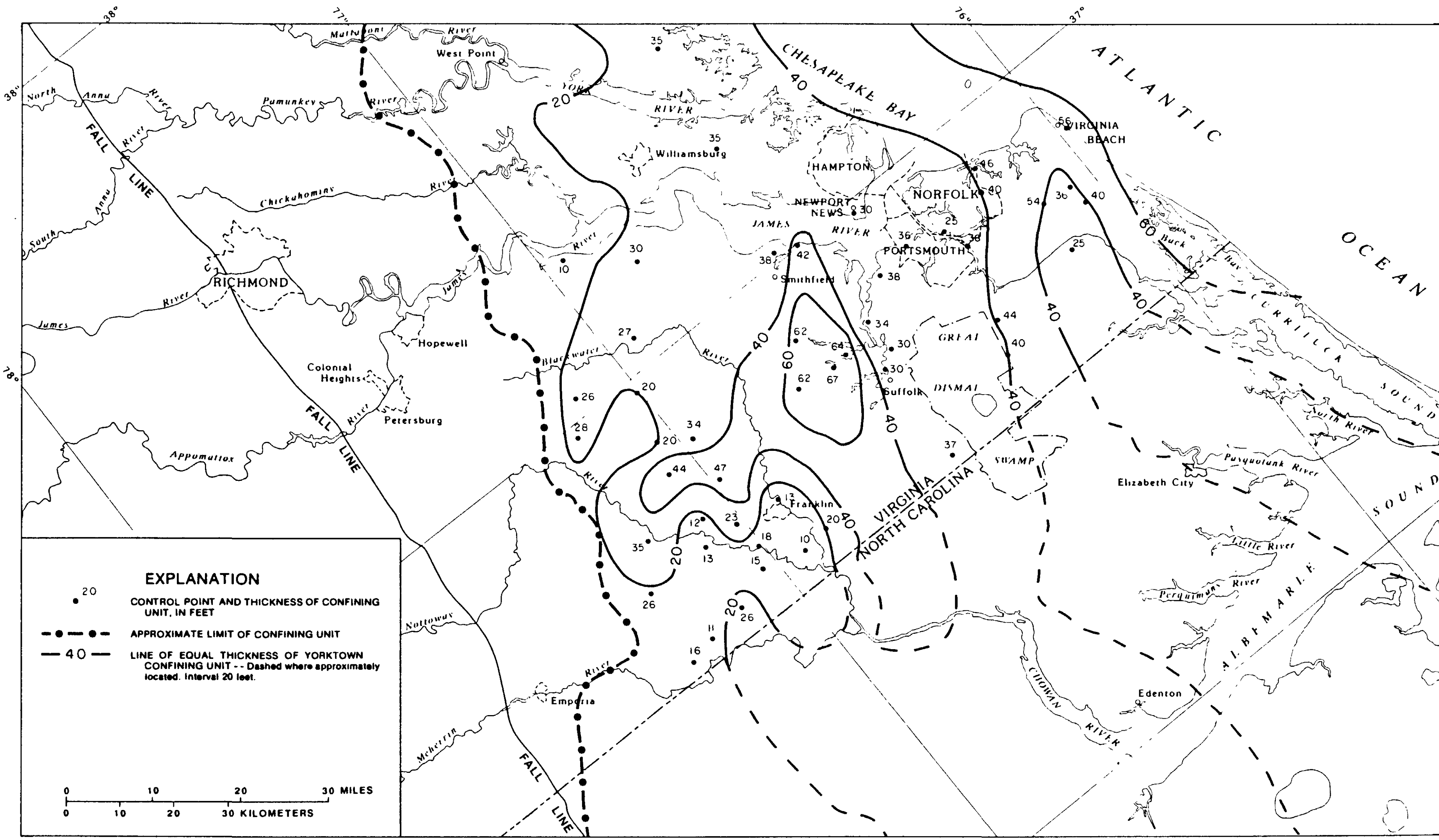

Figure 19.--Thickness and areal extent of Yorktown confining unit.

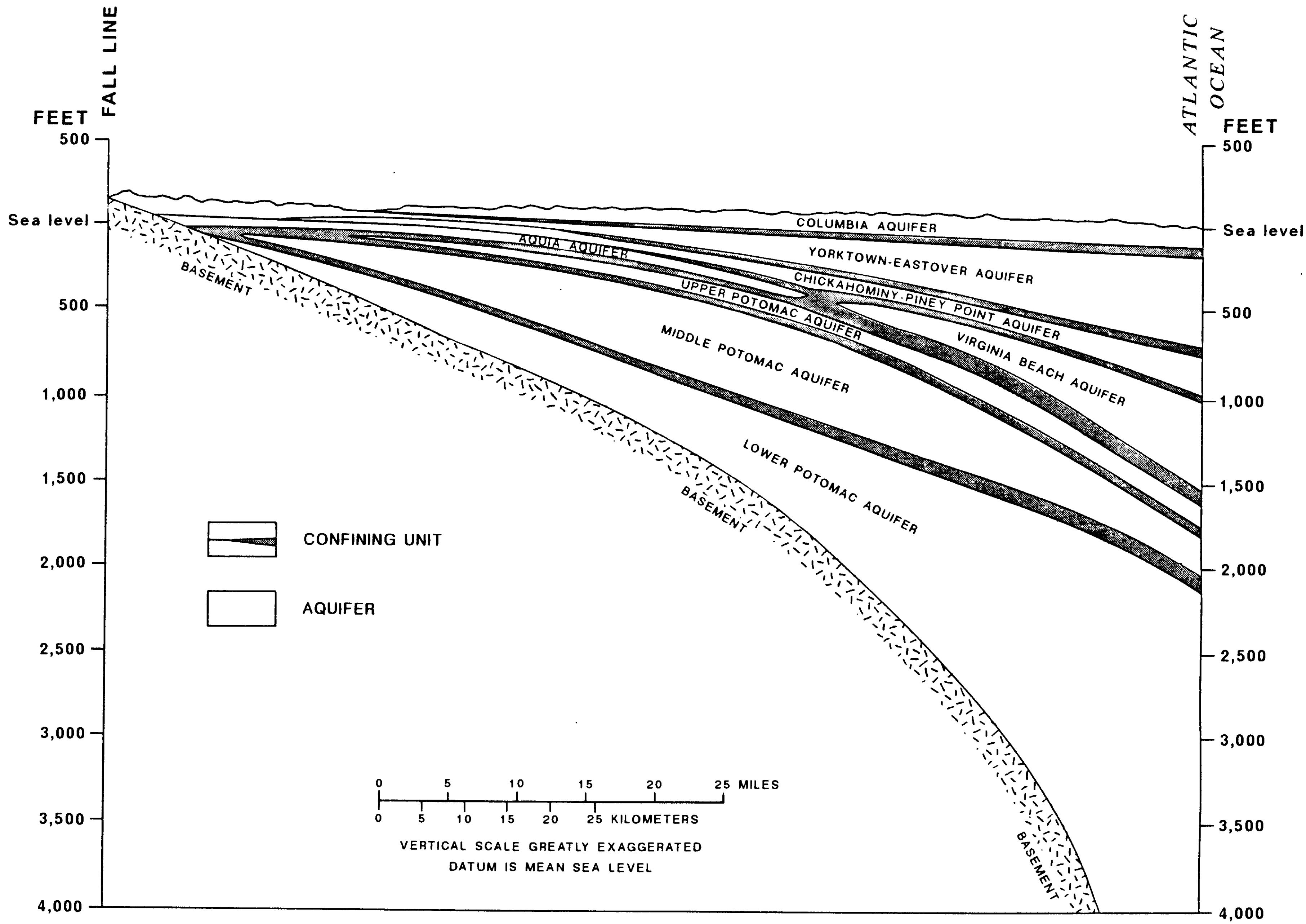

Figure 20.--General depth of aquifers, confining units, and basement from the Fall Line through southeastern Virginia.

Table 2.--Description of aquifers and well yields in model area
[Values in gallons per minute]

Aquifer name and description	Well Yield Common range	Well Yield May exceed	General remarks
Columbia aquifer: Sand and gravel, commonly clayey; interbedded with silt and clay. Fluvial to marine in origin; deposition resulted in terrace-type deposits from varying Pleistocene sea levels.	5-30	40	Generally unconfined, semi-confined locally. Most productive in eastern areas, very thin to missing in central and western areas. Water is very hard, calcium-bicarbonate type. Highly susceptible to pollutants from surface contamination. High concentrations of iron and nitrate in some areas. Possibility of salty water in coastal regions.
Yorktown-Eastover aquifer: Sand, commonly shelly; interbedded with silt, clay, shell beds, and gravel. Shallow, embayed marine in origin; deposition resulted in interfingering near-shore deposits from marine transgressions.	5-80	200	Multiaquifer unit. Mostly confined, unconfined updip in outcrop areas. Thickness dependent on altitude of land surface. Highest yields in eastern areas, thin to missing in western areas. Water is hard, sodium-calcium-bicarbonate type. Salty water in lower part of aquifer in eastern areas.
Chickahominy-Piney Point aquifer: Sand, moderately glauconitic, shelly; interbedded with silt, clay, and thin, indurated shell beds. Shallow, inner marine shelf in origin; deposition result of marine transgression.	10-110	200	Generally confined, except where it crops out along major stream valleys in the west. Important aquifer in central parts of Coastal Plain. Yields moderate to abundant supplies to domestic, small industrial, and municipal wells. Aquifer missing in western areas. Water is soft to hard, calcium-sodium-bicarbonate type and generally of good quality.
Aquia aquifer: Sand, glauconitic, shelly; interbedded with thin, indurated shell beds and silty clay intervals. Shallow, inner to middle marine shelf in origin; deposition result of marine transgression.	15-210	350	Generally confined, except where it crops out along major stream valleys in the west. Important aquifer in northern two-thirds of Coastal Plain. Yields moderate supplies to domestic, small industrial, and municipal wells. Aquifer missing in eastern areas. Water is soft sodium-bicarbonate type, with high iron, sulfide, and hardness locally.
Peedee aquifer: Sand, glauconitic and shelly; interbedded with dark, micaceous silt and clay. Near-shore marine in origin; deposition resulted from Late Cretaceous marine transgression.	5-40	50	Restricted to North Carolina Coastal Plain; not extensively developed. Yields small to moderate supplies to primarily domestic wells. Water is soft, sodium-bicarbonate type, with high chlorides in eastern areas.
Virginia Beach aquifer: Sand, fine- to medium-grained, glauconitic, micaceous, and lignitic; interbedded with thin clay layers and indurated zones. Shallow, inner marine shelf in origin; deposition result of marine transgression.	20-200	500	Multiaquifer unit. Restricted to southeastern Virginia and North Carolina Coastal Plain. Yields moderate to abundant supplies to domestic and industrial wells. Water is soft, sodium-bicarbonate type, with high chlorides in eastern areas and areas of high fluoride and dissolved solids.
Upper Potomac aquifer: Sand, very fine to medium, micaceous, lignitic, and clayey; interbedded with silty clay. Shallow, estuarine and marginal marine in origin; sediments result of first major marine inundation of Cretaceous deltas.	20-400	1000	Multiaquifer unit. Confined, restricted to central and eastern areas. Yields second largest supply of water in Coastal Plain. Water is soft, sodium-chloride-bicarbonate type, with high chlorides in eastern areas.
Middle Potomac aquifer: Sand, fine to coarse, occasional gravel; interbedded with silty clay. Fluvial in origin; sediments result of deltaic deposition.	20-160	700	Multiaquifer unit. Generally confined, unconfined in outcrop areas of northwestern Coastal Plain and major stream valleys near Fall Line. Yields second largest supply of water in Coastal Plain. Water is moderately hard, sodium-chloride -bicarbonate type, with high chlorides in eastern half of Coastal Plain.
Lower Potomac aquifer: Sand, medium to very coarse, and gravel, clayey. Fluvial in origin; sediments result of deltaic deposition.	100-800	1,500	Multiaquifer unit. Generally confined, unconfined in outcrop areas of northwestern area of Coastal Plain. Yields third largest supply of water in Coastal Plain. Water is soft to very hard, and of sodium-bicarbonate to sodium-chloride type, with high chlorides in eastern half of Coastal Plain.

Virginia Beach (fig. 11). It is overlain by the middle Potomac aquifer throughout its extent.

The middle Potomac aquifer in the middle part of the Potomac Formation is the second thickest confined aquifer. It is present throughout the study area. It ranges in thickness in the study area from a thin edge along the Fall Line to approximately 500 feet in the city of Norfolk (well 61C1). The aquifer is composed of interlensing clay, silt, and fine- to coarse-grained sand, with interbedded gravel. The aquifer is capable of supplying large quantities of water and is utilized by most large industrial and municipal users throughout the western and central part of the study area. However, as with the underlying aquifer, high chloride concentrations are present in the eastern part of this aquifer, restricting its use as a potable source of water. The middle Potomac aquifer is overlain by the middle Potomac confining unit throughout its extent. As with the lower Potomac confining unit, this confining unit is highly variable in thickness throughout the study area, ranging from a featheredge in the west to 132 feet in the city of Chesapeake (well 60B3, fig. 12). It is overlain by the upper Potomac aquifer in the central and eastern part of the study area and the Aquia aquifer in the western part.

The upper Potomac aquifer in the upper part of the Potomac Formation is composed of Upper Cretaceous sediments and is the thinnest of the three Potomac aquifers. The aquifer is present in the eastern two-thirds of the study area and is confined throughout its extent. The sands thicken to the east, ranging from a thin edge at the updip limit to approximately 280 feet in the city of Virginia Beach (well 63C1). It is composed of very fine- to medium-grained, thickly-bedded sand interlayered with silty, thin clay. Gravel and coarse-grained sands are rare. The aquifer is capable of producing large quantities of generally good quality water and is a principal source of ground water for municipal and industrial use throughout the central part of the study area. Water quality degrades somewhat in the east because of increasing chloride and fluoride concentrations. The upper Potomac aquifer is overlain by the upper Potomac confining unit. The confining unit is relatively thick, attaining its maximum thickness of 192 feet in southeastern Virginia (well 61B2, fig. 13). It is overlain by the Aquia aquifer, except in the southeastern part of the study area and northeastern North Carolina where it is overlain by the Virginia Beach aquifer, and in the northeastern part of the study area where it is overlain by the Chickahominy-Piney Point aquifer.

The Virginia Beach aquifer is composed of unnamed Upper Cretaceous sediments. It is present only in southeastern Virginia and is equivalent to the Black Creek Formation in northeastern North Carolina. The aquifer is named for the city of Virginia Beach for the purpose of this report. It is confined throughout its extent. The sediments in the study area range in thickness from near zero at the updip limit to approximately 110 feet in the city of Chesapeake (well 61B2). They predominantly consist of fine- to medium-grained glauconitic sand, interbedded with thin clay layers and indurated zones. Shell material is common. The aquifer is capable of producing moderate to abundant quantities of generally good quality water for domestic and industrial use. The aquifer is overlain entirely by the Virginia Beach confining unit. This unit consists of a series of clay, silty clay, and sandy clay beds and ranges in thickness within the study area from less than 10 feet near their updip limit to 29 feet in the city of Virginia Beach (well 61A2, fig. 14). The confining unit is overlain by the Aquia aquifer, except in northeastern North Carolina where it is overlain by the Peedee aquifer, and in the northeastern part of the study area where it is overlain by the Chickahominy-Piney Point aquifer.

The Peedee aquifer in the Peedee Formation is restricted to the North Carolina Coastal Plain and is not present in the study area. However, it is described here because it is included in the model framework for hydrologic analysis. It is confined throughout its extent. The sediments range from a featheredge at their western limit to about 300 feet along the Atlantic Coast (M.D. Winner, U.S. Geological Survey, written commun., 1984), and predominantly consist of glauconitic and shelly sand, interbedded with dark, micaceous silt and clay. The aquifer is not extensively developed and primarily yields small to moderate supplies to domestic users. It is entirely overlain by the Peedee confining unit. Confining unit sediments are composed of clay, silty clay, and sandy clay and range in thickness from a thin edge at the updip limit to approximately 100 feet beneath eastern Albemarle Sound (fig. 15). The confining unit is overlain by the Aquia aquifer.

The Aquia aquifer in the Aquia Formation is the deepest Tertiary aquifer in the framework. It is present throughout the study area, except in a band along the Fall Line, in the Chesapeake Bay region, and in a band along the coast. The aquifer is confined throughout its extent, except where it crops out along major stream valleys in the west. The aquifer is thickest in the central part of the study area (approximately 65 feet at well 55F20) and thins to a featheredge along both the updip and downdip limits. The updip limit is erosional and the downdip limit is gradational where the sandy sediments change facies to clay. The sediments, deposited in shallow marine waters, are typically fine- to medium-grained glauconitic sand, interbedded with silt, clay, and thin, indurated shell beds. The aquifer is an important ground-water resource, particularly in the central part of the study area where it yields moderate supplies to domestic, small industrial, and municipal wells. The Aquia aquifer is overlain by the Nanjemoy-Marlboro confining unit. This unit is fairly uniform in thickness throughout the study area, ranging from a thin edge at its western limit to approximately 62 feet in the central part (well 57F26, fig. 16). It is overlain by the Chickahominy-Piney Point aquifer.

The Chickahominy-Piney Point aquifer in the Chickahominy and Piney Point Formations is the middle Tertiary aquifer and is present throughout the study area, except in a band along the Fall Line. It is confined throughout its extent, except where it crops out along major stream valleys in the west. The aquifer is generally wedge-shaped in cross section, ranging from near zero along its western limit to approximately 160 feet in the city of Virginia Beach (well 63C1). It is lenticular-shaped north of the James River from the updip limit to the eastern part of Williamsburg, thinning to a featheredge at its updip limit, thickening to 82 feet at well 55H6, and thinning to 30 feet in central York County (well 58F18). The aquifer then becomes wedge-shaped as it thickens eastward. The sediments, deposited in a shallow marine environment, are typically medium- to coarse-grained glauconitic sand, interbedded with silt, clay, and thin, indurated shell beds. The aquifer is an important ground-water resource in the central part of the study area and yields moderate to abundant supplies to domestic, small industrial, and municipal users. The Chickahominy-Piney Point aquifer is overlain by the Calvert confining unit in the Calvert Formation. The confining unit forms an eastward-thickening wedge of dark-green clay interbedded with sandy clay and marl. It attains a maximum thickness in the study area of 460 feet in the city of Virginia Beach (well 63C1, fig. 17). It is overlain by the Yorktown-Eastover aquifer throughout the study area. In the north-central part of the model area, it is overlain by the St. Marys confining unit.

The St. Marys confining unit in the St. Marys Formation and basal part of the overlying Eastover Formation is present only in the north-central part of the model area and consists of shelly to laminated clay interbedded with very fine-grained sand. It ranges in thickness from near zero at its southern limit to approximately 88 feet in the northern part of the model area (well 58H4, fig. 18). It is overlain by the Yorktown-Eastover aquifer.

The Yorktown-Eastover aquifer in the lower part of the Yorktown Formation and upper part of the underlying Eastover Formation is the uppermost Tertiary aquifer. It is present throughout the study area, except in the middle and upper reaches of major stream valleys where it has been removed by erosion. The aquifer is unconfined in a broad area parallel to the Fall Line in the western part of the study area, and is confined in the central and eastern parts (fig. 10). It forms an eastward-thickening wedge of shelly, very fine- to coarse-grained sand, interbedded with silt, clay, shell beds, and gravel. Thickness in the study area ranges from near zero at its western and eroded limits to approximately 280 feet in the city of Virginia Beach (well 63C1). The aquifer is an important ground-water resource in southeastern Virginia for domestic, commercial, and light industrial use. It is an important source of recharge to the underlying confined system in the western part of the study area where it is unconfined. The Yorktown-Eastover aquifer is overlain by the Yorktown confining unit in the upper part of the Yorktown Formation. This unit consists of massive, well-bedded clay and silty clay, containing shells and fine-grained sand. It ranges in thickness in the study area from a featheredge at its western limit to approximately 56 feet in the city of Virginia Beach (well 63C1, fig. 19). Along its western limit, the confining unit is highly dissected. The unit is overlain by the Columbia aquifer in the eastern part of the study area.

The Columbia aquifer is the uppermost aquifer and is unconfined throughout its extent. It is present only in the central and eastern parts of the study area. The aquifer contains the youngest sediments of the Virginia Coastal Plain, consisting of interbedded gravel, sand, silt, and clay. The sediments range in thickness from 10 to 80 feet and represent Holocene sediments and terrace-type deposits laid down during Pleistocene time when sea levels fluctuated considerably. The aquifer is an important ground-water resource for rural and domestic users. It is also a major source of recharge to the underlying aquifer system.

Hydraulic Characteristics of Aquifers

Hydraulic characteristics describe the ability of an aquifer to transmit, store, or release water. The ability to transmit water is described in terms of its transmissivity or its hydraulic conductivity[1]. Transmissivity of an aquifer is the rate at which water will flow horizontally through a vertical strip 1-foot wide extending through the full saturated thickness. It is the product of the horizontal hydraulic conductivity and saturated thickness. Hydraulic conductivity involves the water-transmitting properties of the sediment, which depend on such things as the size and arrangement of pores. Water flows more freely in coarse-grained sediment, such as gravel, than in fine-grained sediment, such as silt and clay. The ability of an aquifer to store or release water is described by its storage coefficient. Storage coefficient is the volume of water released from or taken into storage per unit of surface area of the aquifer per unit change in hydraulic head. The relative magnitude of the storage coefficient depends on whether the aquifer is confined or unconfined. In unconfined aquifers, water is released from storage primarily because of gravity drainage of sediments. Values for storage in unconfined aquifers range from 1×10^{-2} to 3×10^{-1} (Freeze and Cherry, 1979). In confined aquifers, water is released from compression of the aquifer and expansion of water. Values for confined aquifers generally range from 1×10^{-5} to 1×10^{-3} (Lohman, 1972).

Transmissivity and storage coefficient were estimated for confined aquifers within the model area and later used in model development. These estimates were derived from analyses of aquifer- and specific-capacity-test data. The aquifer tests involved collection of time-drawdown data at a pumping well and at one or more observation wells. Water-level decline was monitored in all wells throughout the pumping period. Specific-capacity tests involved one pumping well. Specific capacity is the ratio of the rate at which water is withdrawn to water-level decline in a well. Aquifer-test and specific-capacity-test data were collected from local drillers, private firms, and State and local agencies. The method of data collection and length of record and pumpage vary with each test and, therefore, data may be quite variable.

Methods developed by Theis (1935), Cooper-Jacob (1946), and Hantush (1960) were used to analyze aquifer-test data. The Theis and Cooper-Jacob methods assume that the only source of water to a pumping well is from the penetrated aquifer--no water is derived from the overlying or underlying confining units. These methods commonly are referred to as "non-leaky" solutions. The Hantush method includes vertical leakage through confining units as a source of water to a pumping well and is known as a "leaky" solution. Transmissivity values obtained by the Hantush method are lower than those computed by the non-leaky methods because of the contribution of vertical leakage. This method is considered to be the most appropriate of the three methods for analysis of aquifer-test data in Coastal Plain aquifers because confining units contribute a significant amount of water. Values for aquifer transmissivity and storage coefficient for individual aquifers in the model area that were derived from aquifer-test data are summarized by method in table 3. The values were determined as part of this study using the three methods described above where field data were obtainable. Where field data were not available, the values were obtained from State and local agencies who used one, two, or all of the above methods. No distinction is made in table 3 on the source.

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[1] Hydraulic conductivity referred to in this report is in a horizontal direction unless specifically discussed to the contrary.

Table 3.--Statistical summary of transmissivity and storage coefficient for individual aquifers in the model area derived from Hantush, Theis, and Cooper-Jacob analytical methods[a]

[ft²/d is square feet per day; a dash indicates no value]

Aquifer		Analytical method: Leaky type curve (Hantush) Transmissivity (ft^2/d)	Leaky type curve (Hantush) Storage coefficient (dimensionless)	Nonleaky type curve (Theis) Transmissivity (ft^2/d)	Nonleaky type curve (Theis) Storage coefficient (dimensionless)	Nonleaky straight line (Cooper-Jacob) Transmissivity (ft^2/d)	Nonleaky straight line (Cooper-Jacob) Storage coefficient (dimensionless)
Yorktown-Eastover	Max	5,750	6.3×10^{-3}	8,820	---	8,820	1.3×10^{-2}
	Min	330	1.4×10^{-4}	210	---	30	1.0×10^{-4}
	Median	3,070	1.1×10^{-3}	2,470	---	2,160	2.5×10^{-4}
	Mean	3,020	1.7×10^{-3}	2,750	1.1×10^{-4}	1,900	2.6×10^{-3}
	Number of tests	6	6	14	1	32	10
Chickahominy-Piney Point	Max	---	---	11,300	---	16,100	---
	Min	---	---	3,710	---	130	---
	Median	---	---	5,530	---	4,790	---
	Mean	---	---	6,960	---	6,740	3.1×10^{-2}
	Number of tests	---	---	7	---	7	1
Aquia	Max	---	---	---	---	8,010	---
	Min	---	---	---	---	2,780	---
	Median	---	---	---	---	---	---
	Mean	---	---	8,680	---	---	---
	Number of tests	---	---	1	---	2	---
Upper Potomac	Max	8,750	2.4×10^{-4}	13,200	6.7×10^{-4}	15,000	---
	Min	1,850	4.1×10^{-5}	4,410	1.4×10^{-4}	2,360	---
	Median	---	---	9,350	2.6×10^{-4}	8,300	---
	Mean	---	---	9,390	3.6×10^{-4}	9,230	5.0×10^{-4}
	Number of tests	2	2	8	3	11	1
Middle Potomac	Max	---	---	38,000	9.3×10^{-3}	56,800	1.4×10^{-3}
	Min	---	---	950	1.6×10^{-6}	425	1.6×10^{-6}
	Median	---	---	4,920	---	2,540	2.2×10^{-5}
	Mean	5,960	---	9,130	---	8,870	3.2×10^{-4}
	Number of tests	1	---	10	2	15	7
Lower Potomac	Max	---	---	---	---	3,540	2.2×10^{-4}
	Min	---	---	---	---	1,370	2.0×10^{-4}
	Median	---	---	---	---	---	---
	Mean	2,630	3.5×10^{-4}	3,260	1.5×10^{-4}	---	---
	Number of tests	1	1	1	1	2	2

[a]No data available for Virginia Beach and Peedee aquifers

Table 4 summarizes well yield, specific capacity, transmissivity, and hydraulic conductivity for individual aquifers in the model area that were derived from specific-capacity tests. Specific capacity most often is used to determine the ability of a well to yield water, however, it also is used to estimate transmissivity and hydraulic conductivity. Transmissivity was derived using a solution developed by Brown (1963) and Theis (1963) where it is a function of specific capacity, time, and storage. Storage was assumed to be 1.5×10^{-1} for unconfined aquifers and 1.0×10^{-4} for confined aquifers in this solution. Hydraulic conductivity was computed by dividing transmissivity by saturated thickness. The table also gives values for specific capacity, transmissivity, and hydraulic conductivity that were adjusted for partial penetration of the well into the aquifer. These hydraulic characteristics were adjusted using a solution by Turcan (1963). Transmissivity derived from specific-capacity tests compare reasonably well with those obtained in the same areas from aquifer tests. Specific-capacity data, generally easier to obtain, may therefore be appropriate for general evaluation of aquifers in areas lacking aquifer-test data.

Occurrence and Movement of Ground Water

Following is a discussion of standard hydrological concepts as applied to the ground-water system in southeastern Virginia. These are integrated with the known hydrogeology described earlier and with water-level data from the past 100 years. This description served as the basic conceptualization necessary for model development.

Major flow boundaries are the Fall Line to the west (which separates relatively impervious, metamorphic rocks of the Piedmont physiographic province from the relatively permeable, unconsolidated sediments of the Coastal Plain physiographic province), the freshwater-saltwater interface to the east, and granitic basement. The system is part of the global hydrologic cycle (fig. 21), and depends on precipitation as its primary source of water. In southeastern Virginia about half of the precipitation returns relatively quickly to the atmosphere through evapotranspiration (water vaporization from land, surface water, and plants). The remainder either becomes overland flow or infiltrates into the ground. Infiltration first replaces soil moisture near the surface and then recharges the water-table aquifer. Ground-water movement predominantly is lateral through this aquifer. Some movement occurs vertically through confining units into deeper aquifers and laterally through these aquifers. Discharge ultimately occurs at a variety of points, including springs, streams, lakes, Chesapeake Bay, and the Atlantic Ocean.

The rate of movement within an aquifer depends on the hydraulic conductivity and hydraulic gradient. Hydraulic gradient is the change in total head (water level) per unit distance; water moves from higher to lower head. Total head involves two components: elevation and hydraulic pressure. In a water-table aquifer the water is at atmospheric pressure; therefore, the water level in a nonpumping well tapping only the water table would be the same as that of the water table. In deeper, confined aquifers the hydraulic pressure is greater than atmospheric pressure; therefore, the level in a nonpumping well tapping a confined aquifer would be some distance above the top of the aquifer.

Confining units generally have hydraulic conductivities that are much smaller than those of aquifers. As a result, most ground-water flow is

Table 4.--Statistical summary of well yield, specific capacity, transmissivity, and hydraulic conductivity for individual aquifers in the model area derived from specific-capacity tests[a]

[Gal/min is gallons per minute; gal/min/ft is gallons per minute per foot; ft^2/d is square feet per day; ft/d is feet per day]

Aquifer		Well yield (gal/min)	Specific capacity: Unadjusted (gal/min/ft)	Specific capacity: Adjusted[b] (gal/min/ft)	Transmissivity: Unadjusted (ft^2/day)	Transmissivity: Adjusted[b] (ft^2/day)	Horizontal hydraulic conductivity: Unadjusted (ft/d)	Horizontal hydraulic conductivity: Adjusted[b] (ft/d)
Columbia	Max	100	16.7	35.5	3,790	8,500	92.7	170.0
	Min	3	.2	1.7	21	328	1.7	6.4
	Median	30	1.2	6.1	223	1,070	8.3	28.7
	Mean	33	3.4	8.3	760	1,730	30.0	52.1
	Number of tests	12	12	9	9	9	9	9
Yorktown-Eastover	Max	450	31.6	123.0	10,100	44,200	156.0	353.0
	Min	1	.1	.2	23	42	.1	.7
	Median	46	1.5	8.1	523	2,460	4.1	23.1
	Mean	78	3.9	18.6	1,300	6,200	11.8	50.4
	Number of tests	77	79	72	73	72	72	72
Chickahominy-Piney Point	Max	316	48.0	126.0	16,600	42,100	331.0	701.0
	Min	5	.2	.2	54	67	1.2	1.5
	Median	77	3.0	9.6	1,100	2,950	22.4	64.0
	Mean	103	7.4	15.8	2,580	5,270	57.2	103.7
	Number of tests	42	43	38	40	38	38	38
Aquia	Max	550	21.6	102.0	6,980	34,700	189.0	301.0
	Min	5	.2	.2	46	40	.7	1.8
	Median	80	2.2	5.7	640	1,670	16.6	35.1
	Mean	140	3.8	10.3	1,140	3,320	33.9	60.3
	Number of tests	30	30	30	30	30	30	30
Upper Potomac	Max	2,100	83.3	68.0	24,300	24,700	385.5	344.0
	Min	20	.6	.7	170	194	2.8	4.0
	Median	240	6.7	11.6	2,200	3,630	35.6	59.2
	Mean	403	11.1	16.5	3,560	5,380	56.7	80.3
	Number of tests	117	117	113	114	113	113	113
Middle Potomac	Max	3,000	53.1	201.0	17,500	76,300	76.7	347.0
	Min	3	.1	.2	20	60	.2	.7
	Median	120	2.7	9.3	790	3,350	6.1	22.3
	Mean	257	7.8	26.7	2,540	9,230	14.0	46.3
	Number of tests	123	133	126	126	123	123	123
Lower Potomac	Max	2,000	11.5	11.6	3,550	3,560	50.7	50.7
	Min	100	.5	.5	120	120	3.4	3.4
	Median	554	5.9	7.4	1,990	2,250	15.9	18.0
	Mean	802	5.6	6.7	1,950	2,040	20.2	21.0
	Number of tests	6	7	6	6	6	6	6
Multiple-aquifer wells	Max	3,000	55.0	---	18,900	---	---	---
	Min	5	.1	---	23	---	---	---
	Median	602	13.4	---	3,830	---	---	---
	Mean	943	19.1	---	6,230	---	---	---
	Number of tests	65	66	---	53	---	---	---

[a]No data available for Virginia Beach and Peedee aquifers

[b]Adjusted for effects of partial penetration

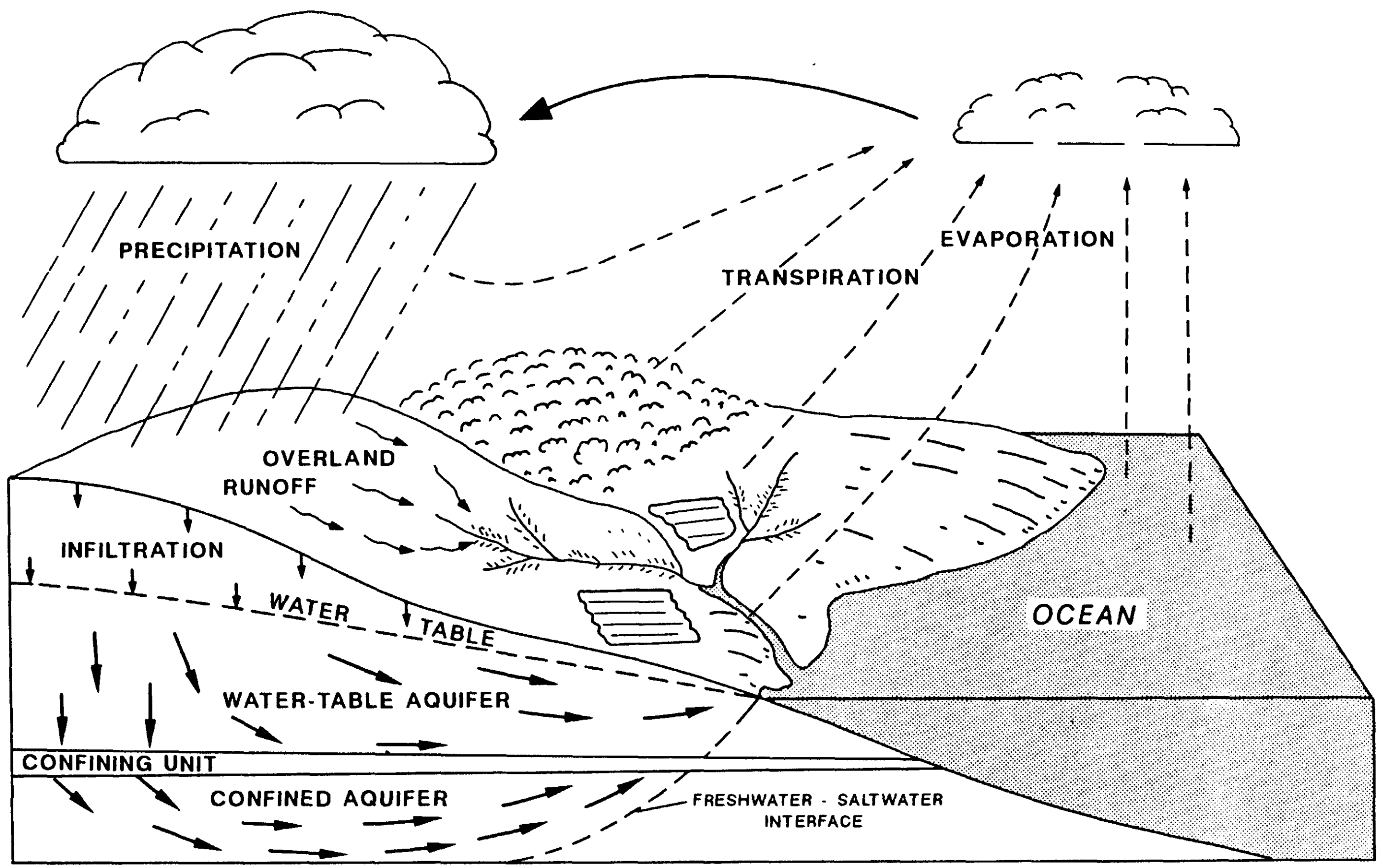

Figure 21.--Hydrologic cycle (modified from Heath, 1983).

lateral through aquifers. A small amount of vertical flow through confining units occurs, controlled by the vertical hydraulic conductivity and unit thickness. Because confining units extend over large areas, the total contribution to aquifer budgets from such vertical flow may be significant. Lateral flow through confining units is negligible.

The presence of deep river channels in southeastern Virginia, incised during the Pleistocene, significantly affects ground-water flow through aquifers and confining units. 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. Vertical flow through confining units in the Chesapeake Bay area and river channels is enhanced; lateral flow through aquifers in these areas is decreased. Approximate depths of the incised rivers in the Virginia Coastal Plain are presented in Harsh and Laczniak (1986) and discussed in Hack (1957).

Prior to the development of wells in southeastern Virginia, a hydraulic equilibrium existed in the multiaquifer system. Recharge to the total system balanced discharge to surface waters. The downward movement of water into the confined aquifers primarily occurred along a narrow band approximately parallel to the Fall Line and in higher elevations between major river valleys. Lateral movement within aquifers primarily was from the Fall Line eastward to Chesapeake Bay and the Atlantic Ocean and from interfluves toward major river valleys. In the east, ground water that encountered the denser saltwater was forced upward through the confining units before discharging to the Bay or Ocean (fig. 22).

The development of wells imposed new discharges on the previously stable system. Before 1920, most withdrawal was from wells that were under sufficient pressure so that water flowed to the land surface. With more drilling, water levels dropped below land surface. Pumps became necessary to maintain supplies.

In any well, pumpage is first balanced by a reduction in ground-water storage in the immediate vicinity, which results in a lower water level and a surrounding cone of depression. This in turn may affect natural flow patterns. In southeastern Virginia, the major pumpage centers (which have correspondingly large cones of depression) caused decreases or reversals in discharge to surface waters. Although the details vary depending on the specific well and its relation to discharge points, a general scenario for this kind of change is presented in figure 23 for a water-table well in the vicinity of a stream. With no pumpage, water in a fully-screened well would be the same as that of the water table, and ground water would discharge at a given rate to the stream which is at a lower level (fig. 23.2). As pumpage begins, water is removed from storage, resulting in a cone of depression (fig. 23.3). As pumpage continues, the hydraulic gradient between the ground water and the stream would be reduced and discharge to the stream would decrease; less water is removed from storage (fig. 23.4). A new equilibrium might be reached at some point (no water is removed from storage) so that discharge to the stream continues, but at a new, lower rate. However, if pumpage is high enough so that the ground-water head falls below the stream, ground-water discharge to the stream will cease completely and water will move from the stream into the ground-water system (fig. 23.5). Thus the

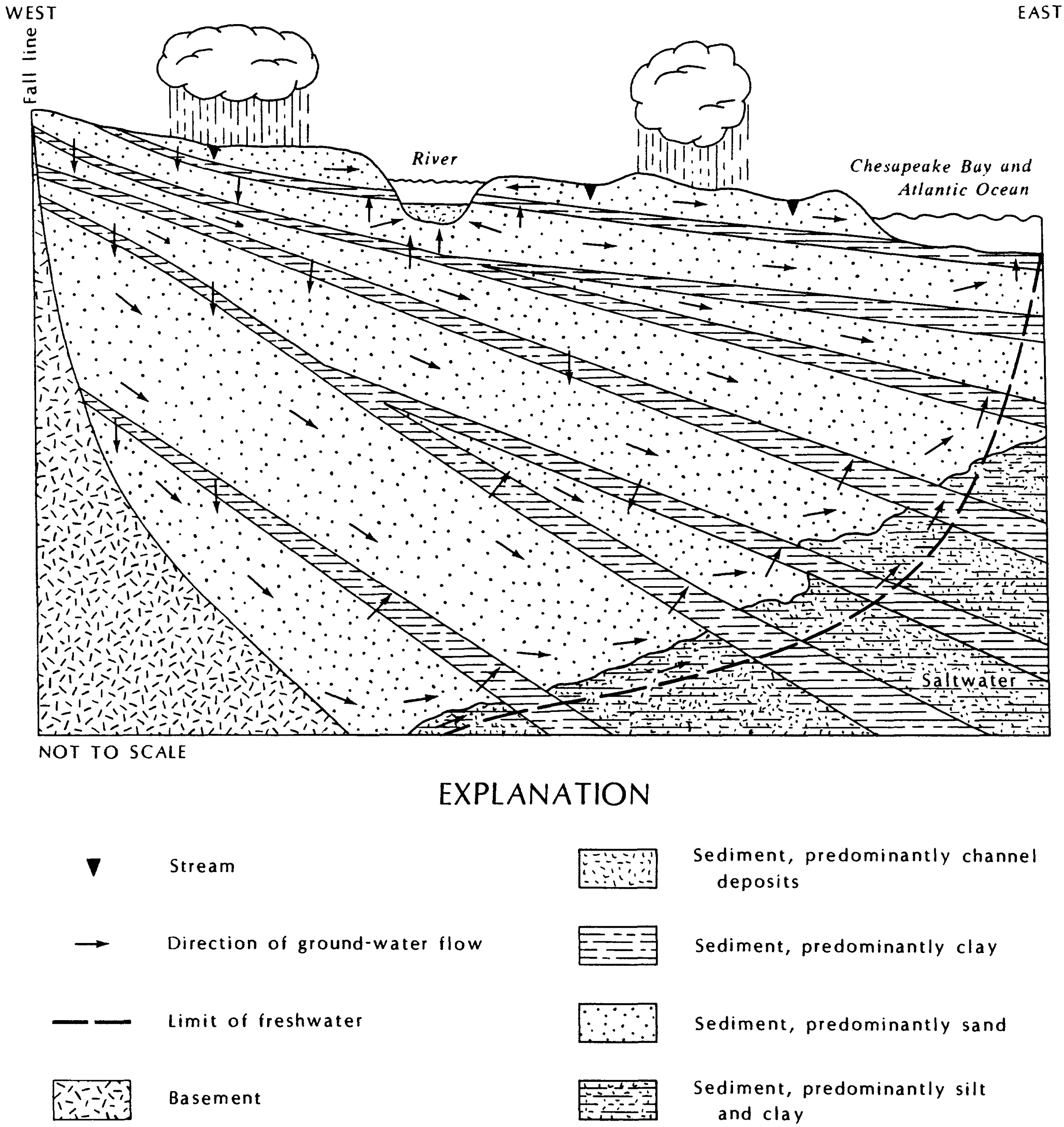

Figure 22.--Conceptualized ground-water flow in the model area for prepumping conditions.

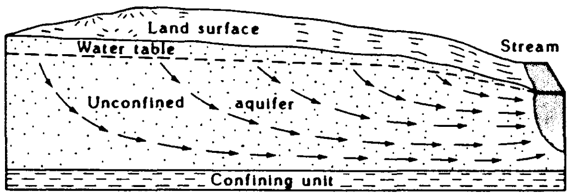

Figure 23.1--Ground-water flow for prepumping conditions; ground water discharging to stream

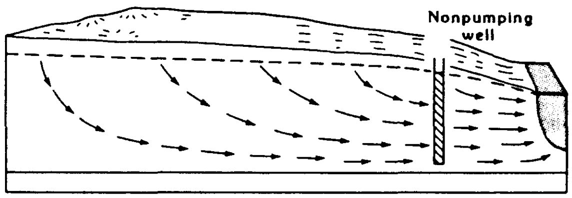

Figure 23.2--Ground-water flow for nonpumping conditions; ground water discharging to stream

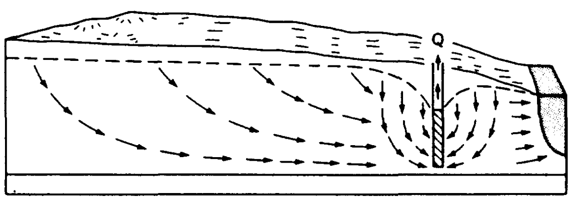

Figure 23.3--Ground-water flow for pumping conditions; reduction in storage equals pumpage

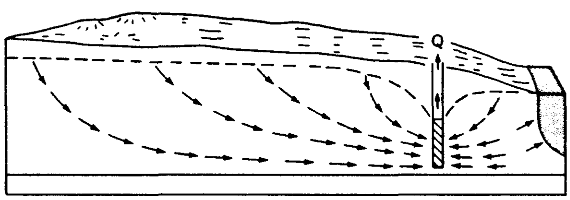

Figure 23.4--Ground-water flow as pumping continues; reduction in storage and reduction in ground-water discharge to stream equals pumpage

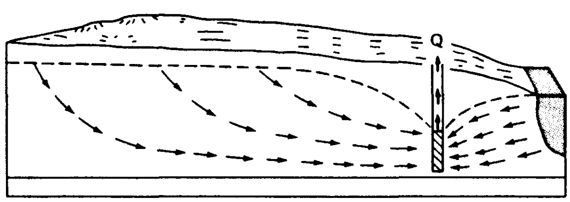

Figure 23.5--Ground-water flow as pumping continues; reduction in ground-water discharge to stream and inducement of stream water into the ground-water system equals pumpage

Figure 23.--Direction of ground-water flow for prepumping and pumping conditions and sources of water derived from a well (modified from Heath, 1983).

stream, originally a discharge point for ground water, becomes a recharge source. Any reduction in ground-water flow to a stream, of course, lowers the stream level. The lowering of the stream level may or may not be significant depending on the flow rate in the stream relative to the rate of ground-water flow to the stream. Overall, these kinds of changes involving reduction or reversal of the natural flow of ground water to surface water are present in southeastern Virginia.

Ground-Water Use

As described above, the development of wells affected the natural flow of ground water in southeastern Virginia. Ground-water use began in southeastern Virginia in the late 1800's (Sanford, 1913) and has increased steadily since that time. Withdrawals, which include naturally flowing and pumping wells and which represent an aggregate of commercial, industrial, and municipal usage, increased from less than 10 Mgal/d in 1891 to about 55 Mgal/d in 1983 (Kull and Laczniak, 1987) in the study area. Water use within the model area, which includes users outside the study area affecting ground-water flow in southeastern Virginia, was approximately 87 Mgal/d in 1983. Figure 24 shows estimated annual commercial, industrial, and municipal withdrawal for the model area from 1891 through 1983. Domestic use was not included because it was assumed to represent only a small percentage of non-returned flow.

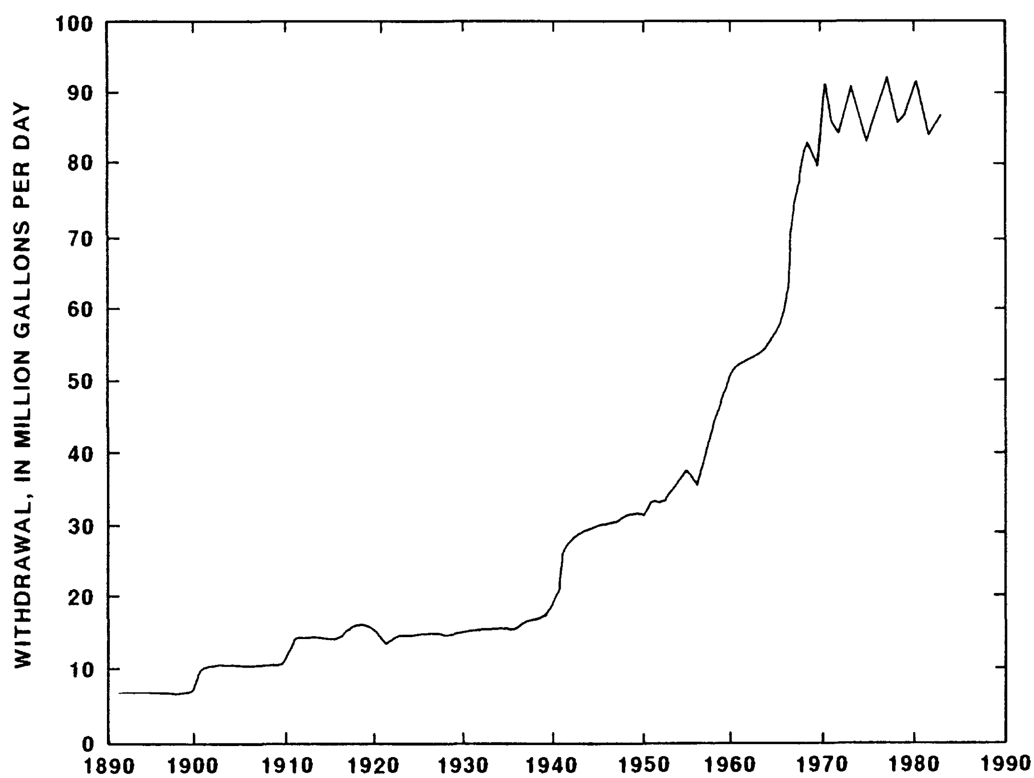

Figure 24.--Estimated annual ground-water withdrawal, 1891-1983.

Major pumpage centers affecting flow in southeastern Virginia are located near the towns of West Point and Smithfield and the cities of Williamsburg, Franklin, Newport News, and Suffolk (fig. 25). These pumpage centers account for about 71 Mgal/d (81 percent) of the total 1983 ground-water pumpage in the model area. The largest pumpage center occurs near Franklin where average pumpage was about 38 Mgal/d.

Figure 26 shows estimated annual ground-water withdrawal in the model area from individual aquifers from 1891 through 1983. Principal sources of ground water in the model area have been the middle and upper Potomac aquifers. These aquifers provided approximately 76 percent of the total water in 1983 and primarily serve large industrial and municipal needs throughout the model area. The lower Potomac aquifer provided approximately 16 percent of the total water in 1983. Other significant sources are the Aquia and Chickahominy-Piney Point aquifers, which primarily serve light industrial and municipal needs in the central part of the model area. The Yorktown-Eastover aquifer is important in meeting light industrial and municipal needs in the eastern part of the model area. Additional information on locations, trends, and amounts of ground-water withdrawals in the Virginia Coastal Plain is provided in Kull and Laczniak (1987).

ANALYSIS OF THE GROUND-WATER FLOW SYSTEM

This section of the report discusses a three-dimensional, digital, ground-water flow model used to describe ground-water flow in the Coastal Plain hydrogeologic system in southeastern Virginia. The digital, ground-water flow model is a mathematical description of the natural ground-water system. The section includes discussions of (1) model development, which involves spatial discretization of the model area into a grid, specification of boundary conditions, and identification of input parameters reflecting aquifer and confining unit characteristics; (2) model calibration, which involves comparison of simulated to measured water levels; (3) model simulation of ground-water flow under prepumping and pumping conditions; (4) model projection of future hydrologic conditions resulting from injection or increased pumpage; (5) model sensitivity, which involves testing the response of the calibrated model to changes in hydraulic characteristics; and (6) model limitations.

Approach

Flow in a multiaquifer system is three dimensional. The digital model used in this study incorporates a quasi-three-dimensional approach. This approach involves a layered sequence of two-dimensional aquifers where intervening confining units are not represented as layers but as vertical conductors of flow between adjacent aquifers and are defined by leakance values. Four assumptions are involved in this approach: (1) water released from confining-unit storage is negligible because simulation time is long enough to minimize its effect (Harsh and Laczniak, 1986); (2) vertical flow is assumed to be controlled by intervening confining units because the vertical hydraulic conductivity of confining units is sufficiently lower than that of aquifers (Neuman and Witherspoon, 1969); (3) horizontal flow mostly occurs within the aquifers and is directly proportional to transmissivity; and (4) horizontal flow in confining units is assumed to be insignificant because of the low hydraulic conductivity associated with fine-grained sediments.

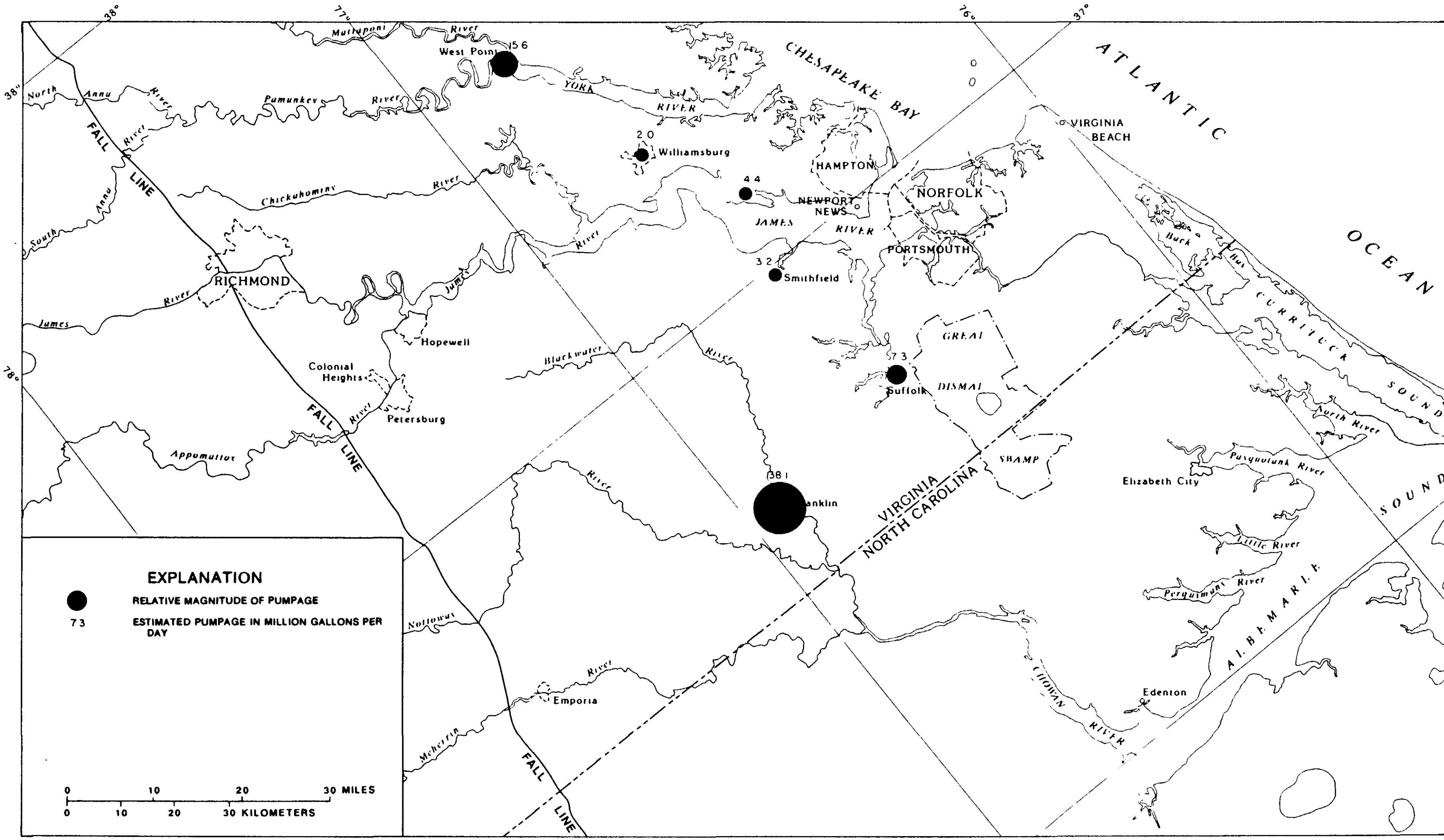

Figure 25.--Location of major pumping centers.

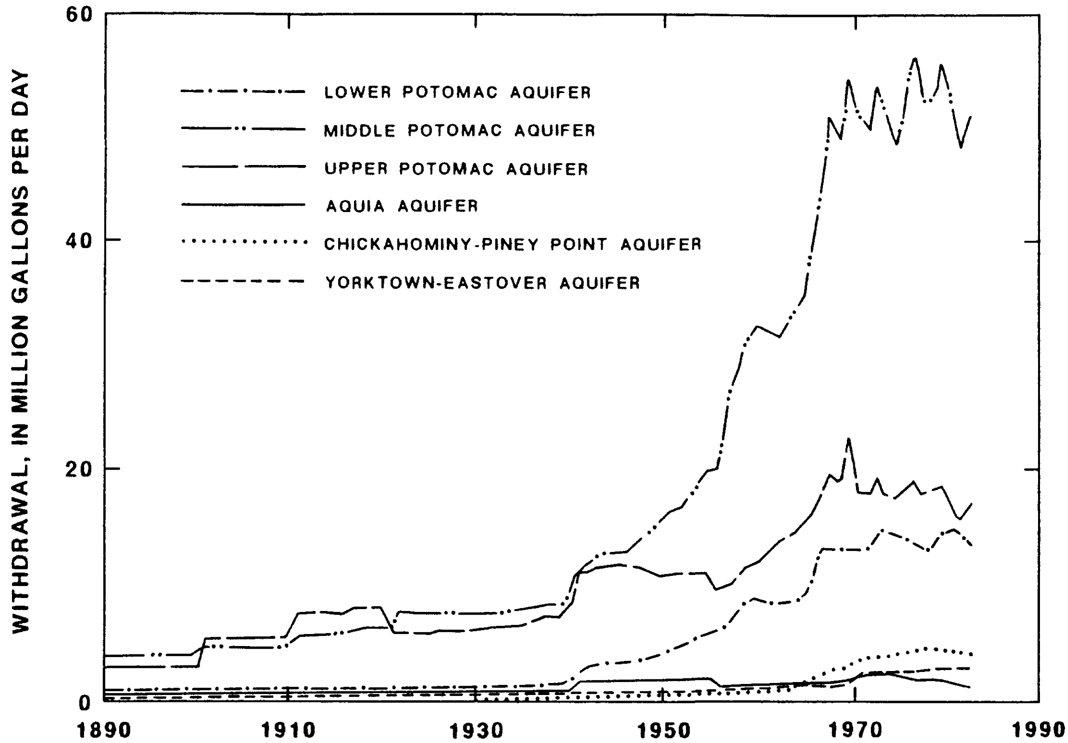

Figure 26.--Estimated annual ground-water withdrawal from individual aquifers (1891-1983).

Description of the Three-Dimensional Model

The equation for three-dimensional flow of ground water in a porous medium may be described by the partial-differential equation:

$$\frac{\partial}{\partial_x}\left(K_{xx}\frac{\partial h}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(K_{yy}\frac{\partial h}{\partial_y}\right) + \frac{\partial}{\partial_z}\left(K_{zz}\frac{\partial h}{\partial_z}\right) - W = S_s\frac{\partial h}{\partial t} \quad (1)$$

where

x, y, and z are cartesian coordinates aligned along the major components of the hydraulic conductivity tensor Kxx, Kyy, and Kzz,

h is the hydraulic head, in length (L) units;

W is the volumetric flux per unit volume of porous medium per unit time and represents a source-sink term, in inverse time units (1/t);

Ss is the specific storage, in inverse length units (1/L); and

t is the time, in time units (t).

Flow is along the horizontal x and y axes, which are oriented in the plane of the aquifers, and the vertical z-axis, which is orthogonal to the aquifers. The ground-water flow equation describes flow under nonequilibrium conditions in a heterogeneous and anisotropic medium; Ss, Kxx, Kyy, and Kzz may be functions of space, and h and W may be functions of both space and time (McDonald and Harbaugh, 1984). The equation, together with head conditions for aquifer boundaries and initial-head conditions, constitutes a mathematical model of the ground-water system. The solution to the equation can be obtained using a finite-difference method in which the continuous system is replaced by a finite set of points in space and time, and the partial derivatives are replaced by differences between functional values at these points. Specific details about the solution algorithm are provided in the computer program documentation (McDonald and Harbaugh, 1984).

Model Grid

A three-dimensional grid of nodal blocks (1.75 miles per side) was superimposed over the model area. This spatial discretization incorporates the physical limits of each of the aquifers and the spatial variation of hydraulic properties within the system. A two-dimensional representation of the grid is shown in figure 27. The grid lies approximately northwest to southeast and is comprised of 92 rows by 52 columns, totaling 4,784 3-square-mile blocks. Three thousand and eighty-five of these blocks are located within model boundaries and are considered active blocks. A similar grid was used for each of the nine aquifers (described in section, "Stratigraphy and Areal Extent of Aquifers and Confining Units"), forming a three-dimensional, nine-layered representation of the system. Each block was assigned values representative of average aquifer characteristics; the continuous physical properties of the porous medium (the ability to store and transmit water) are, therefore, assumed to be uniform within each block. The selected grid orientation is consistent with a regional ground-water flow model of the Virginia Coastal Plain (Harsh and Laczniak, 1986).

Model Boundaries

The western, eastern, lower, and upper model boundaries were selected to approximate natural hydrologic boundaries acting on the flow system (fig. 27). The western model boundary coincides with the Fall Line and is considered impermeable to flow. This assumption is supported by the large difference in permeability between the igneous and metamorphic rocks of the Piedmont physiographic province and the unconsolidated sediments of the Coastal Plain physiographic province. The eastern boundary represents an assumed freshwater-saltwater interface located where the ground water contains concentrations of chloride of 10,000 mg/L (milligrams per liter) (Meisler, 1986). The boundary is considered a stationary no-flow boundary (Larson, 1981; Leahy and Martin, 1986). The location of the 10,000 mg/L chloride concentration is different for each aquifer because of its wedge-shaped nature. Figure 27 represents the

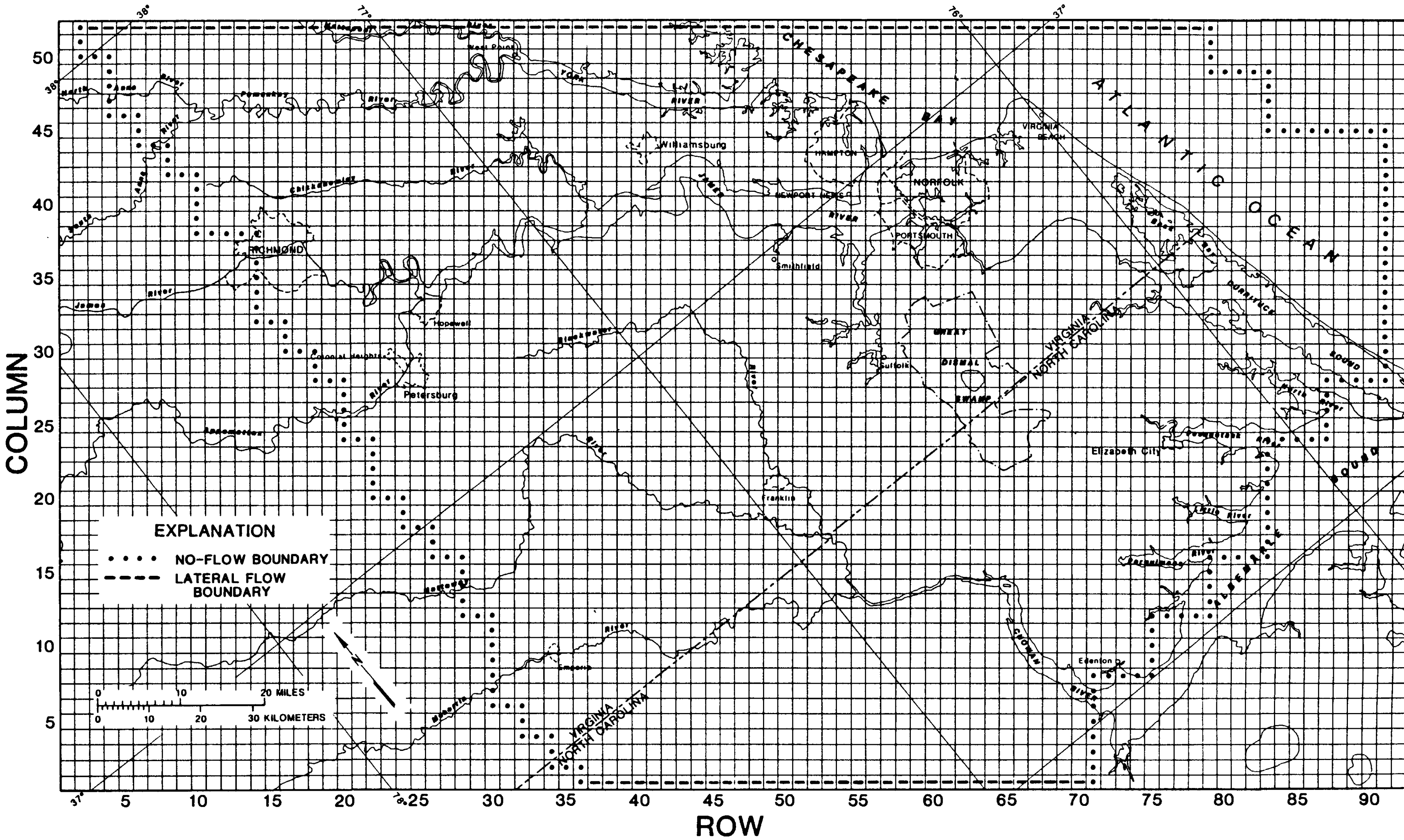

Figure 27.--Finite-difference grid and boundaries used in model analysis.

easternmost position of the 10,000 mg/L chloride concentration (freshwater-saltwater interface) within the modeled system. Variations in salinity and their effects on the ground-water system, as well as the potential movement of the freshwater-saltwater interface under natural or pumping conditions, are not considered in this model boundary condition. Sensitivity simulations, conducted with the regional Atlantic Coastal Plain ground-water flow model, showed that transmissivities are relatively low in the vicinity of the freshwater-saltwater interface because of density variations resulting from salinity changes (P.P. Leahy, U.S. Geological Survey, written commun., 1987). On the basis of Leahy's findings, the eastern no-flow boundary in this model represents a first approximation of the eastern limits of the fresh ground-water system where transmissivities equal zero. This approximation results in maximum water-level decline. Sensitivity simulations were conducted with this model in which the position of the boundary was moved seaward to test the effect of locating a stationary boundary at the 10,000 mg/L chloride concentration within each aquifer. Simulated water levels and rates of ground-water flow were not sensitive to the position of the stationary boundary for the model simulations presented in this report (described in detail in section "Sensitivity Analysis"). The lower boundary coincides with the contact between the lower Potomac aquifer and the underlying granitic basement and is considered a no-flow boundary. This assumption is supported by the large difference in permeability between the two rock types. The upper boundary is simulated as a constant-head boundary condition and is the average altitude of surface-water bodies within each block (Harsh and Laczniak, 1986; Leahy and Martin, 1986). Average altitude of surface water was estimated from U.S. Geological Survey 7.5-minute topographic maps. This boundary condition is used to approximate recharge-discharge relations between surface water and the water-table aquifer. Estimates of streambed leakance, which controls the amount of ground water flowing between the water-table aquifer and surface water, were obtained from stream baseflow values, ground-water recharge rates, and water-table and surface-water levels (details provided in section, "Streambed Leakance"). The relative consistency in water levels within surface-water bodies over the time and scale of simulation supports the use of this boundary condition.

Because aquifers extend beyond the northern and southern limits of the study area, model boundaries were extended to include ground-water users that may affect ground-water flow within the study area (fig. 27). Continuity of the aquifers across lateral model boundaries to the north and south was simulated with boundary fluxes. Details on the calculation of boundary fluxes are provided in section, "Lateral Boundary Flow".

Properties of Aquifers and Confining Units

Ground-water flow is controlled by the transmissivity and storage coefficient of the aquifers and vertical leakance of the intervening confining units. Field values for transmissivity, storage coefficient, and vertical leakance were not available for each grid block; block values were estimated from physical and hydrologic properties defining these characteristics and later refined and verified using field, laboratory, and literature values (tables 3 and 4). Values for each block are stored in computer files at the Virginia Office of the U.S. Geological Survey in Richmond.

Transmissivity

Transmissivity controls lateral ground-water flow within each aquifer. Hydraulic conductivity, a measure of the capacity of an aquifer to transmit water, was multiplied by average sand thickness to compute transmissivity. Average sand thickness was determined for each block from maps of aquifer tops and confining-unit thicknesses (figs. 3 through 19) and from a map delineating basement top (Meng and Harsh, 1984). Initial estimates of hydraulic conductivity were based on values used in a regional model of the Virginia Coastal Plain (Harsh and Laczniak, 1986). These initial estimates were adjusted slightly during steady-state model development. Finalized estimates of hydraulic conductivity used in model analysis are summarized by aquifer in table 5.

Table 5.--Estimated values for horizontal hydraulic conductivity used in model analysis
[Values in feet per day]

Aquifer	Estimated hydraulic conductivity
Columbia	18.1
Yorktown-Eastover	14.7
Chickahominy-Piney Point	12.1
Aquia	15.1
Peedee	23.3
Virginia Beach	43.2
Upper Potomac	64.8
Middle Potomac	51.8
Lower Potomac	41.5

Maps representing finalized estimates of transmissivity for all aquifers are presented in figures 28 through 36. Low transmissivities are present in areas with thin aquifer sediment or with sediment deposited in a low-energy marine environment. A low-energy marine environment generally results in finer-grained sediment and a decrease in sediment permeability. Higher transmissivities are present in areas of thick aquifer sediment and in areas where sediment was deposited in a continental or high-energy marine environment. As shown in the figures, transmissivity generally increases eastward (downdip) from the western limit of each aquifer. This is because of an increase in sediment thickness. Sediment thickness is greatest in the lower, middle, and upper Potomac aquifers, resulting in the highest transmissivity in the model area. Transmissivity begins to decrease toward the eastern limit of each aquifer because of changes in the depositional environment. For example, lower transmissivities are present in the eastern part of the lower, middle, and upper Potomac aquifers where the depositional environment changed from continental to marine, and in the eastern part of the Aquia, Chickahominy-Piney Point, and Yorktown-Eastover aquifers where the depositional environment changed from high- to low-energy marine. Relatively low transmissivities also are present along the freshwater-saltwater interface of the aquifers because of a decrease in thickness of aquifer containing freshwater. Low transmissivities also are present along major river valleys and Chesapeake Bay where ori-

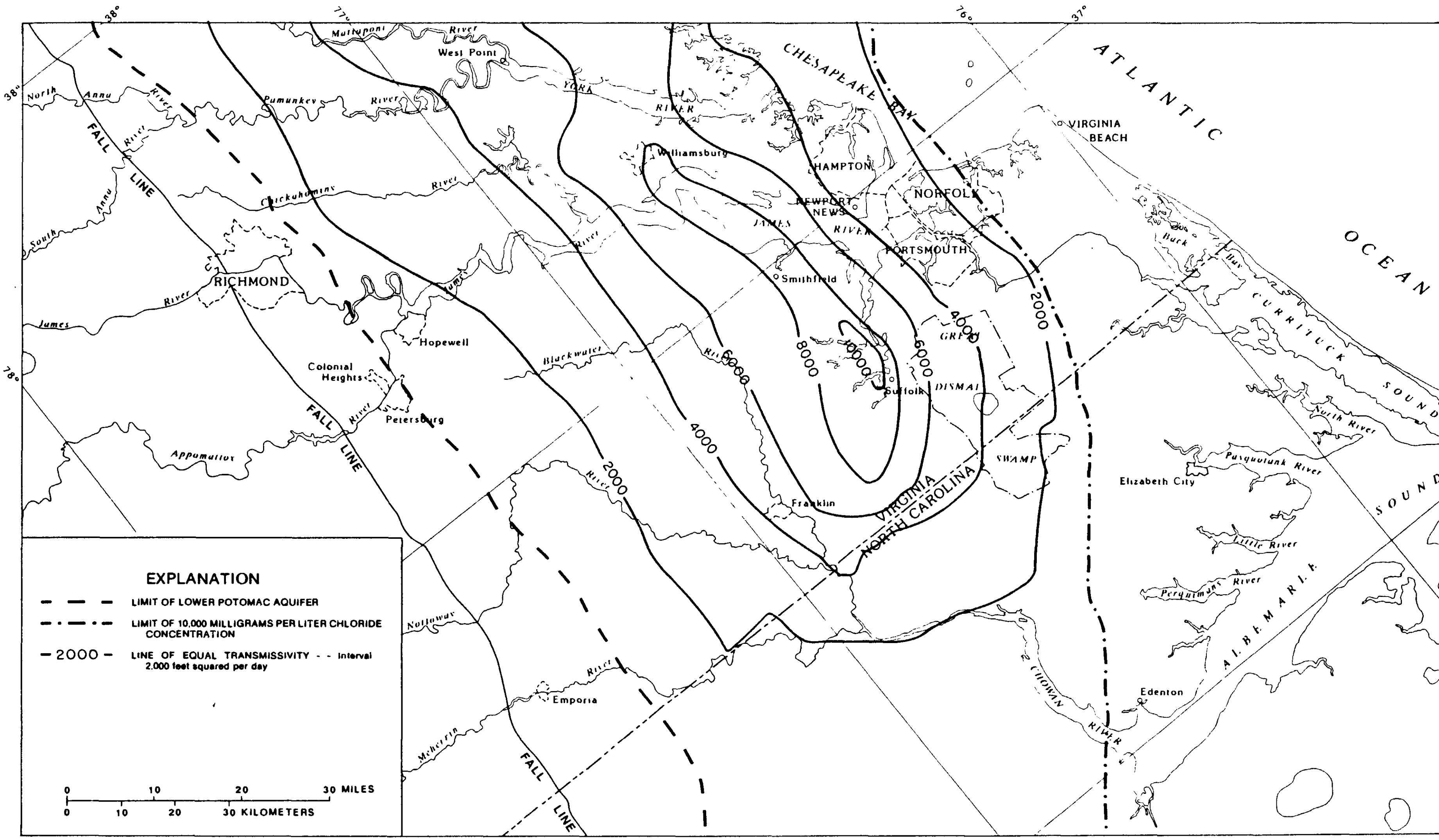

Figure 28.--Transmissivity of the lower Potomac aquifer used in model analysis.

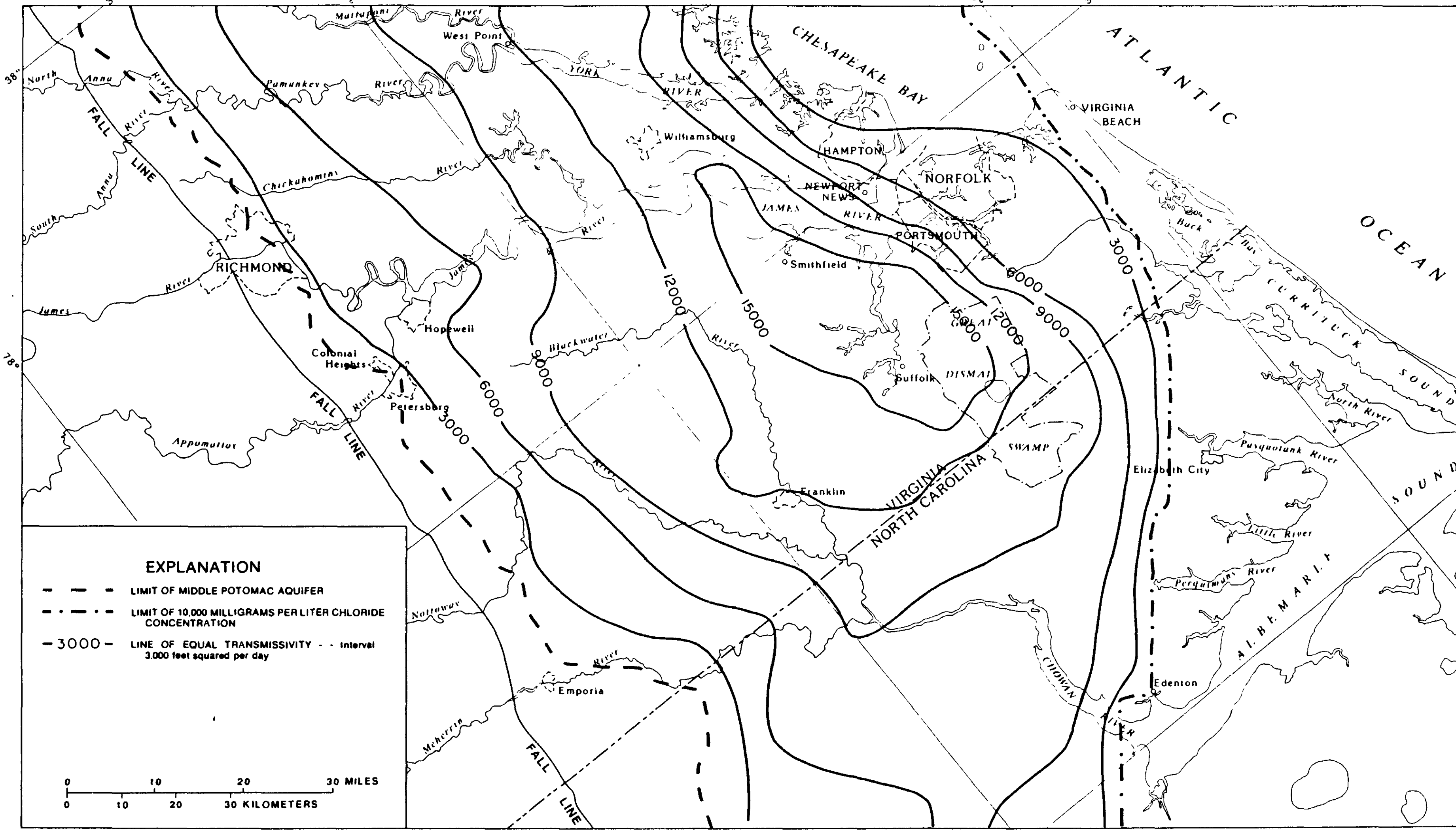

Figure 29.--Transmissivity of the middle Potomac aquifer used in model analysis.

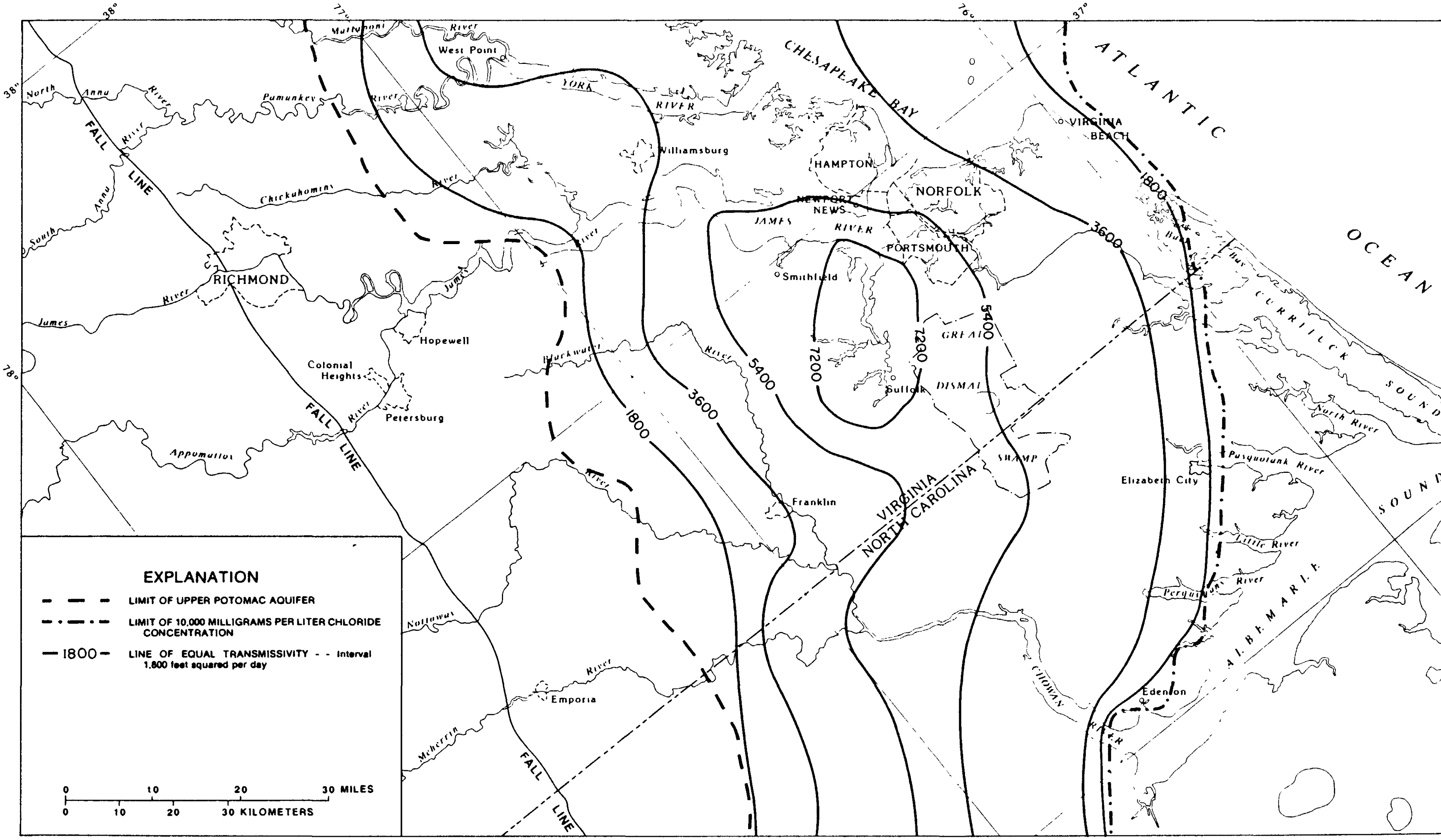

Figure 30.--Transmissivity of the upper Potomac aquifer used in model analysis.

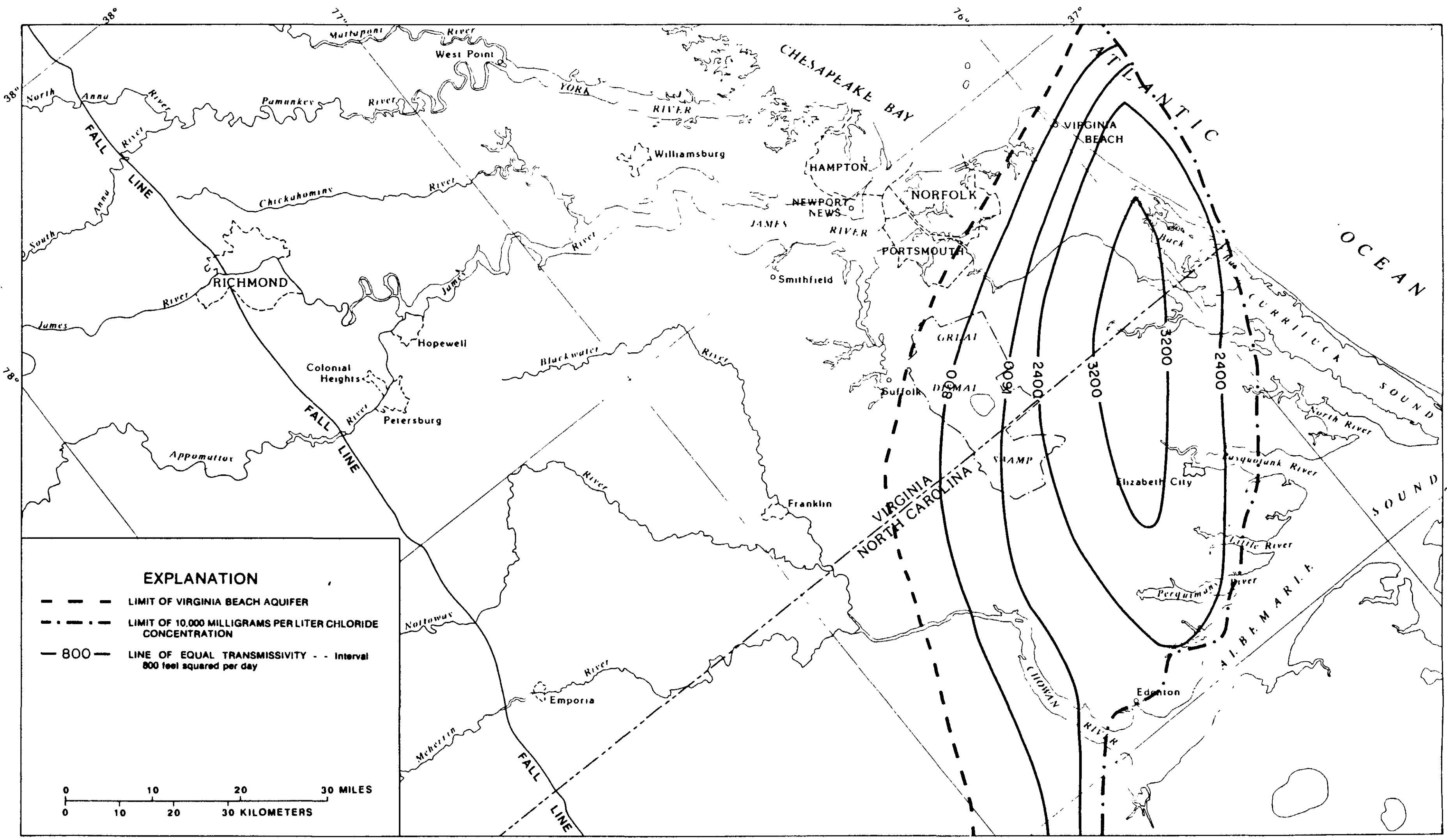

Figure 31.--Transmissivity of the Virginia Beach aquifer used in model analysis.

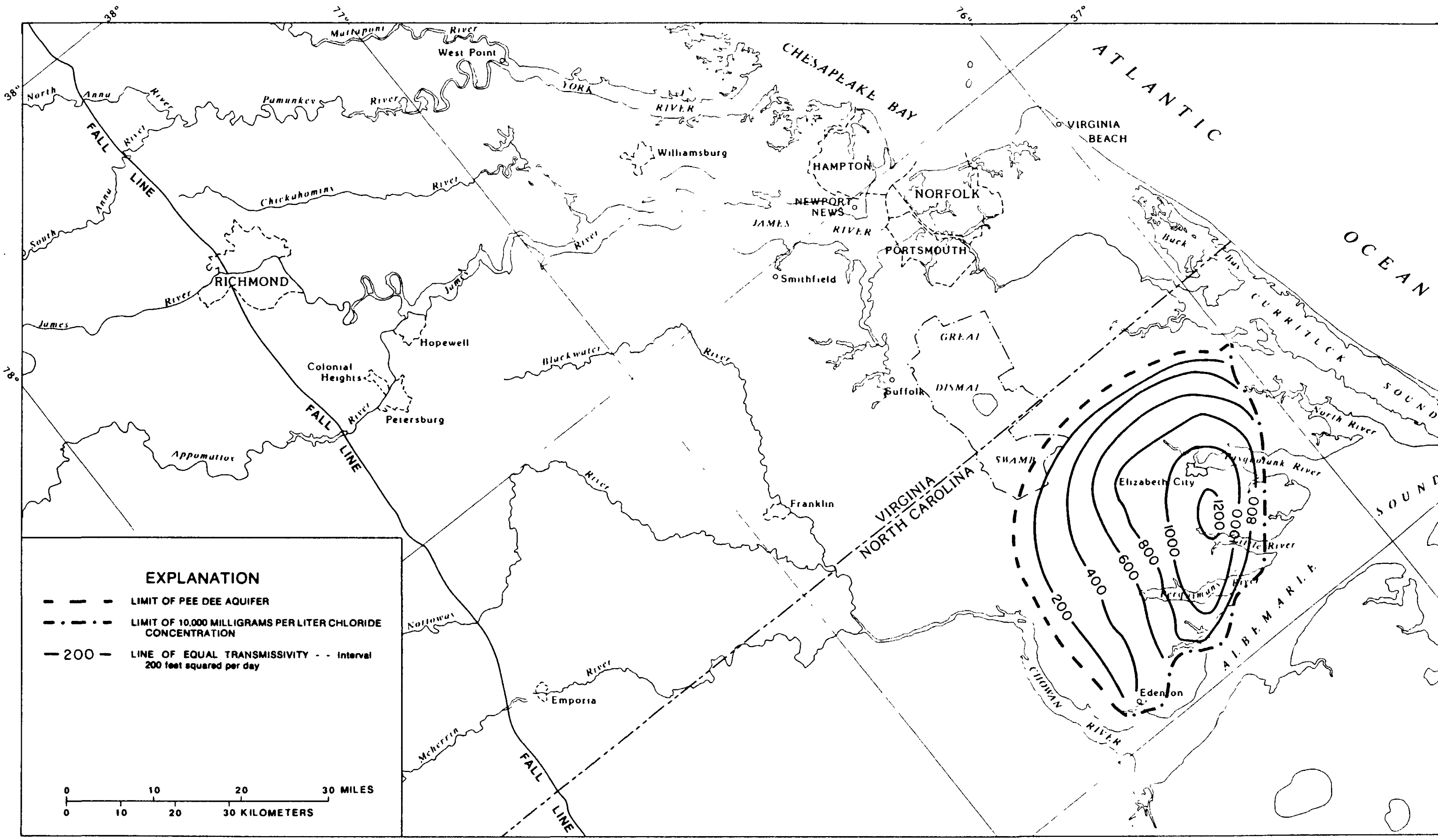

Figure 32.--Transmissivity of the Peedee aquifer used in model analysis.

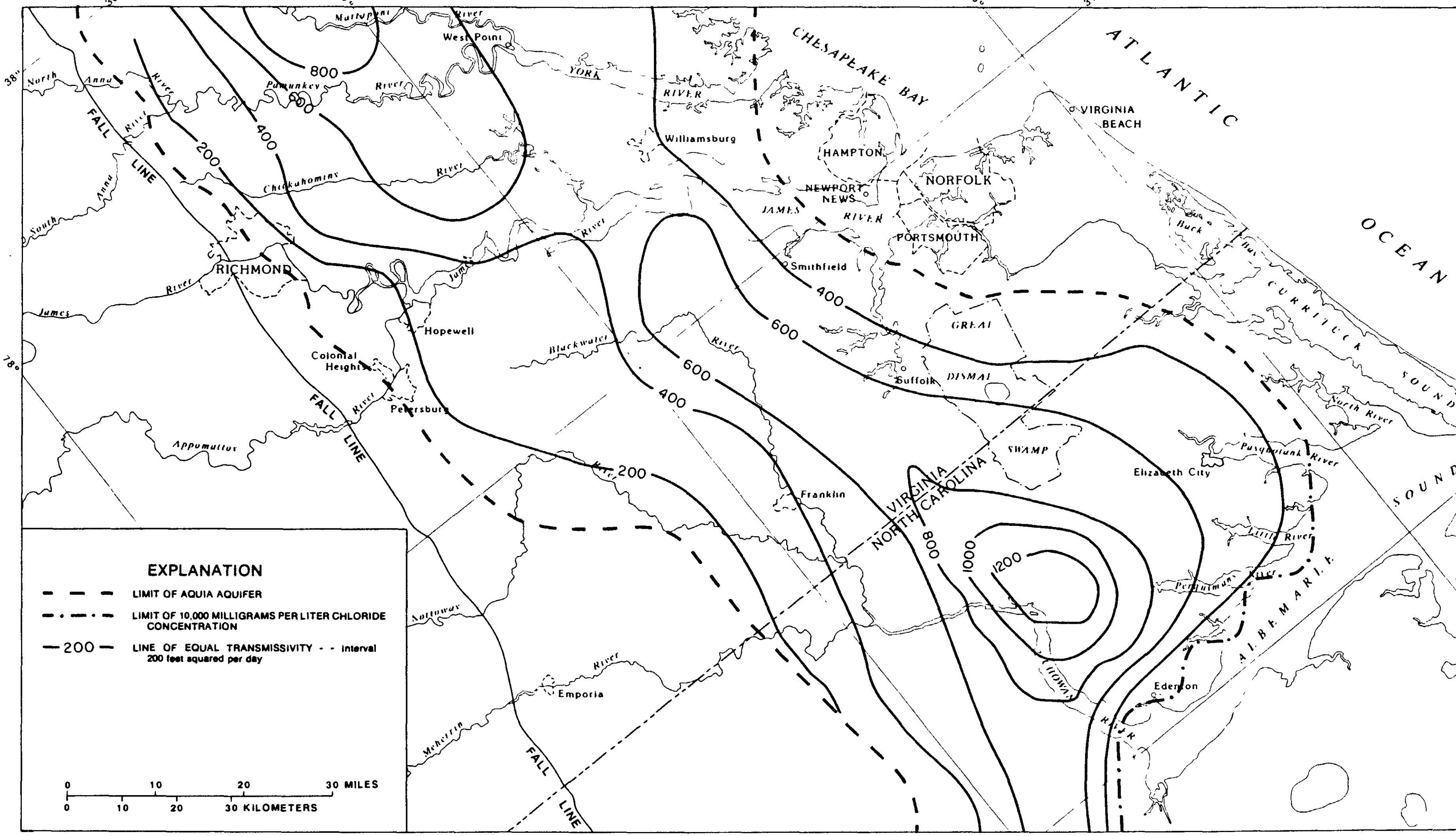

Figure 33.--Transmissivity of the Aquia aquifer used in model analysis.

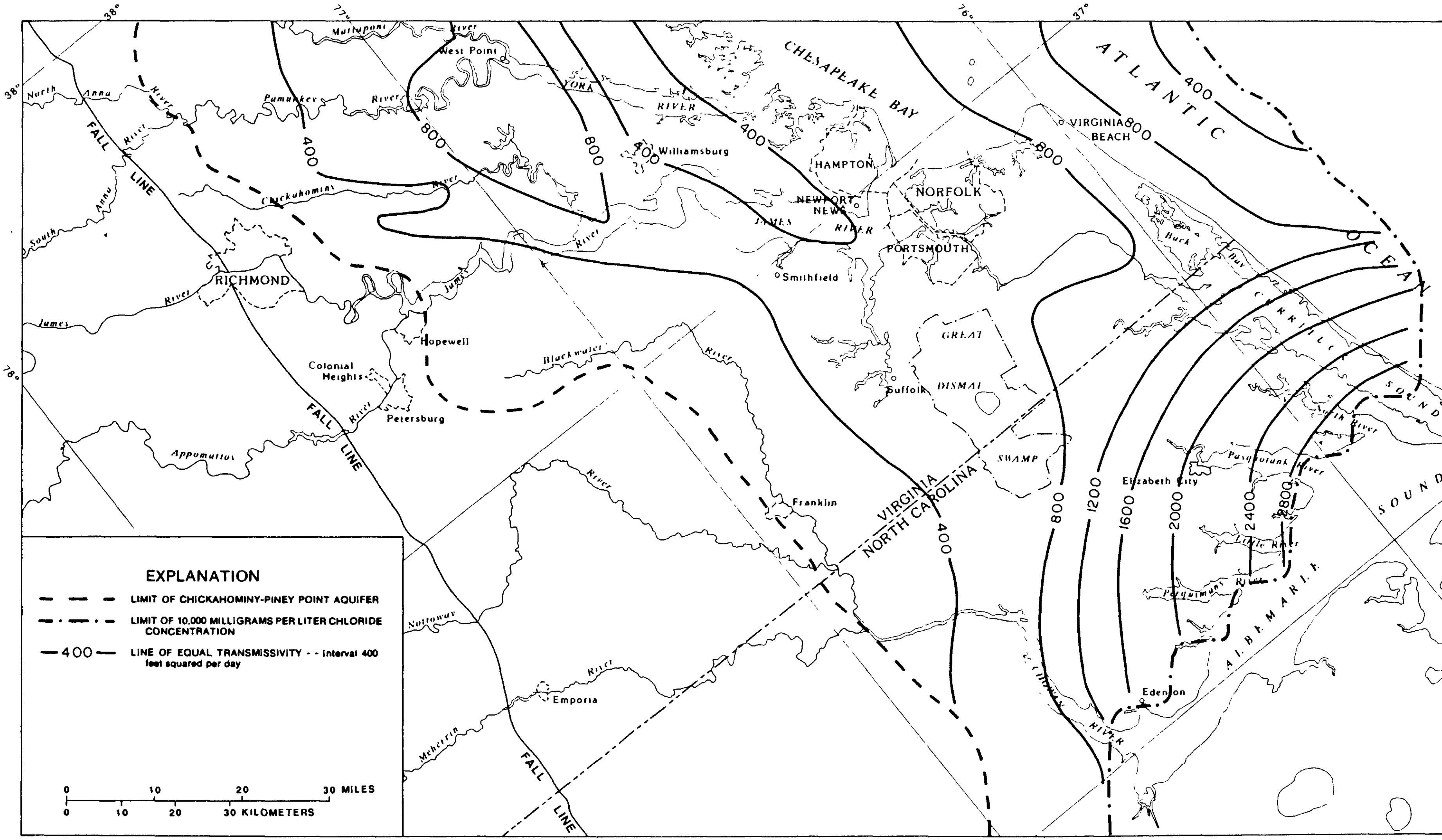

Figure 34.--Transmissivity of the Chickahominy-Piney Point aquifer used in model analysis.

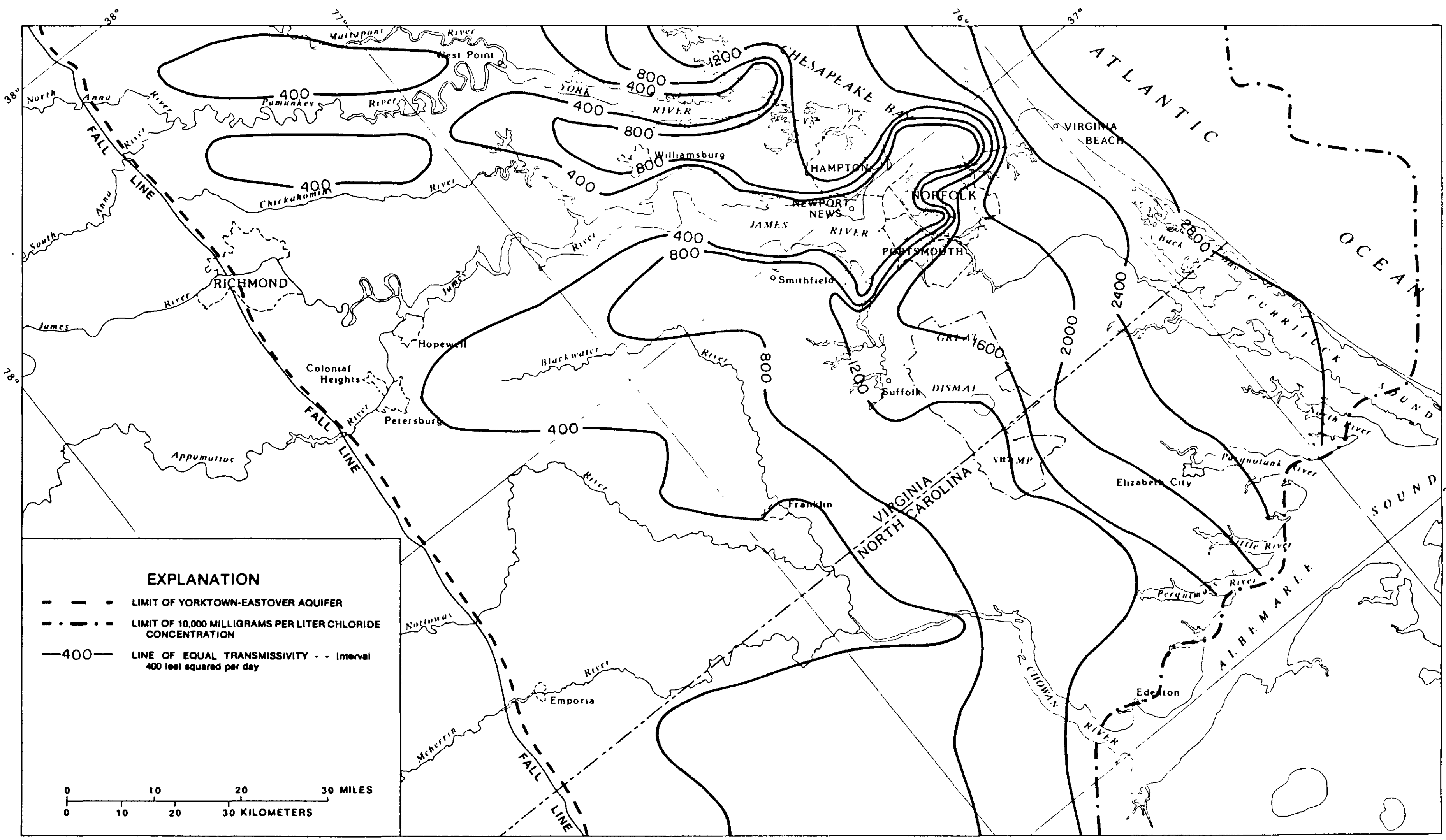

Figure 35.--Transmissivity of the Yorktown-Eastover aquifer used in model analysis.

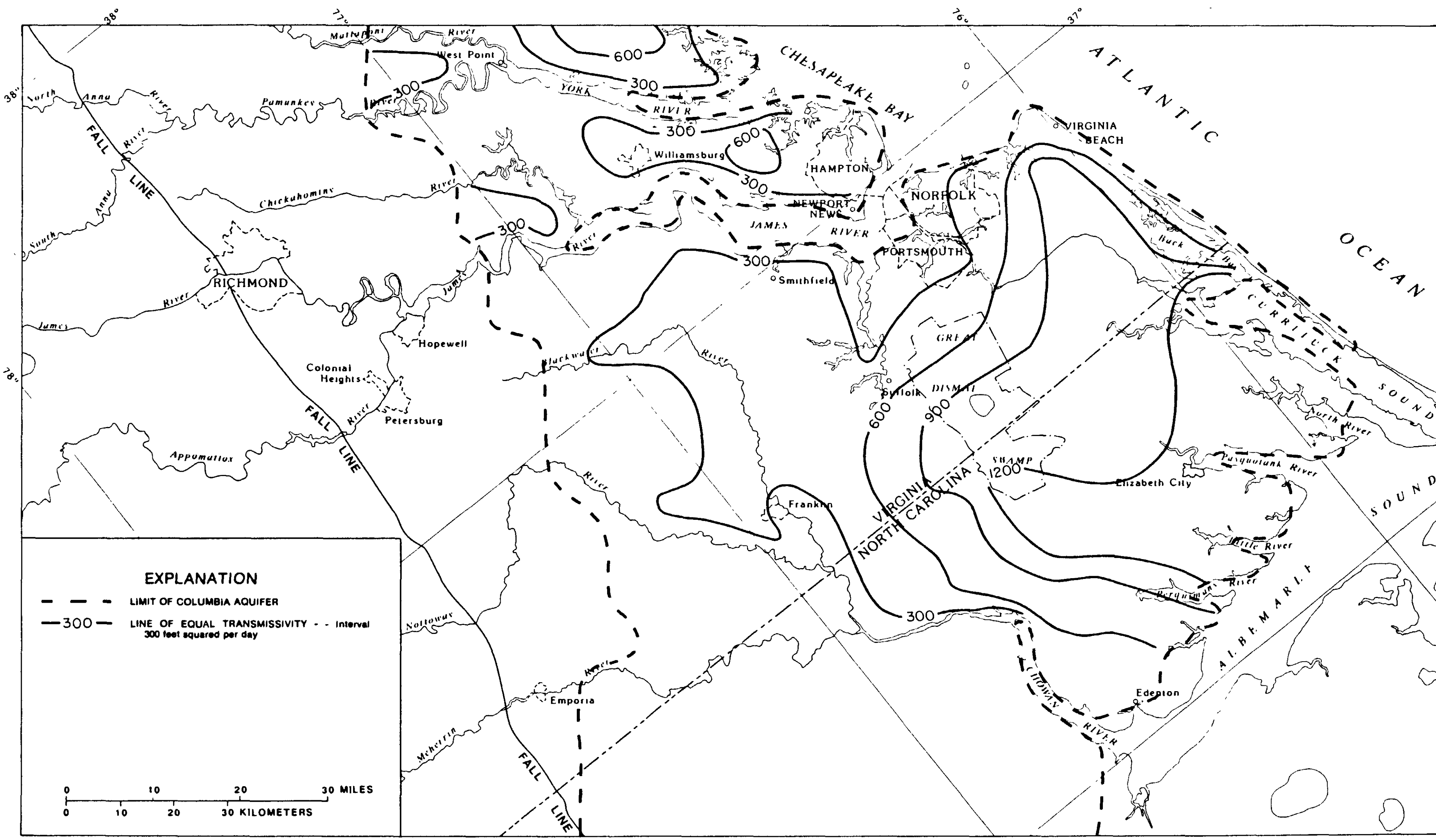

Figure 36.--Transmissivity of the Columbia aquifer used in model analysis.

ginal aquifer material was eroded and replaced with less permeable river deposits.

Storage coefficient

Storage coefficient was computed by multiplying specific storage by average sand thickness. Specific storage was estimated from literature to be about $1x10^{-6}$ per foot of thickness (Lohman, 1979). Higher values, representing specific yield and equal to $1.5x10^{-1}$, were used to approximate water-table conditions within an aquifer. Initial estimates for storage coefficient were adjusted slightly during the transient model development. Maps showing areal distributions of storage coefficient are not shown but closely parallel trends in transmissivity because both are functions of sediment thickness. The range of finalized estimates for storage coefficient used in model analysis is summarized by aquifer in table 6.

Table 6.--Estimated minimum and maximum values for storage coefficient used in model analysis
[Values are dimensionless]

Aquifer	Estimated minimum storage coefficient	Estimated maximum storage coefficient
Columbia	$1.50x10^{-1}$	$1.50x10^{-1}$
Yorktown-Eastover	$7.00x10^{-6}$	$1.50x10^{-1}$
Chickahominy-Piney Point	$6.00x10^{-6}$	$2.60x10^{-4}$
Aquia	$9.99x10^{-6}$	$8.50x10^{-5}$
Peedee	$5.00x10^{-6}$	$5.50x10^{-5}$
Virginia Beach	$5.00x10^{-6}$	$8.50x10^{-5}$
Upper Potomac	$1.50x10^{-5}$	$1.22x10^{-4}$
Middle Potomac	$1.00x10^{-5}$	$3.40x10^{-4}$
Lower Potomac	$8.00x10^{-6}$	$2.50x10^{-4}$

Vertical leakance

Vertical leakance controls vertical flow between aquifers. Vertical leakance is dependent on physical properties of the confining unit and is the vertical hydraulic conductivity divided by confining unit thickness. Confining unit thicknesses were approximated for each block from maps (figs. 11 through 19). Initial estimates for vertical hydraulic conductivity were based on values used in the Virginia Coastal Plain regional model (Harsh and Laczniak, 1986). Initial estimates were adjusted slightly during steady-state model development. Finalized estimates for vertical hydraulic conductivity used in model analysis are summarized by confining unit in table 7. Finalized estimates of maximum and minimum vertical leakance used in model analysis are presented by confining unit in table 8.

Table 7.--Estimated values for vertical hydraulic conductivity used in model analysis
[Values in feet per day]

Confining unit	Estimated vertical hydraulic conductivity
Yorktown	8.64×10^{-4}
St. Marys	4.15×10^{-4}
Calvert	3.89×10^{-5}
Nanjemoy-Marlboro	6.48×10^{-5}
Peedee	6.91×10^{-5}
Virginia Beach	7.34×10^{-5}
Upper Potomac	6.05×10^{-5}
Middle Potomac	6.48×10^{-5}
Lower Potomac	4.32×10^{-5}

Table 8.--Estimated minimum and maximum values for vertical leakance used in model analysis
[Values per day]

Confining unit	Estimated minimum vertical leakance	Estimated maximum vertical leakance
Yorktown	1.88×10^{-5}	9.60×10^{-3}
St. Marys	6.10×10^{-6}	4.15×10^{-3}
Calvert	5.40×10^{-8}	7.78×10^{-4}
Nanjemoy-Marlboro	1.16×10^{-7}	5.89×10^{-4}
Peedee	6.91×10^{-7}	9.87×10^{-6}
Virginia Beach	1.10×10^{-6}	2.29×10^{-5}
Upper Potomac	6.06×10^{-8}	1.89×10^{-4}
Middle Potomac	3.24×10^{-7}	5.40×10^{-4}
Lower Potomac	3.93×10^{-7}	5.40×10^{-6}

Values for vertical leakance generally decrease from west to east because of increased thickness of the confining unit (figs. 11 through 19) and decreased vertical hydraulic conductivity of the sediment. The deeper confining units are characterized by lower vertical leakance. Relatively high vertical leakance resulting from high vertical conductivity is present along major river valleys and Chesapeake Bay where original confining unit sediment was eroded and replaced with more permeable river deposits.

Ground-Water Recharge

Average annual precipitation in the model area is about 43 in/yr (inches per year) (Cushing and others, 1973; National Oceanic and Atmospheric Administration, 1980). Approximately one-half of this precipitation is lost to evapotranspiration, and the remaining occurs as surface runoff and ground-water recharge. Approximately 10 to 15 inches are estimated to recharge the water-table aquifer throughout the Virginia Coastal Plain (Harsh, 1980; Geraghty and Miller, 1978b; Johnston, 1977). An average annual recharge rate of 12 in/yr (4,780.8 Mgal/d) was used in model analysis and assigned to all grid blocks that simulate water-table conditions. The recharge rate is assumed to be constant throughout time and space; data are lacking to define any spatial variations that may occur in the model area. Sensitivity analyses were conducted using 10 and 15 in/yr as recharge rates. Simulated water levels were not sensitive to changes in this parameter within this range, particularly in the confined aquifers which were the primary focus of this study.

Recharge to the confined aquifers occurs as water moves downward from the water-table aquifer through confining units. This recharge is not constant throughout time and space but is a function of vertical leakance of the confining units and pumpage from the aquifers. Simulated recharge to the confined aquifers is discussed in detail in sections on simulated ground-water flow using the steady-state and transient models.

Streambed Leakance

Streambed leakance controls the rate of water flowing through a streambed into and out of the water-table aquifer from and to a stream. It is defined as the vertical hydraulic conductivity of streambed sediment divided by sediment thickness. Data for streambed conductivity are scarce; therefore, this parameter was estimated on the basis of its relation to stream baseflow which is ground water flowing into a stream. Stream baseflow is the product of streambed leakance and the difference between water levels in the water-table aquifer and stream (hydraulic gradient). Stream baseflow was first calculated for each block using a prepumping water-budget analysis, where baseflow equals recharge to the water-table aquifer plus or minus flow into or out of the underlying confined aquifer system (Harsh and Laczniak, 1986; Leahy and Martin, 1986):

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

where

BF = baseflow per unit area, in feet per second;

QRE = volumetric rate of ground-water recharge to water-table aquifer per unit area, in feet per second; and

DP = deep percolation or volumetric rate of flow into or out of the underlying confined aquifer system per unit area, in feet per second.

Streambed leakance was then calculated by dividing stream baseflow by the hydraulic gradient. Streambed leakance is assumed to remain constant throughout the simulated period of ground-water development. Further detail on calculation of streambed leakance is provided in Harsh and Laczniak (1986).

Lateral Boundary Flow

The continuity of aquifers across lateral model boundaries to the north and south was simulated with boundary fluxes. The fluxes represent movement of water into and out of the modeled area. The use of these lateral boundaries reduced the size of the model by eliminating parts of aquifers outside the area of interest. Flux values were calculated for each pumping period by means of Darcy's Law and were based on the simulated head gradient and transmissivity across lateral boundaries. Head gradients were generated from a regional model of the Virginia Coastal Plain (Harsh and Laczniak, 1986). The fluxes were incorporated into the model as recharge and discharge wells placed along the boundaries.

Steady-State-Model Simulation of Prepumping Conditions

Prepumping conditions were modeled using a steady-state solution to the ground-water flow equation. The period prior to 1891 was chosen to represent prepumping conditions because ground-water withdrawals at that time are considered insignificant. A steady-state solution implies that flow into the system approximates flow out of the system and no significant change in ground-water storage or water levels occurs over time.

Calibration

Accuracy of the prepumping simulation was evaluated by comparing simulated to measured water levels. The model is considered accurate, or calibrated, when a reasonable correlation between measured and simulated levels is obtained and when estimates of aquifer hydraulic properties are consistent with known values. Some adjustments to transmissivity and vertical leakance were necessary to obtain satisfactory agreement between simulated and measured water-level values. (Contours of calibrated transmissivities are shown in figures 28 through 36, and calibrated estimates of vertical leakance are summarized in table 8.) Contours of simulated and measured water levels in wells prior to 1891 are shown in figures 37 through 43. Results only are shown for those aquifers present within the study area; results for the Peedee aquifer are, therefore, not included. The maps show simulated water levels to be consistent with measured values. Because prepumping measured water levels are sparse, simulated prepumping water levels also were compared to maps describing prepumping conditions published in Siudyla and others (1977), Bal (1978), and Harsh and Laczniak (1986). Simulated contours and flow directions are in agreement with the maps.

Results of Simulation

Simulated water levels (figs. 37 through 43) show agreement with the conceptualization of ground-water flow in the multiaquifer system--water moved regionally from the Fall Line toward Chesapeake Bay and the Atlantic Ocean and locally to streams, swamps, and bays.

The simulated ground-water budget, describing sources and discharges of water in the aquifer system, is illustrated in figure 44. The modeled values

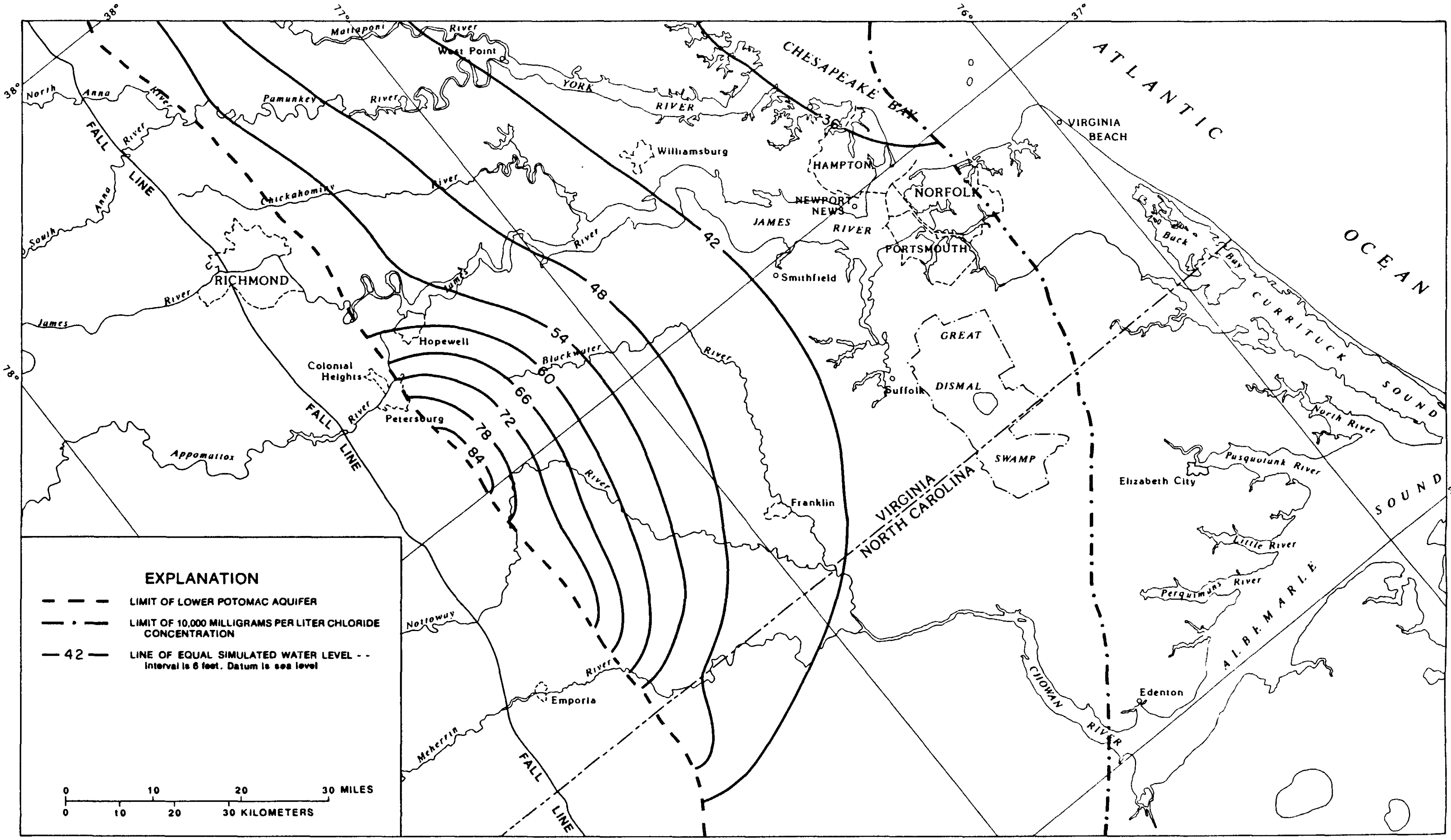

Figure 37.--Simulated water levels in the lower Potomac aquifer for prepumping conditions.

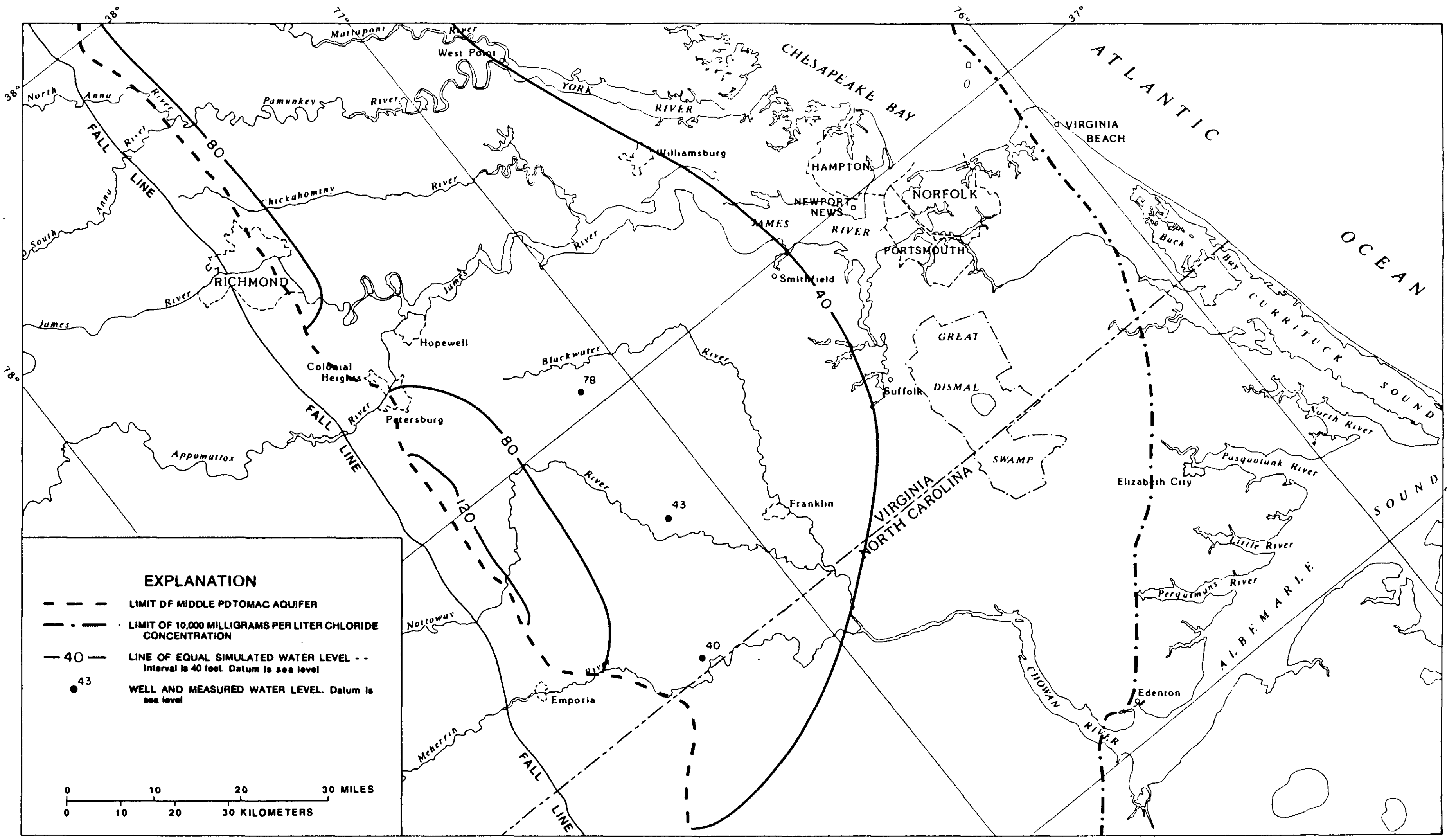

Figure 38.--Simulated and measured water levels in the middle Potomac aquifer for prepumping conditions.

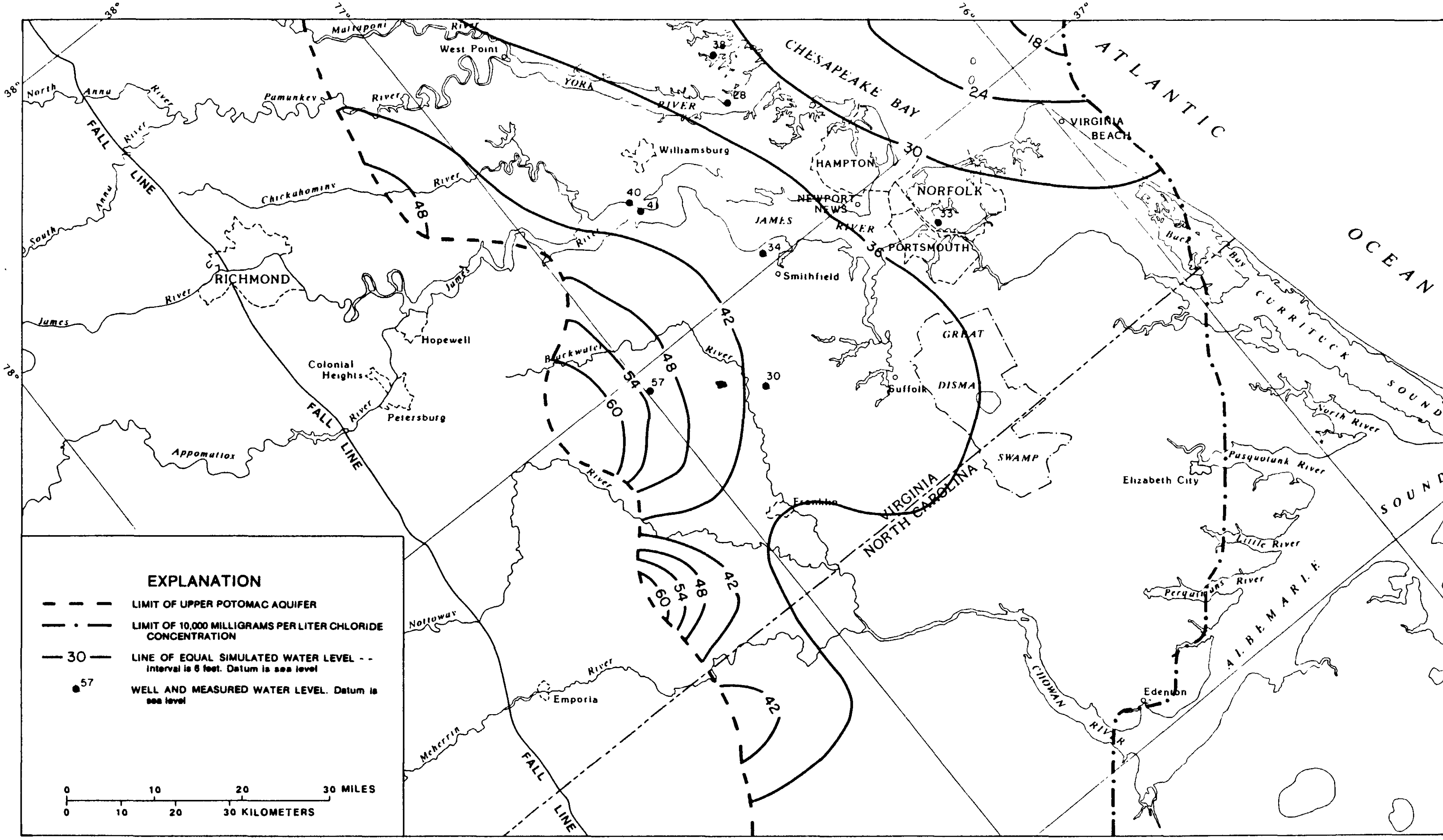

Figure 39.--Simulated and measured water levels in the upper Potomac aquifer for prepumping conditions.

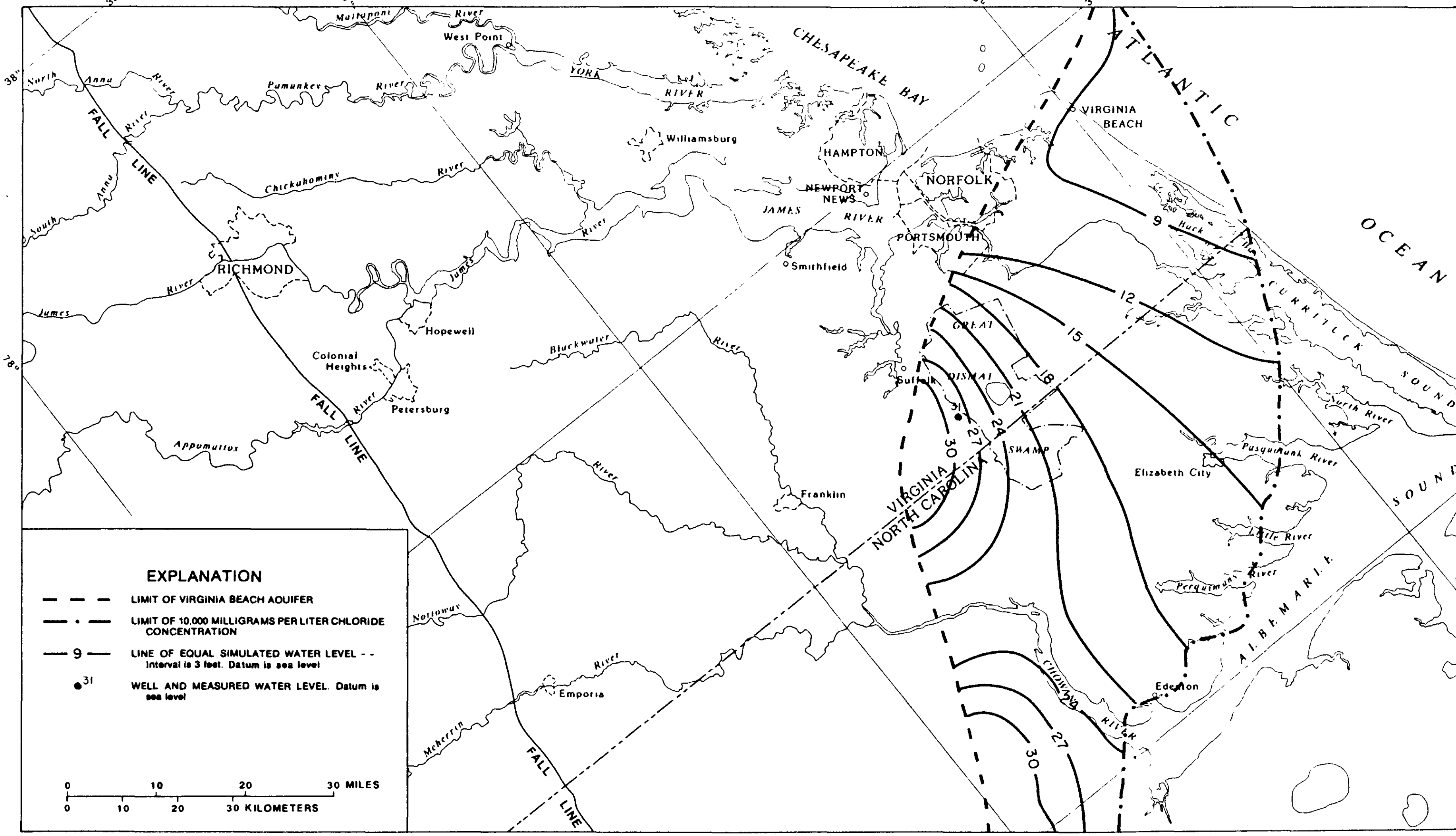

Figure 40.--Simulated and measured water levels in the Virginia Beach aquifer for prepumping conditions.

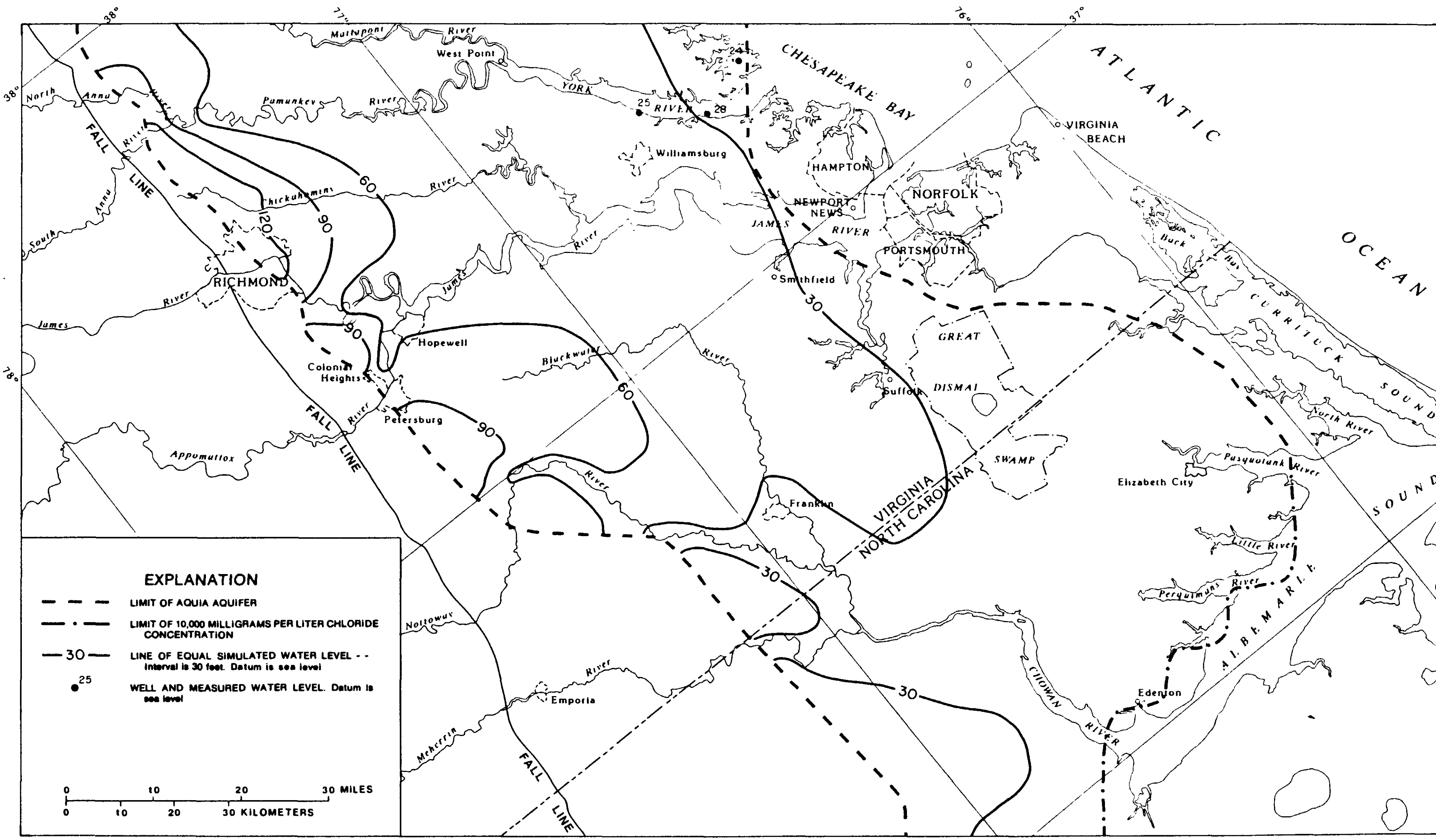

Figure 41.--Simulated and measured water levels of the Aquia aquifer for prepumping conditions.

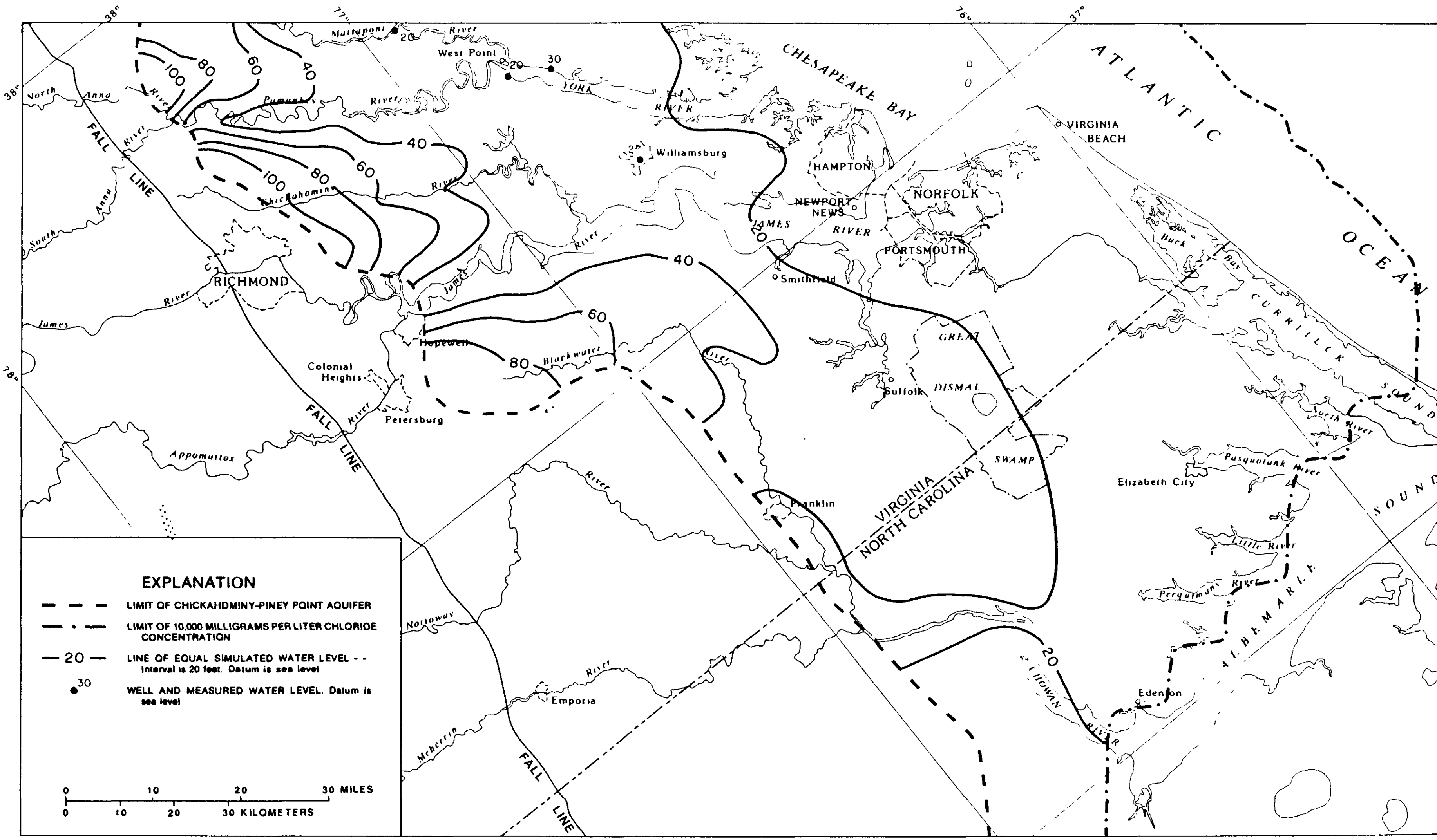

Figure 42.--Simulated and measured water levels in the Chickahominy-Piney Point aquifer for prepumping conditions.

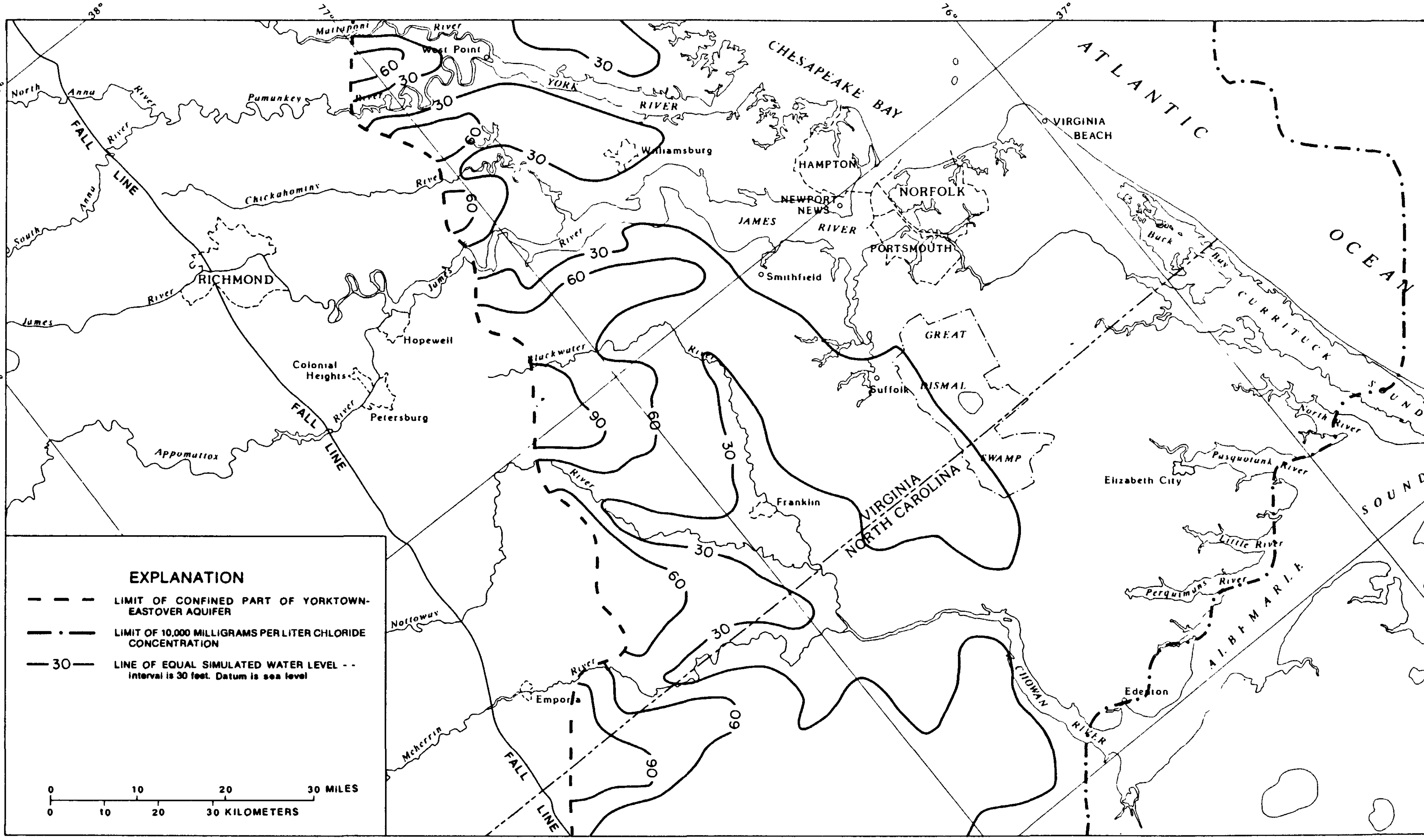

Figure 43.--Simulated water levels in the Yorktown-Eastover aquifer for prepumping conditions.

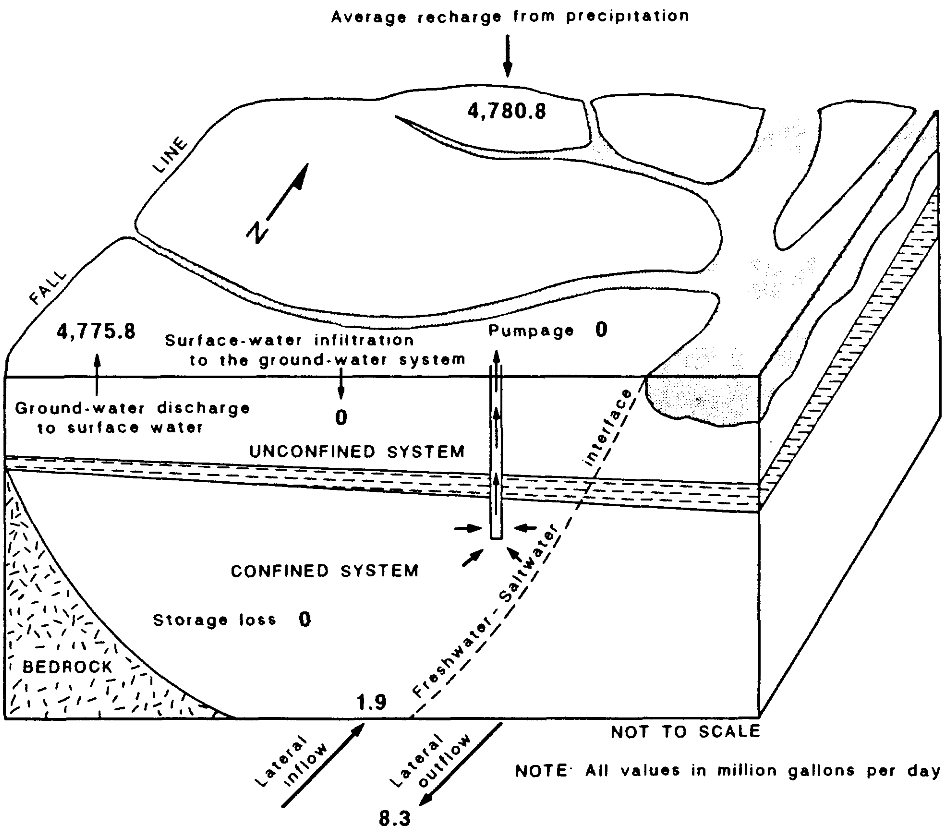

Figure 44.--Simulated ground-water budget for prepumping conditions.

presented in the text, figures, and tables are not intended to imply accuracy to the precision shown. Water-budget sources include recharge from precipitation and lateral inflow across the northern and southern model boundaries. Water-budget discharges include lateral outflow and discharge to surface water. Lateral inflow and outflow across the northern and southern model boundaries are summarized for each aquifer in table 9. Under prepumping conditions, a hydraulic equilibrium prevailed in the multiaquifer system--average areal recharge (4,780.8 Mgal/d or 12 in/yr) to the water-table aquifer approximated ground-water discharge to surface water (about 4,775.8 Mgal/d). This discharge is composed of (1) ground water that directly discharged from the water-table aquifer to surface water or (2) ground water that had recharged the confined system, ultimately moving upward along the freshwater-saltwater interface and major river valleys to surface water. The small difference between recharge and discharge was attributed to lateral inflow and outflow across the northern and southern model boundaries in the water-table and confined aquifers. The complete water budget for prepumping conditions, resulting in less than 0.03 percent error in mass balance, is given in table 10.

Recharge to the confined aquifers occurred as water moved downward from the water-table aquifer through confining units. Areas of simulated vertical recharge to and discharge from each confined aquifer through the overlying confining unit are shown in figures 45 through 51 and summarized in table 11. The maps define the direction of flow across major confining units. The

Table 9.--Lateral flow across northern and southern boundaries of the model area for prepumping and pumping conditions

[Modeled values, in million gallons per day, are reported to hundredths and are not intended to imply accuracy to the precision shown]

Aquifer	Prepumping	Lateral inflow across northern and southern model boundaries during indicated pumping period										
		1	2	3	4	5	6	7	8	9	10	11
Columbia	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Yorktown-Eastover	1.07	1.07	1.07	1.07	1.07	1.07	1.08	1.08	1.09	1.09	1.09	1.09
Chickahominy-Piney Point	.39	.38	.39	.39	.39	.38	.37	.37	.43	.50	.49	.55
Aquia	.05	.06	.08	.18	.22	.21	.22	.24	.28	.29	.29	.27
Peedee	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Virginia Beach	.04	.03	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Upper Potomac	.00	.02	.29	1.25	1.58	1.62	2.09	2.48	3.24	3.22	3.17	2.99
Middle Potomac	.00	.01	.24	1.16	1.59	2.00	2.95	3.75	4.69	4.56	4.62	4.33
Lower Potomac	.00	.00	.03	.21	.31	.52	1.03	1.49	2.07	2.60	2.25	2.61
Total	1.94	1.96	2.49	4.65	5.55	6.19	8.13	9.80	12.19	12.65	12.30	12.23

Aquifer	Prepumping	Lateral outflow across northern and southern model boundaries during indicated pumping period										
		1	2	3	4	5	6	7	8	9	10	11
Columbia	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
Yorktown-Eastover	1.16	1.17	1.17	1.17	1.17	1.17	1.16	1.16	1.16	1.16	1.16	1.16
Chickahominy-Piney Point	.40	.38	.38	.37	.37	.37	.37	.37	.39	.39	.40	.39
Aquia	.26	.25	.26	.28	.31	.31	.33	.35	.38	.40	.40	.39
Peedee	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Virginia Beach	.00	.00	.08	.06	.07	.08	.10	.11	.30	.16	.17	.17
Upper Potomac	2.25	1.62	1.58	1.38	1.33	1.21	1.05	.97	.82	.82	.82	.83
Middle Potomac	2.60	1.81	1.70	1.61	1.66	1.59	1.52	1.49	1.53	1.60	1.62	1.56
Lower Potomac	1.02	.60	.66	.62	.78	.61	.54	.51	.55	.59	.62	.60
Total	8.28	6.42	6.42	6.08	6.28	5.93	5.66	5.55	5.72	5.71	5.78	5.69

Table 10.--Simulated ground-water budgets for prepumping and 1983 conditions
[Modeled values, in million gallons per day, are reported to tenths and are not intended to imply accuracy to the precision shown]

	Prepumping	1983	Change from prepumping to 1983 conditions
Sources			
Water released from aquifer storage	0.0	0.4	0.4
Lateral boundary inflow	1.9	12.2	10.3
Recharge from precipitation	4,780.8	4,780.8	.0
Surface-water infiltration to the ground-water system	.0	.8	.8
Total	4,782.7	4,794.2	11.5
Discharges			
Water taken into aquifer storage	.0	1.0	-1.0
Lateral boundary outflow	8.3	5.7	2.6
Ground-water withdrawal from wells	.0	86.6	-86.6
Ground-water discharge to surface water	4,775.8	4,702.2	73.6
Total	4,784.1	4,795.5	-11.4

Footnote: The small error between sources and discharges is due to numerical truncation in digital simulation.

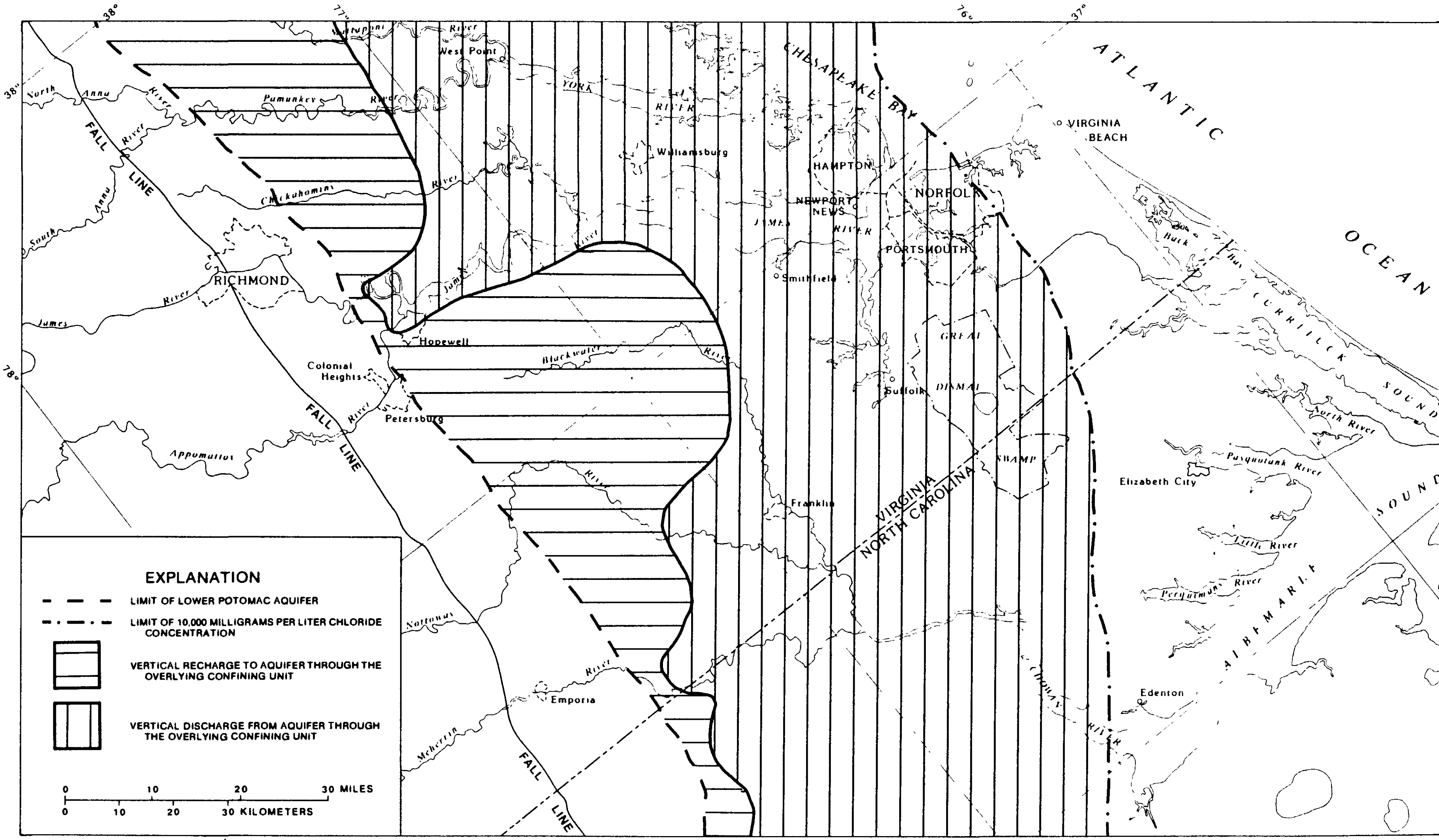

Figure 45.--Simulated areas of vertical recharge to and discharge from the lower Potomac aquifer through the overlying confining unit for prepumping conditions.

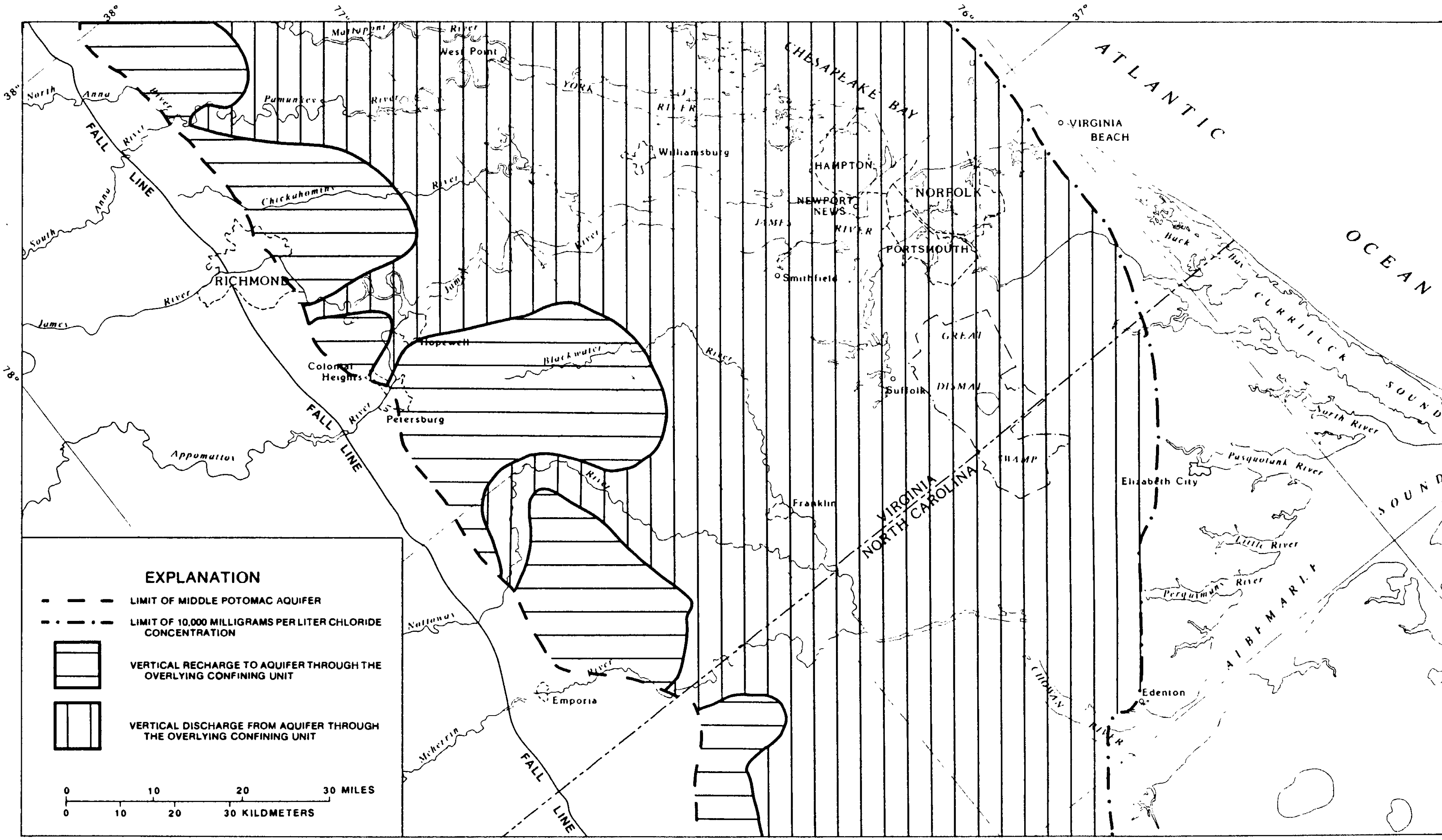

Figure 46.--Simulated areas of vertical recharge to and discharge from the middle Potomac aquifer through the overlying confining unit for prepumping conditions.

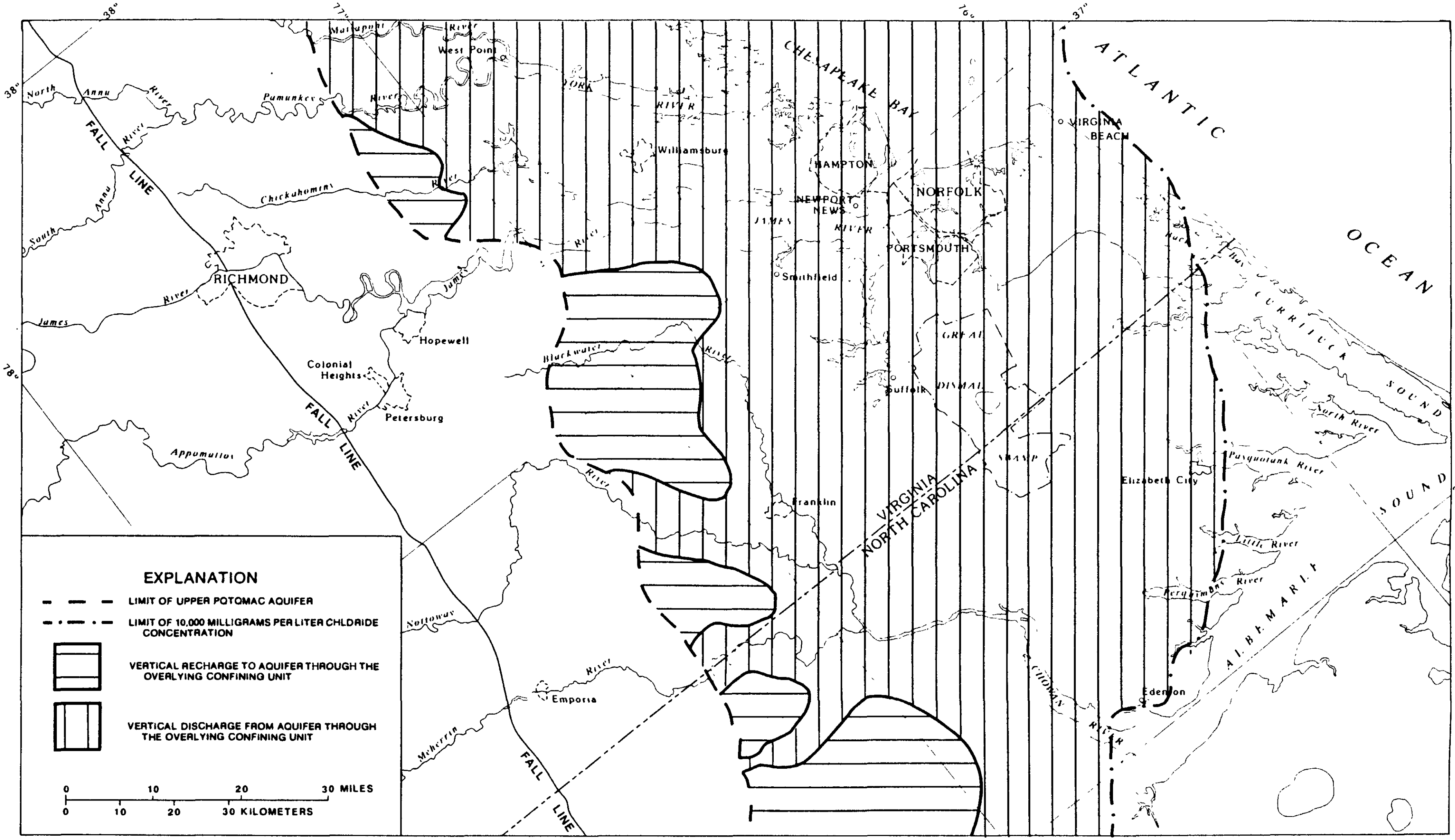

Figure 47.--Simulated areas of vertical recharge to and discharge from the upper Potomac aquifer through the overlying confining unit for prepumping conditions.

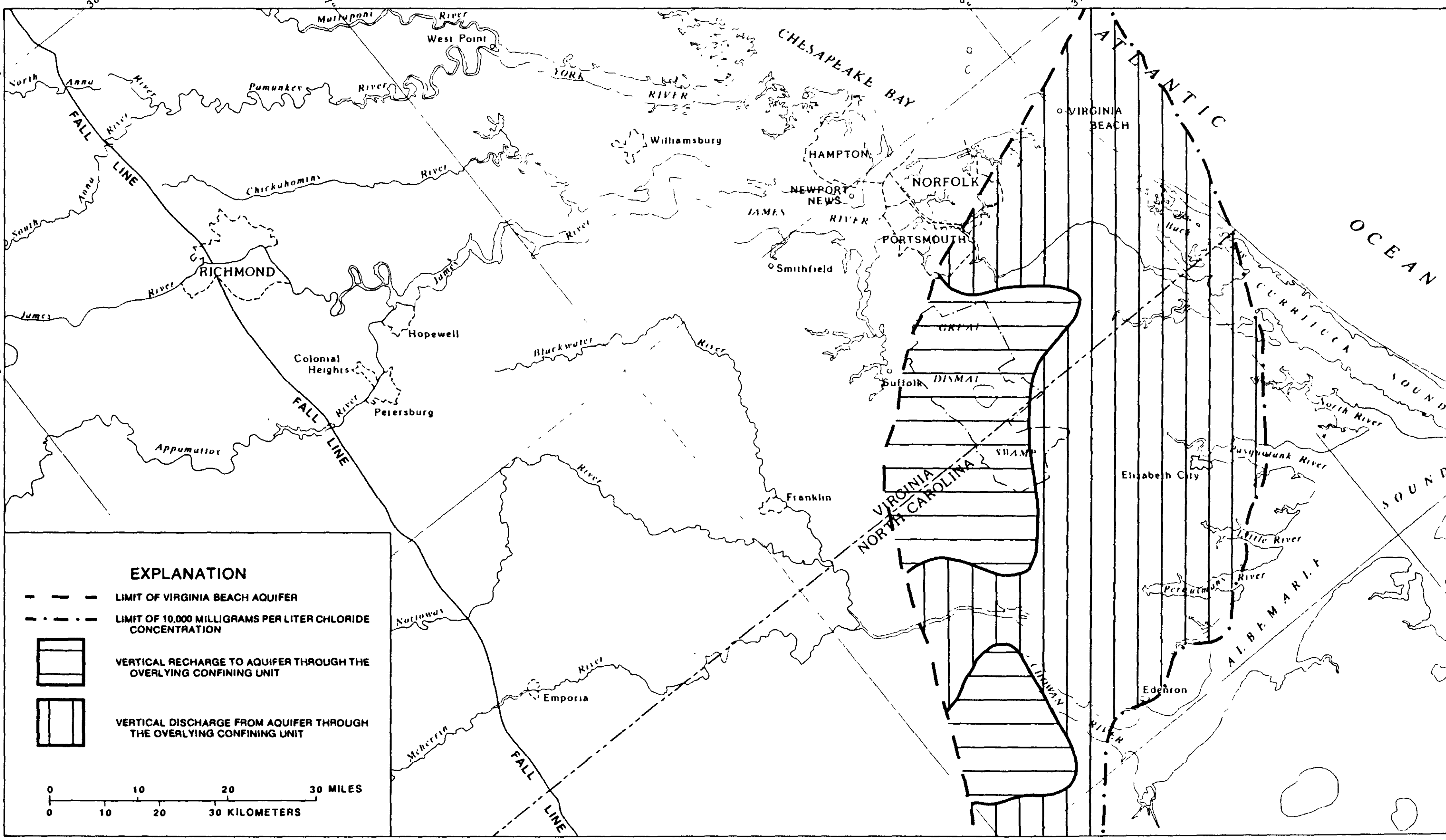

Figure 48.--Simulated areas of vertical recharge to and discharge from the Virginia Beach aquifer through the overlying confining unit for prepumping conditions.

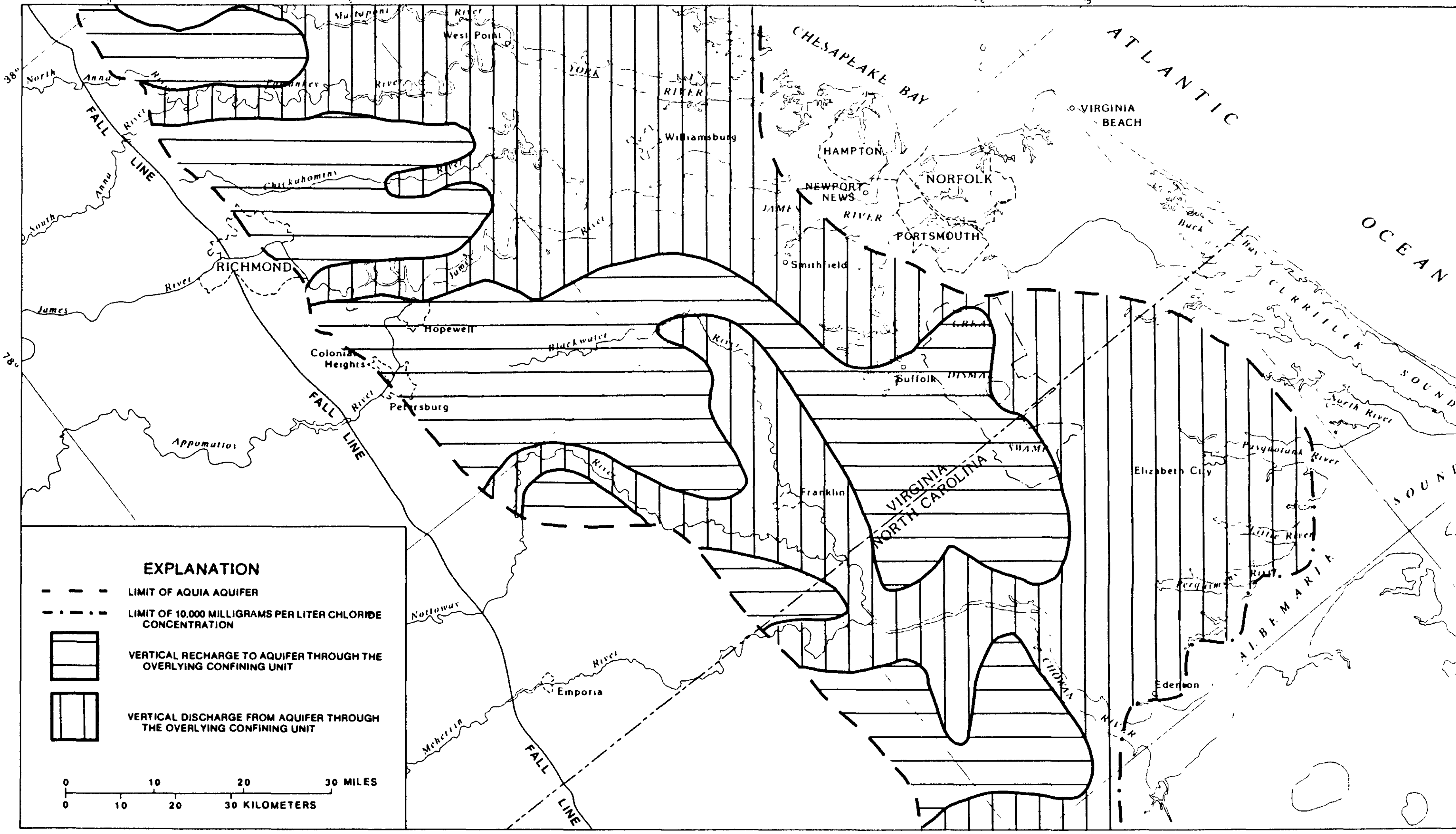

Figure 49.--Simulated areas of vertical recharge to and discharge from the Aquia aquifer through the overlying confining unit for prepumping conditions.

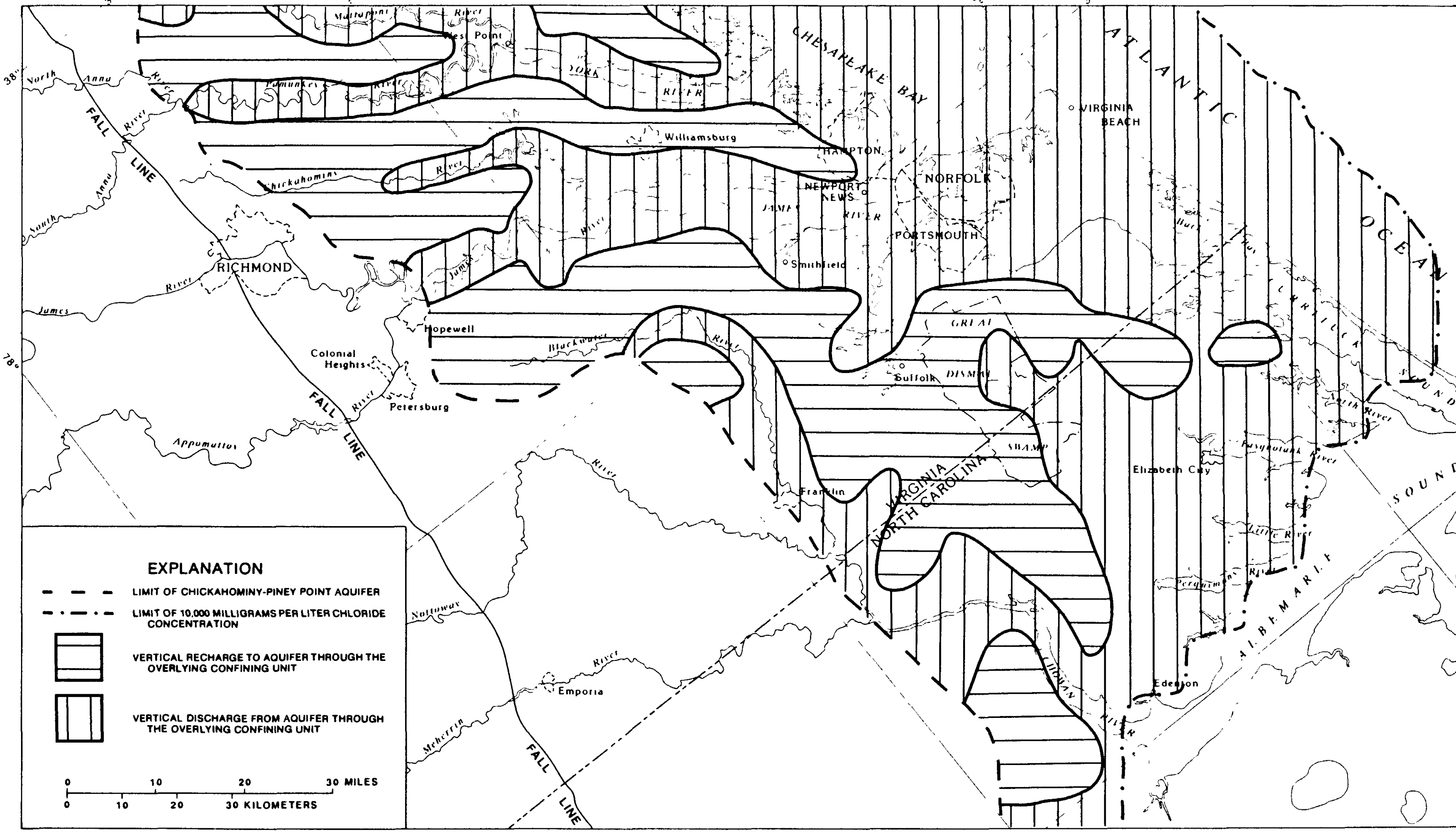

Figure 50.--Simulated areas of vertical recharge to and discharge from the Chickahominy-Piney Point aquifer through the overlying confining unit for prepumping conditions.

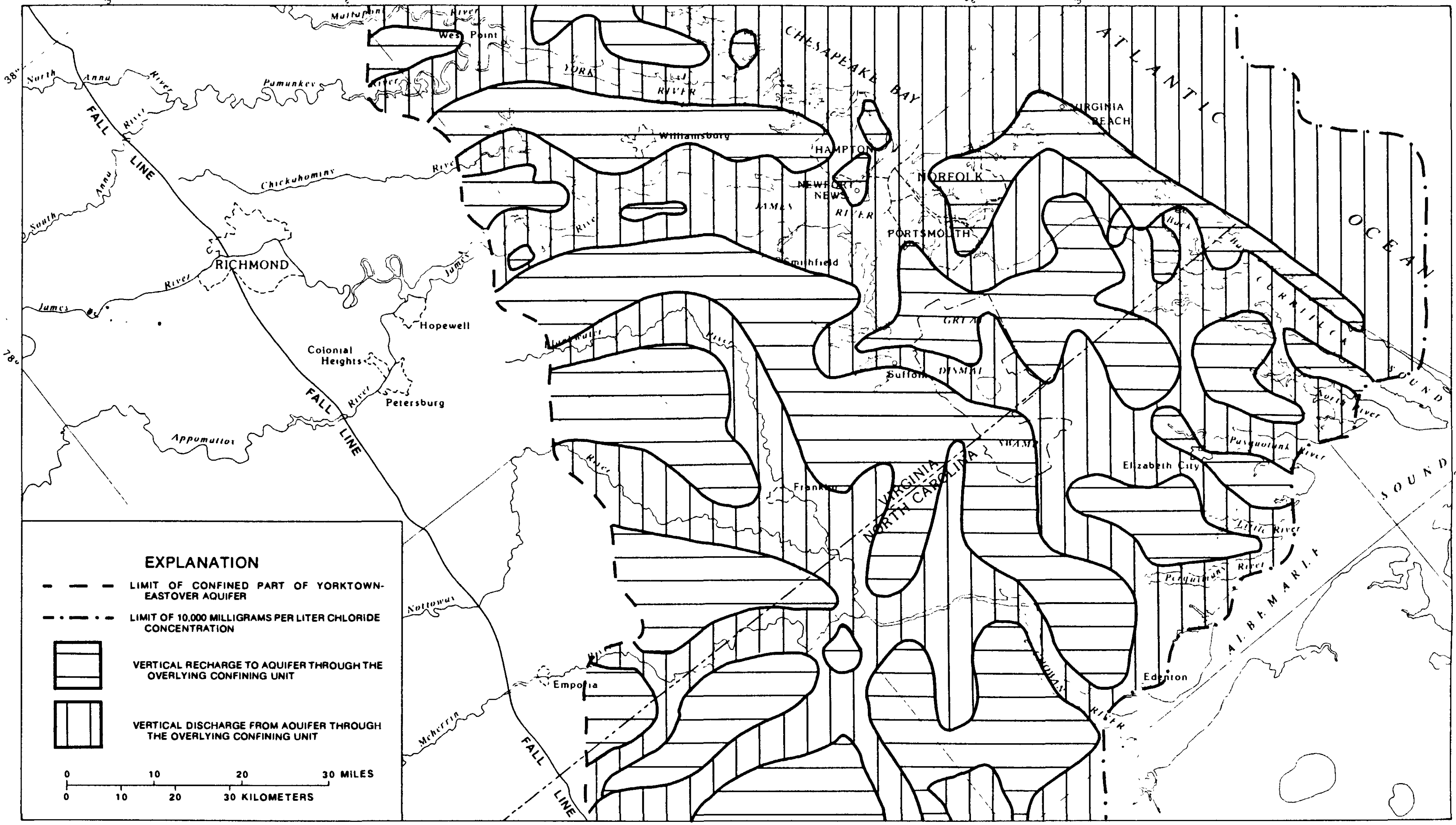

Figure 51.--Simulated areas of vertical recharge to and discharge from the Yorktown-Eastover aquifer through the overlying confining unit for prepumping conditions.

Table 11a.--Simulated areas of vertical recharge to and discharge from each confined aquifer through the overlying confining unit for prepumping and 1983 conditions

[Modeled values in square miles]

Aquifer	Prepumping		1983		Change in area of vertical recharge and discharge from prepumping conditions to 1983	
	Recharge	Discharge	Recharge	Discharge	Recharge	Discharge
Yorktown-Eastover	3,167	4,680	4,558	3,289	1,391	-1,391
Chickahominy-Piney Point	2,548	4,484	5,644	1,388	3,096	-3,096
Aquia	2,453	3,644	5,369	728	2,916	-2,916
Peedee	58	738	701	95	643	-643
Virginia Beach	637	1,862	2,373	126	1,736	-1,736
Upper Potomac	891	5,268	6,134	25	5,243	-5,243
Middle Potomac	1,415	5,901	6,600	716	5,185	-5,185
Lower Potomac	1,669	4,588	5,488	769	3,819	-3,819

Table 11b.--Simulated amounts of vertical recharge to and discharge from each confined aquifer through the overlying confining unit for prepumping and 1983 conditions

[Modeled values, in million gallons per day, are reported to tenths and are not intended to imply accuracy to the precision shown]

Aquifer	Prepumping		1983		Change in amounts of vertical recharge and discharge from prepumping conditions to 1983		
	Recharge	Discharge	Recharge	Discharge	Recharge	Discharge	Total gain from overlying aquifer
Yorktown-Eastover	56.6	62.8	87.0	40.0	30.4	22.8	53.2
Chickahominy-Piney Point	14.1	18.0	37.4	6.9	23.3	11.1	34.4
Aquia	19.8	18.1	55.9	6.4	36.1	11.7	47.8
Peedee	.0	.3	.3	.0	.3	.3	.6
Virginia Beach	.4	1.0	2.3	.1	1.9	.9	2.8
Upper Potomac	3.5	6.4	38.9	.1	35.4	6.3	41.7
Middle Potomac	18.9	15.4	64.6	5.5	45.7	9.9	55.6
Lower Potomac	2.3	1.2	13.0	.4	10.7	.8	11.5

general direction of flow was downward in the western part of the model area and upward in the eastern part into Chesapeake Bay and the Atlantic Ocean. In the shallower aquifers (Aquia, Chickahominy-Piney Point, and Yorktown-Eastover) flow also was influenced by major river systems--downward flow occurred between and upward flow occurred along and under major river valleys. Amounts of vertical recharge to and discharge from each confined aquifer through the overlying confining unit are given in table 11.

Transient-Model Simulation of Pumping Conditions

Pumping conditions from 1891 through 1983 were modeled using a transient solution to the ground-water flow equation. Transient analysis was done by adding pumpage, time, and storage to the steady-state model simulating pre-pumping conditions. Water levels generated by the steady-state model were used as initial water levels in the transient analysis so that resulting changes would be caused entirely by simulated withdrawals. Transient analysis of pumping conditions provides a measure of the ability of the model to simulate the response of the ground-water flow system to pumpage.

Time Discretization and Pumpage

Eleven pumping periods, spanning 93 years, were used in the transient-calibration phase. These periods were 1891-1920, 1921-39, 1940-46, 1947-52, 1953-57, 1958-64, 1965-68, 1969-72, 1973-77, 1978-80, and 1981-83. Maps of aquifer tops and confining-unit thicknesses (figs. 3 through 19) were correlated with the depth of water intake for each well (screened or opened) to identify the aquifer from which withdrawal occurred. For multiaquifer wells, withdrawal was apportioned to aquifers by percentage of total screen present in each aquifer. Simulated withdrawal from individual aquifers for each pumping period is given in table 12. The majority of water withdrawn from the model area occurred in the Potomac aquifers (91.4 percent in the final pumping period). The rate of ground-water withdrawal was averaged uniformly over each pumping period for each node containing a pumping well. Figure 52 illustrates simulated and estimated annual withdrawal from 1891 through 1983. The length and number of pumping periods are consistent with those used in the regional model of the Virginia Coastal Plain (Harsh and Laczniak, 1986) to simplify the calculation of lateral boundary inflow and outflow.

Calibration

Accuracy of the transient simulation was evaluated by comparing simulated and measured water levels. Slight adjustments to storage coefficient were necessary during transient calibration to improve agreement between simulated and measured water levels. Simulated and measured change in water levels for the period of ground-water development at 21 selected observation wells is shown in figures 53 through 58. Hydrographs for two to four wells distributed throughout the model area were selected for each aquifer. These wells generally represent the longest available records. The hydrographs show close agreement between measured and simulated water levels throughout the period of record. Hydrographs for 113 other observation wells are not shown but indicate similar agreement with simulated results. Measured water levels in observation wells in 1983 and contours of simulated water levels generated with the transient model are shown in figures 59 through 65. Measured water levels are included to show the close agreement with simulated levels.

Table 12.--Simulated withdrawal from individual aquifers, 1891-1983

[Modeled values, in million gallons per day, are reported to hundredths and are not intended to imply accuracy to the precision shown]

	Pumping period										
	1	2	3	4	5	6	7	8	9	10	11
Aquifer	1891-1920	1921-39	1940-46	1947-52	1953-57	1958-64	1965-68	1969-72	1973-77	1978-80	1981-83
Columbia	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.08	0.10	0.12
Yorktown-Eastover	.00	.06	.18	.25	.28	.58	1.38	2.53	3.37	3.76	3.41
Chickahominy-Piney Point	.11	.43	.64	.82	.93	1.18	1.45	1.67	2.46	2.66	2.85
Aquia	.13	.46	1.45	1.72	1.44	1.15	1.29	1.58	1.74	1.58	1.10
Peedee	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Virginia Beach	.00	.00	.00	.00	.00	.00	.00	.04	.09	.01	.01
Upper Potomac	5.29	6.27	10.95	11.14	10.01	11.40	13.93	17.06	16.05	15.91	14.93
Middle Potomac	4.68	7.57	11.54	14.70	20.40	31.52	39.65	50.56	51.83	52.76	49.81
Lower Potomac	.61	1.01	2.67	3.86	5.77	8.39	10.65	13.16	14.34	13.61	14.40
Total	10.82	15.80	27.43	32.49	38.83	54.23	68.37	86.65	89.96	90.39	86.63

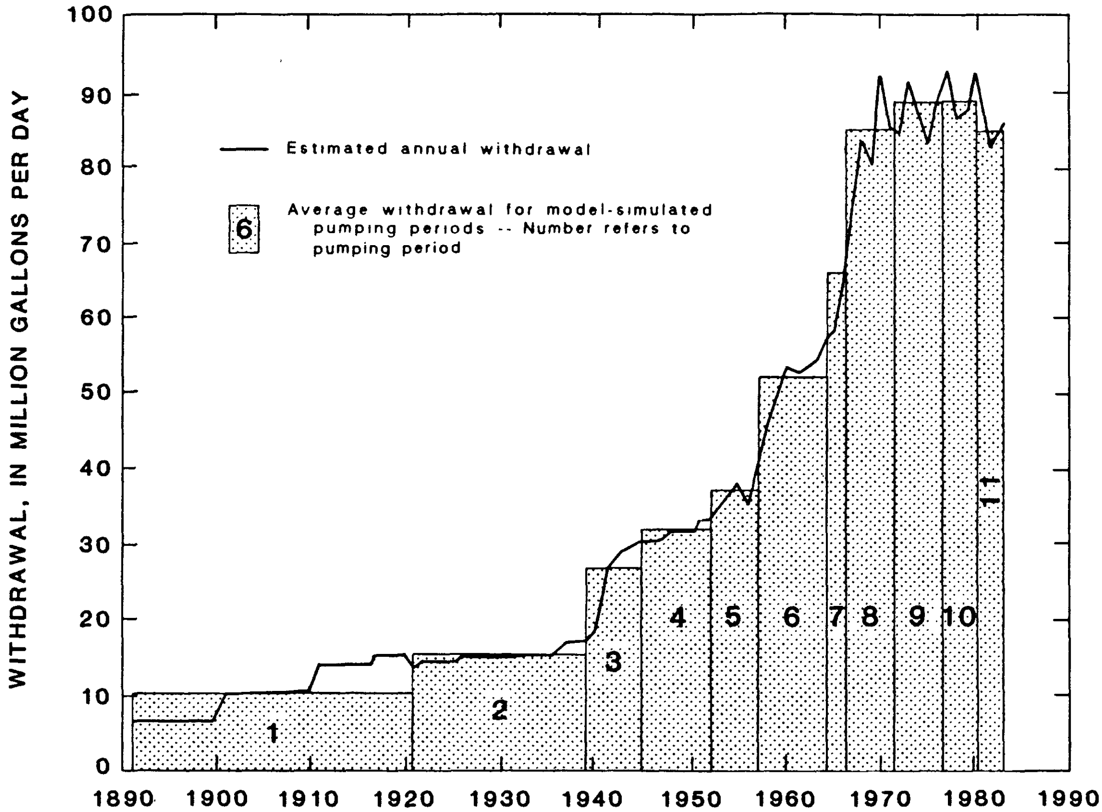

Figure 52.--Estimated annual withdrawal and average withdrawal for simulated pumping periods.

Results of Simulation

Simulation of pumping conditions from 1891 through 1983 demonstrates a significant decline in water levels from prepumping conditions (comparison made between figures 37 through 43 and figures 59 through 65), resulting in regionally-extensive cones of depression around major pumpage centers. Lowering of water levels affected the prepumping ground-water movement, diverting flow toward production wells. Simulated maximum water-level decline and locations of maximum decline for each aquifer are given in table 13. Maximum decline (greater than 250 feet) occurred in the lower and middle Potomac aquifers in the Franklin area. Substantial decline (greater than 90 feet) also occurred in these aquifers in the West Point area, with declines of at least 30 feet occurring in most other areas. Water-level decline (greater than 100 feet) occurred in the upper Potomac aquifer in the West Point, Williamsburg, Smithfield, and Suffolk areas. Decline greater than 20 feet occurred throughout most of this aquifer.

Although the majority of pumpage was from the Potomac aquifers (91.4 percent), significant water-level decline also occurred in the overlying

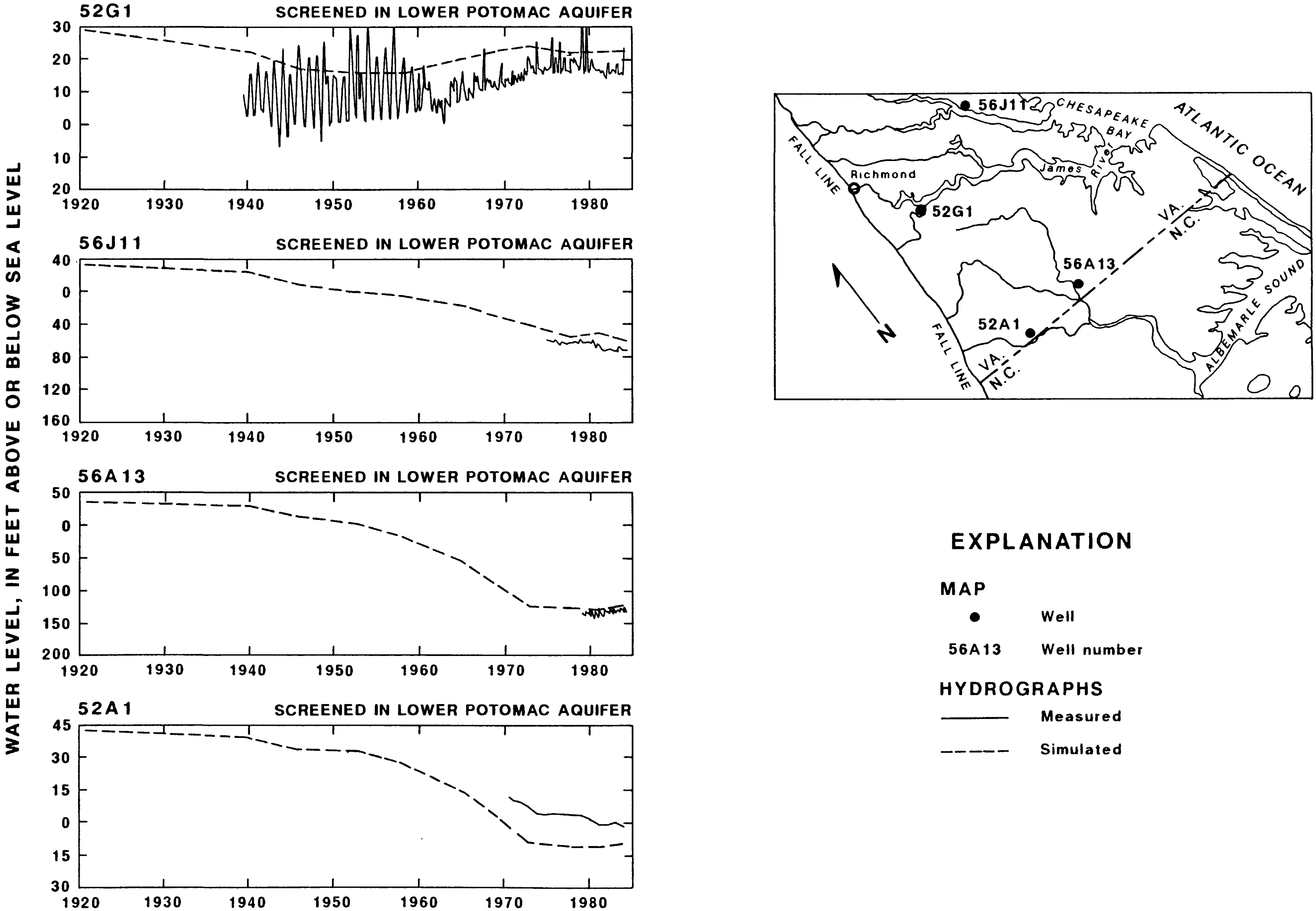

Figure 53.--Simulated and measured changes in water levels for the period of ground-water development in the lower Potomac aquifer.

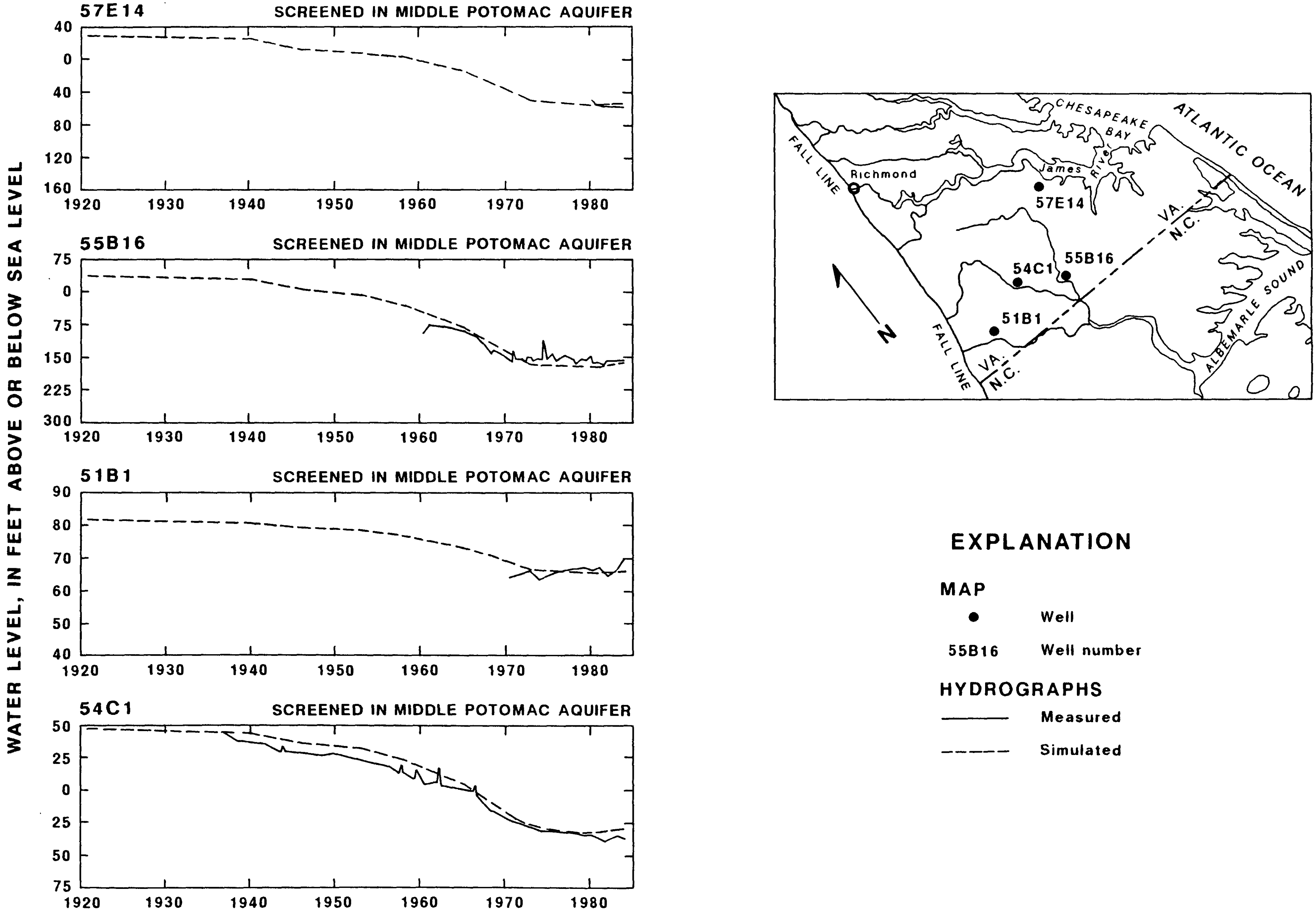

Figure 54.--Simulated and measured changes in water levels for the period of ground-water development in the middle Potomac aquifer.

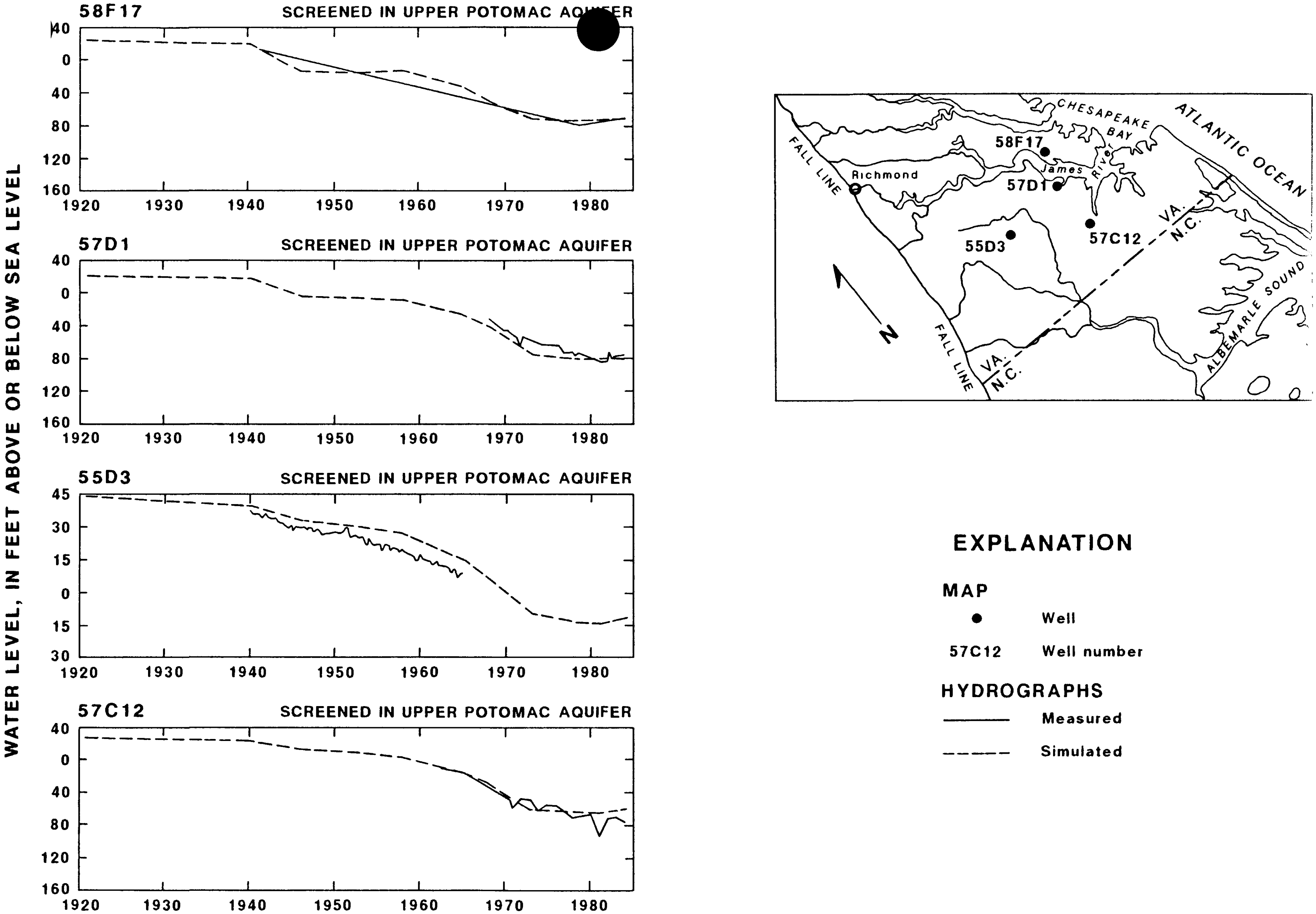

Figure 55.--Simulated and measured changes in water levels for the period of ground-water development in the upper Potomac aquifer.

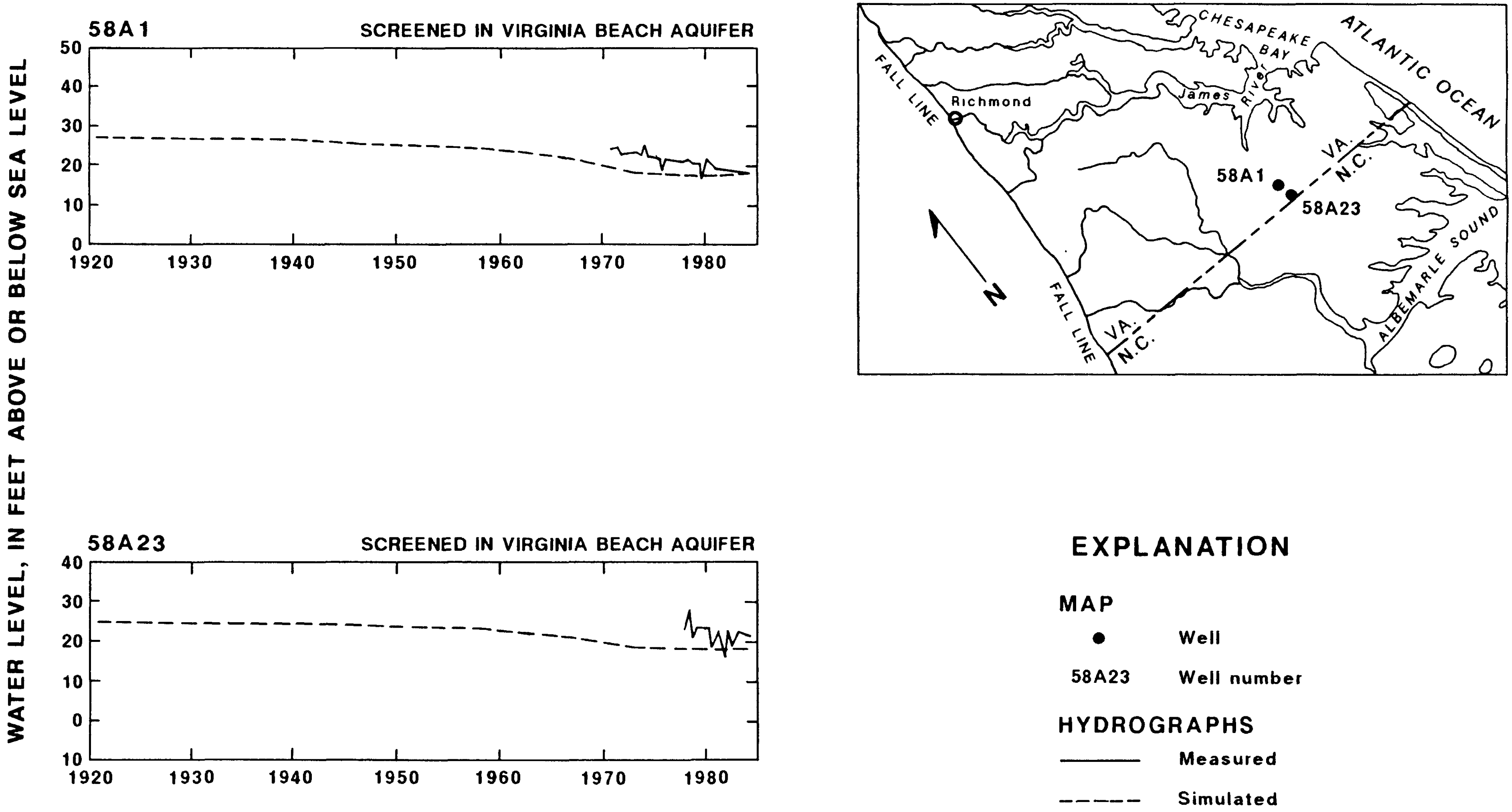

Figure 56.--Simulated and measured changes in water levels for the period of ground-water development in the Virginia Beach aquifer.

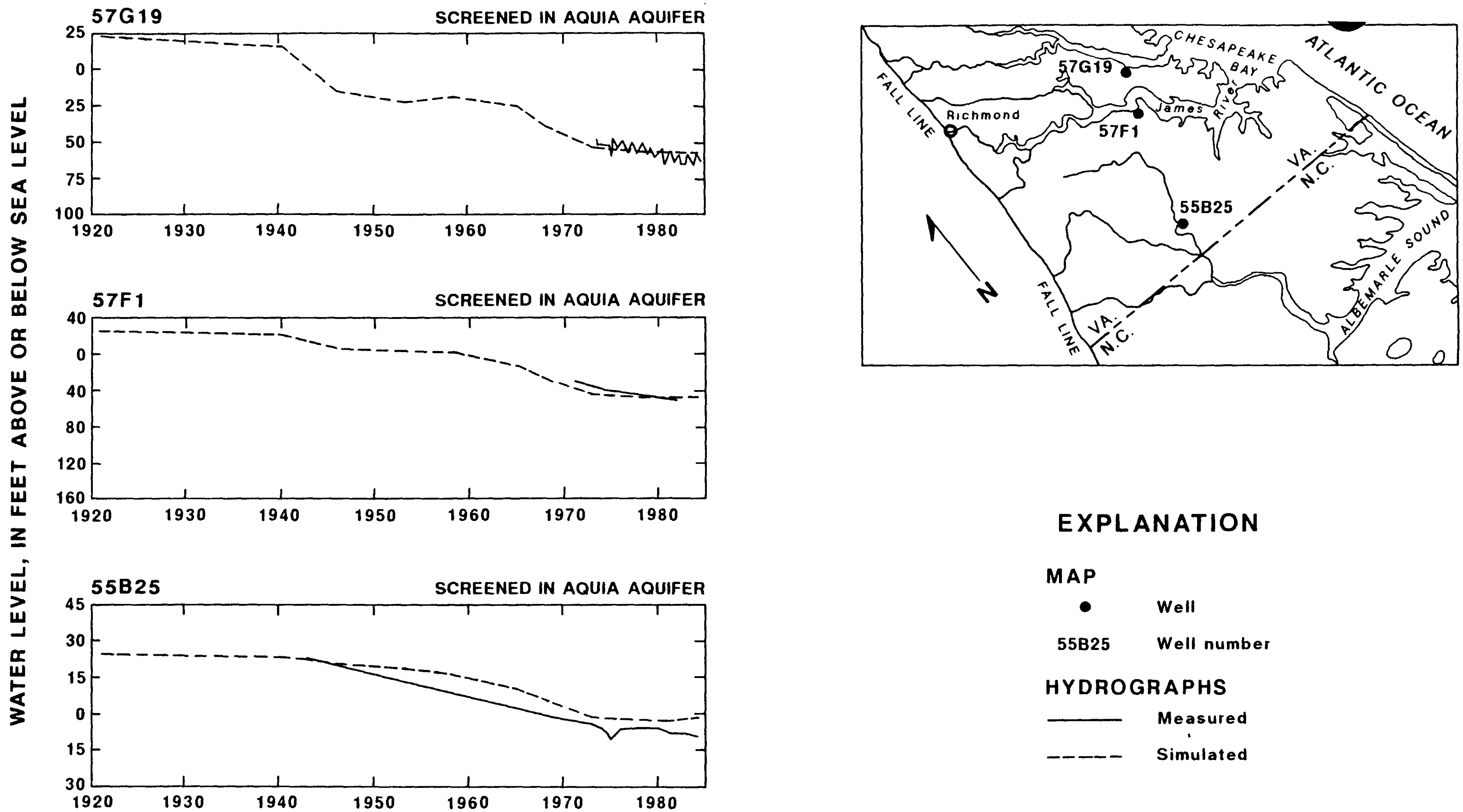

Figure 57.--Simulated and measured changes in water levels for the period of ground-water development in the Aquia aquifer.

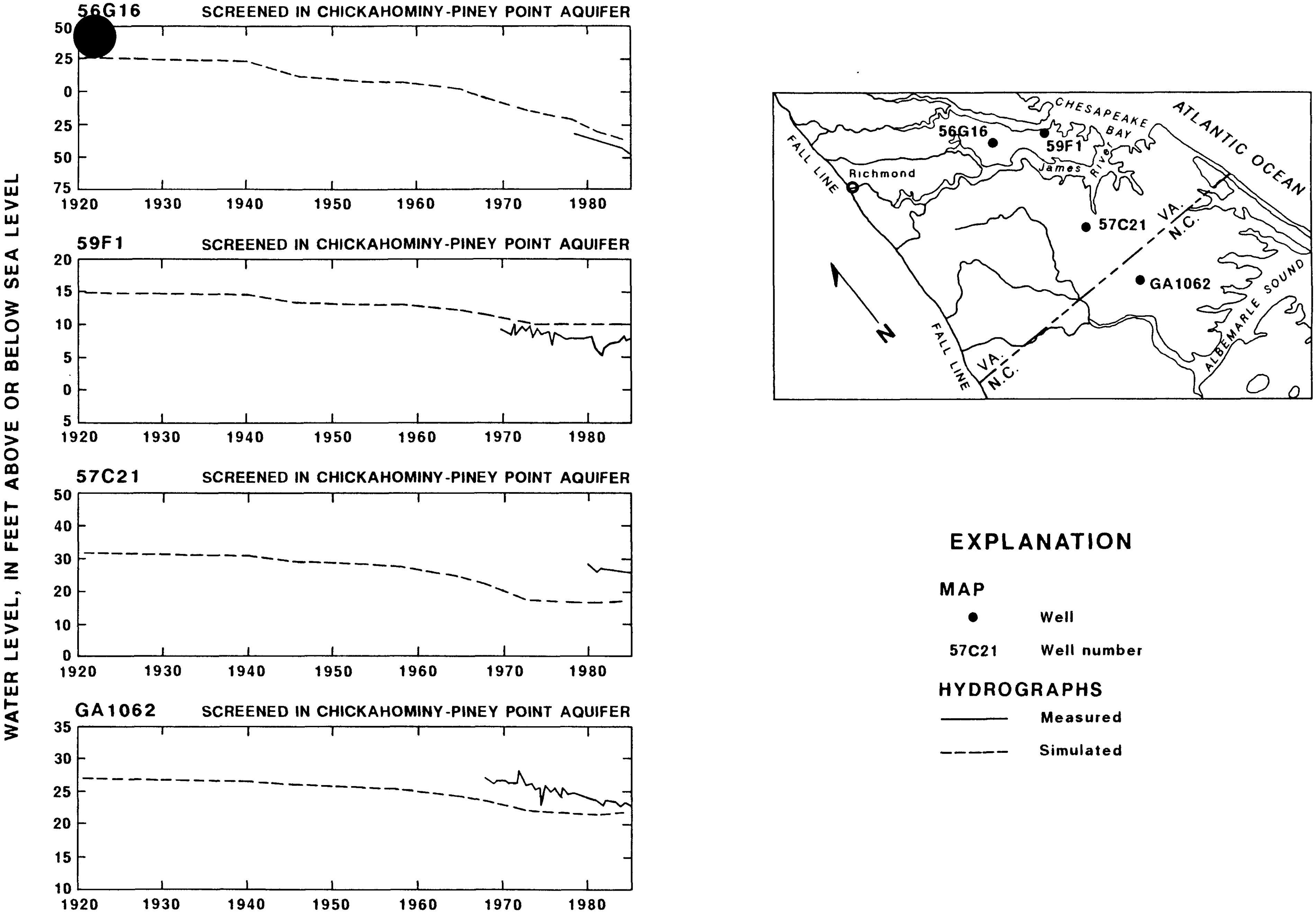

Figure 58.--Simulated and measured changes in water levels for the period of ground-water development in the Chickahominy-Piney Point aquifer.

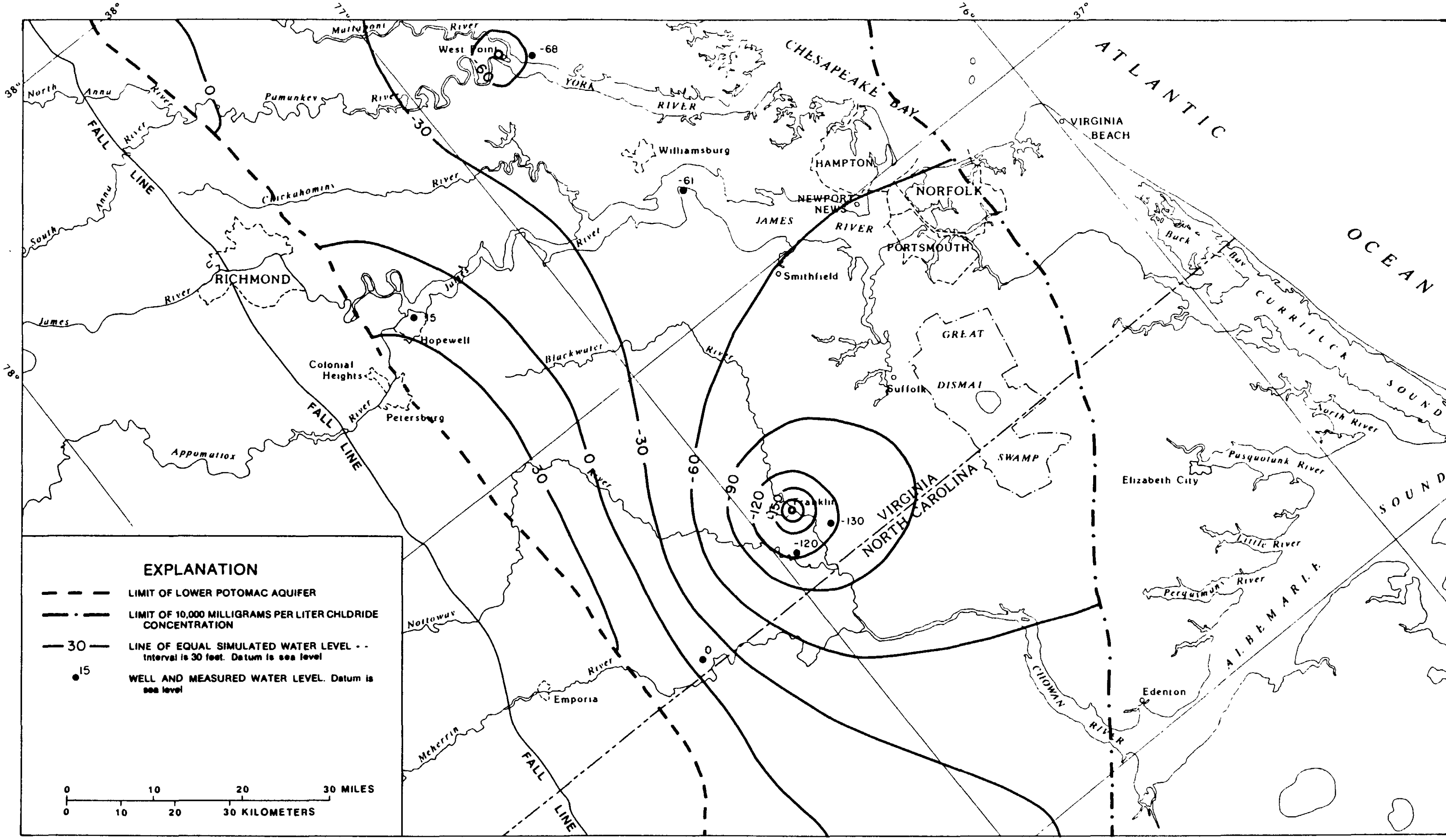

Figure 59.--Simulated and measured water levels in the lower Potomac aquifer, 1983.

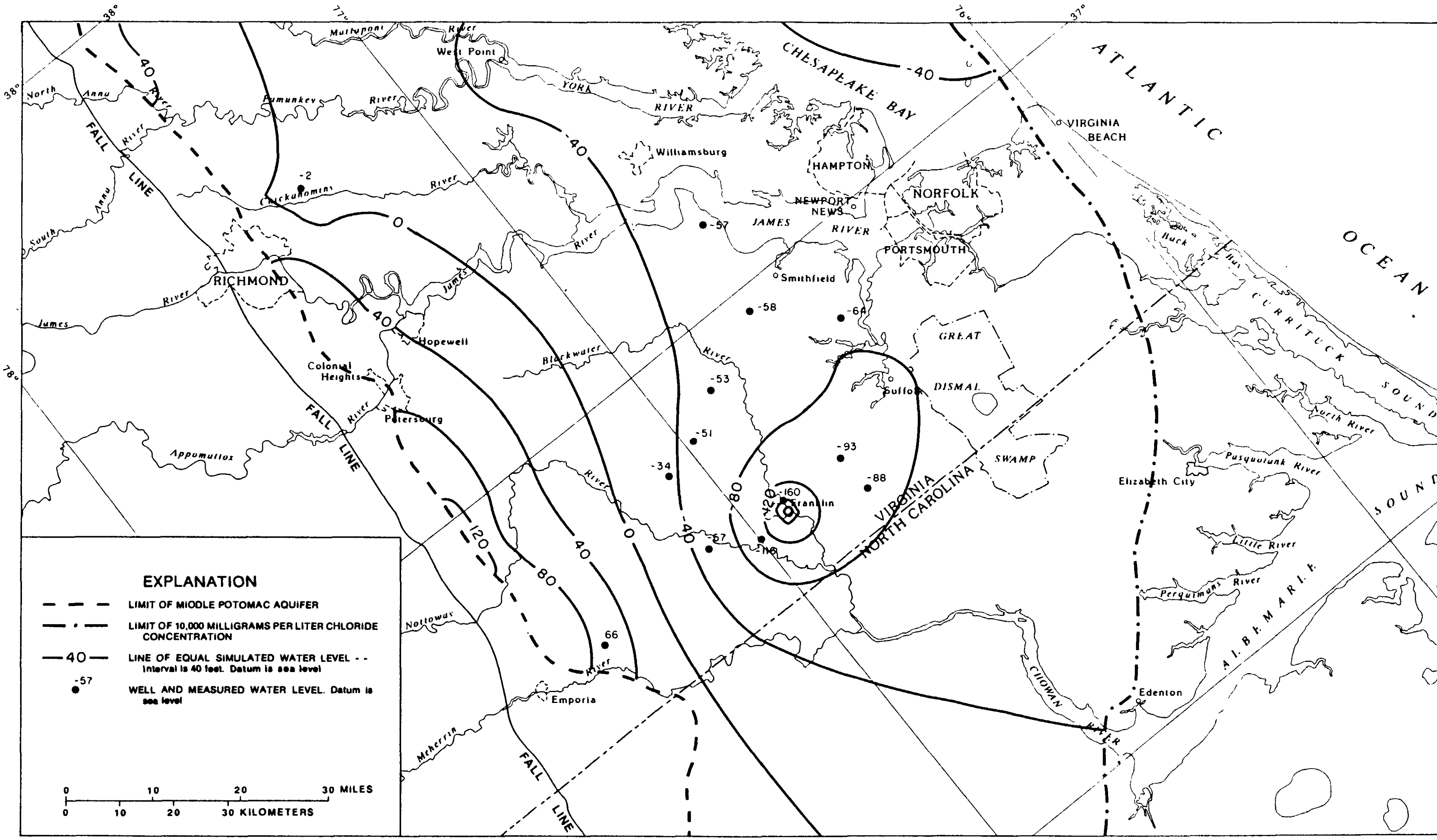

Figure 60.--Simulated and measured water levels in the middle Potomac aquifer, 1983.

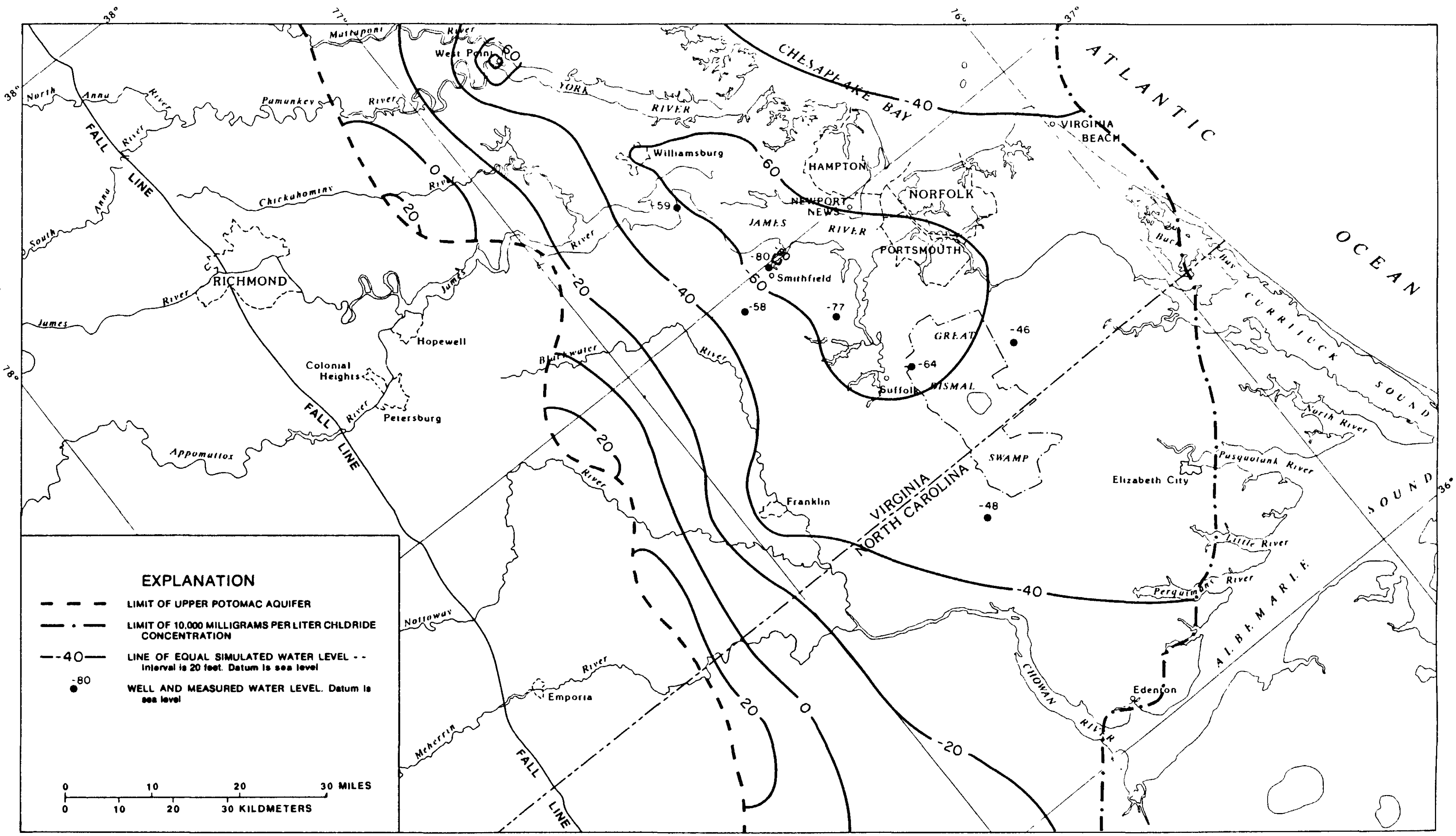

Figure 61.--Simulated and measured water levels in the upper Potomac aquifer, 1983.

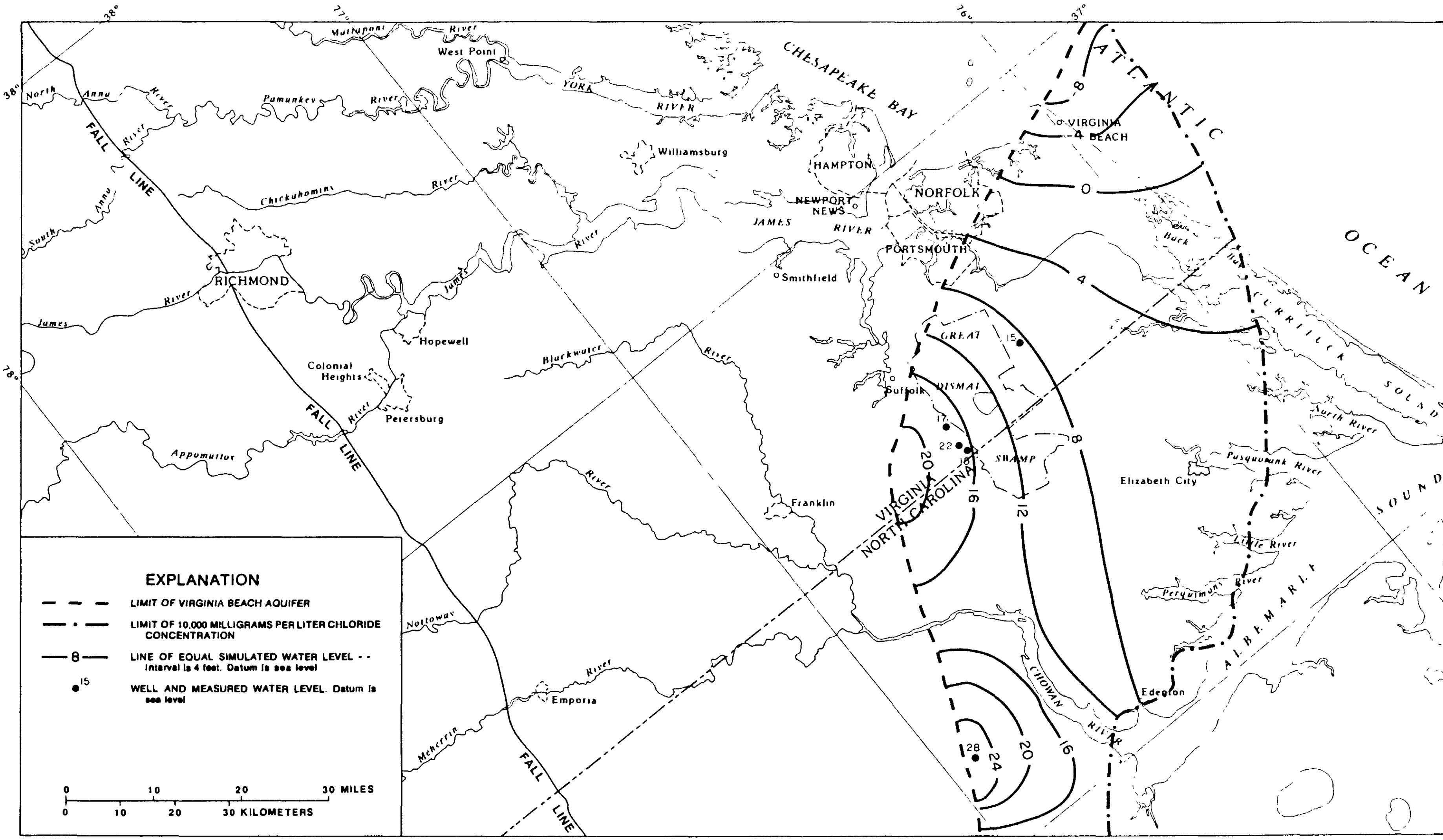

Figure 62.--Simulated and measured water levels in the Virginia Beach aquifer, 1983.

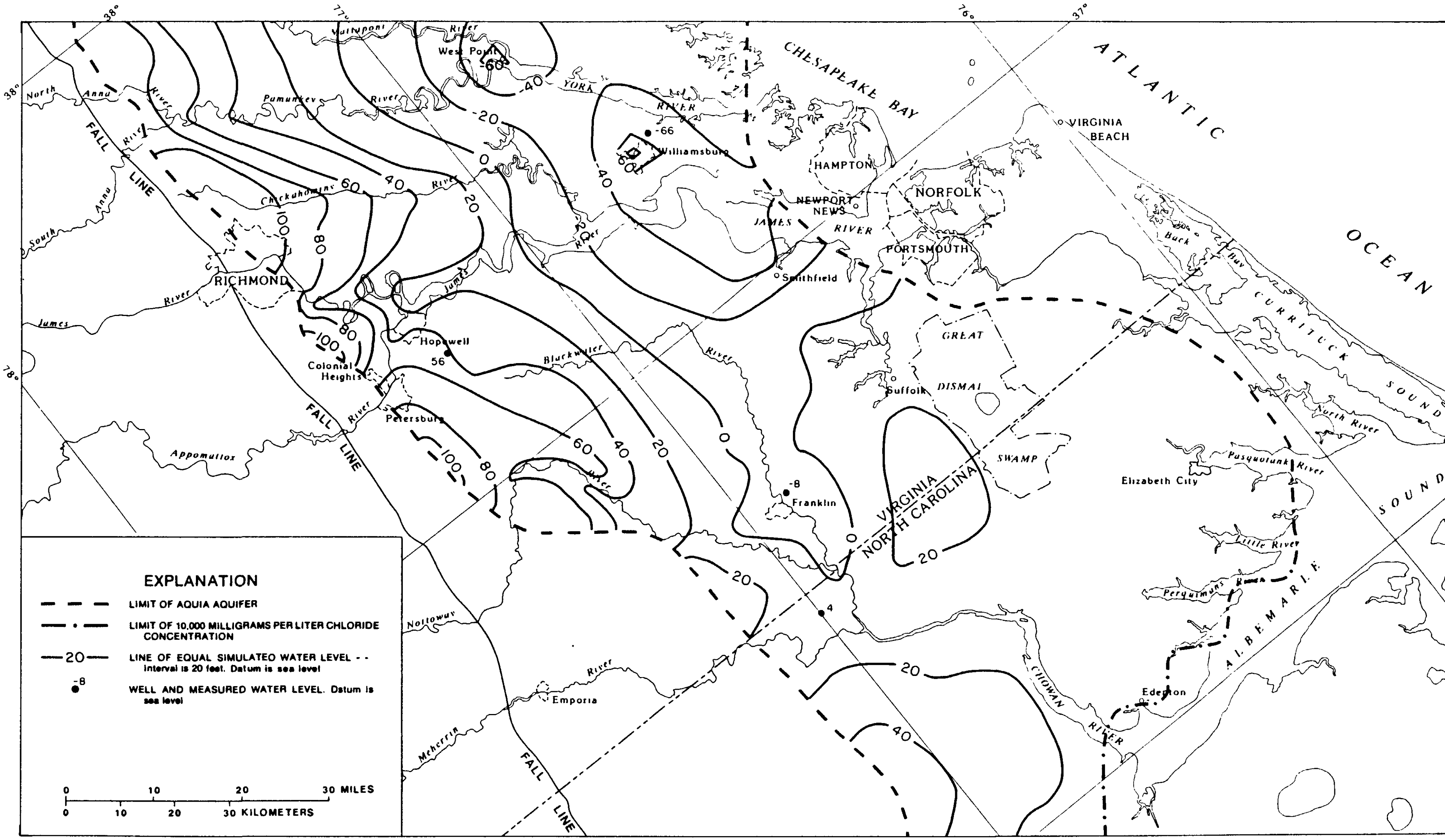

Figure 63.--Simulated and measured water levels in the Aquia aquifer, 1983.

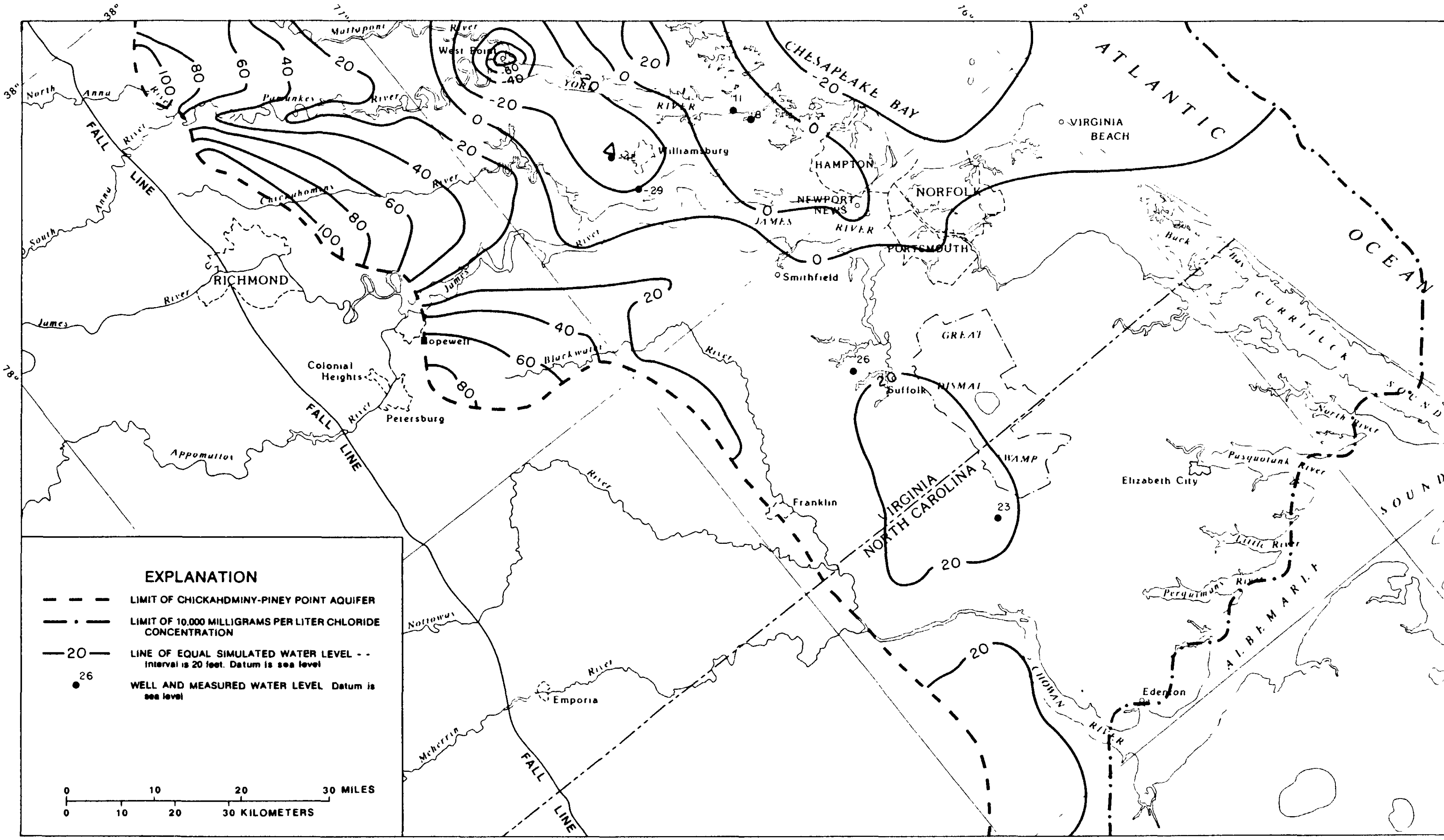

Figure 64.--Simulated and measured water levels in the Chickahominy-Piney Point aquifer, 1983.

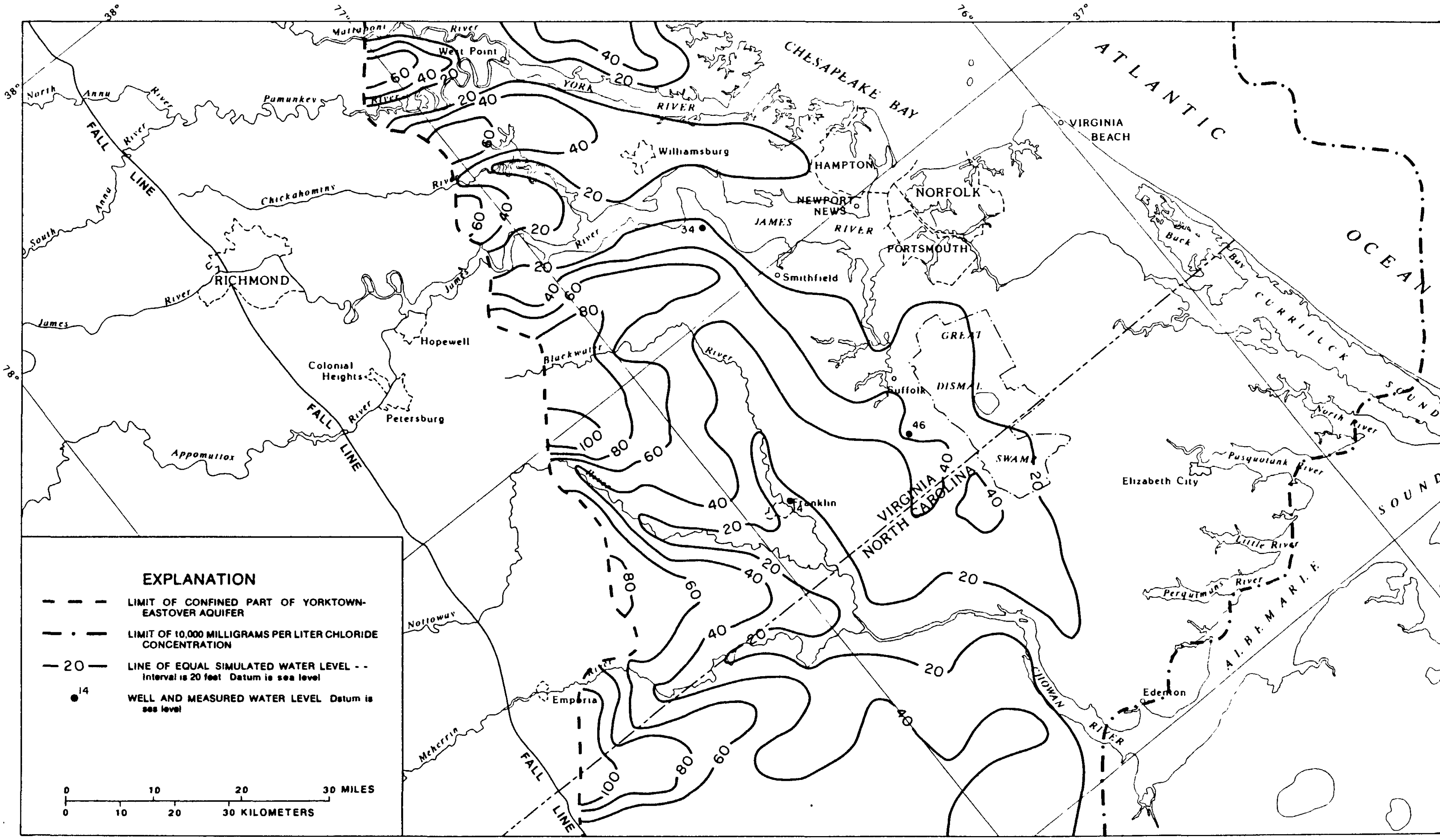

Figure 65.--Simulated and measured water levels in the Yorktown-Eastover aquifer, 1983.

Table 13.--Simulated maximum water-level decline since prepumping conditions and locations of maximum decline for individual aquifers, 1983

[Values in feet]

Aquifer	Maximum water-level decline	Location of maximum water-level decline
Yorktown-Eastover	17	Fall Line
Chickahominy-Piney Point	144	West Point
Aquia	130	Williamsburg
Virginia Beach	21	Virginia Beach
Upper Potomac	134	West Point
Middle Potomac	262	Franklin
Lower Potomac	275	Franklin

aquifers. Greater than a 100-foot decline occurred in the West Point and Williamsburg areas in the Aquia aquifer. The Chickahominy-Piney Point aquifer also was affected in the West Point area (greater than 140-foot decline) and along Chesapeake Bay (greater than 20-foot decline). Decline greater than 10 feet occurred in areas in the Yorktown-Eastover aquifer along the Fall Line. Minimal water-level decline (1-3 feet) occurred throughout the remainder of the Yorktown-Eastover aquifer.

Simulated water-level maps were compared to maps delineating tops of confined aquifers to identify areas where water levels were approaching the top of an aquifer. A decline in water level below the top of a confined aquifer would induce unconfined (water-table) conditions and result in dewatering of the aquifer. Dewatering could cause compaction of aquifer sediment and contribute to subsidence in the area. [Compaction of sediment in the system historically has been minimal on the basis of data collected at two subsidence research stations in Suffolk and Franklin (D.C. Hayes, U.S. Geological Survey, written commun., 1987).] Water levels were well above the top of the aquifers throughout most of the model area. One exception occurred in the Chickahominy-Piney Point aquifer near the town of West Point where water levels were within 100 feet of the top of the aquifer.

Simulated ground-water budgets were evaluated for all pumping periods. The modeled values presented in the text, figures, and tables are not intended to imply accuracy to the precision shown. Water-budget sources include recharge from precipitation, lateral inflow across the northern and southern model boundaries, water released from aquifer storage, and surface-water infiltration to ground water. Water-budget discharges include pumpage, lateral outflow, water taken into aquifer storage, and ground-water discharge to surface water. Lateral inflow and outflow across northern and southern model boundaries are summarized for each aquifer in table 9. As indicated in the table, lateral inflow generally increased and lateral outflow decreased with each pumping period. Exceptions to this trend were caused by pumpage outside the model area.

The remaining water-budget components (water released from or taken into storage, ground-water discharge to surface water, and infiltration from surface water) are summarized in table 14 for each pumping period. The maximum amount of water released from aquifer storage (approximately 5.9 Mgal/d) occurred in the seventh pumping period (1965-68) when a significant increase in pumpage occurred (table 14a). The maximum amount of water taken into aquifer storage occurred in the final pumping period (approximately 1.0 Mgal/d) because of stabilization of pumpage. Water-budget analysis demonstrates that water released from aquifer storage was minimal at the end of the model simulation (approximately 0.4 Mgal/d), suggesting that steady-state conditions were being approached. Under these near steady-state conditions, water pumped from the confined aquifers was primarily replaced by increased ground-water flow from the water-table aquifer to the confined system. This, in turn, resulted in reduced ground-water discharge to surface water from the water-table aquifer (table 14b). Discharge to the surface was reduced mostly in incised stream valleys in the western part of the model area, in areas of major pumpage centers such as Franklin and West Point, and in areas of pumpage centers in the east that penetrate the upper confined aquifer (Yorktown-Eastover aquifer). Figure 66 shows areas where discharge to surface water was reduced by more than 0.25 in/yr. Reduced discharge to surface water as calculated in this regional analysis is negligible relative to total quantity of surface-water flow. However, a more refined modeling analysis, involving finer grid spacing and shorter time time intervals, may indicate local problems with surface-water losses, especially under dry or drought conditions.

Pumpage from the confined system also induced some movement of surface water into the ground-water system. Induced infiltration of surface water into the ground-water system began in the fifth pumping period (1953-57) and continued to the eleventh pumping period (table 14c). The area of surface-water infiltration was about 77 mi^2 in the fifth pumping period and was approximately 533 mi^2 in the final pumping period. It primarily occurred in the Atlantic Ocean and Chesapeake Bay and its major tributaries (fig. 66). The surface water generally is saline and has the potential for degrading the water quality of underlying aquifers; however, this water entered the ground-water system in areas generally not used for freshwater supply.

The 1983 simulated ground-water budget of the multiaquifer system is illustrated in figure 67 and summarized in table 10. The average areal recharge to the water-table aquifer was estimated to be the same as under prepumping conditions (about 4,780.8 Mgal/d). About 4,702.2 Mgal/d discharged to surface water--a decrease of 73.6 Mgal/d from prepumping conditions. Reduced discharge to the surface accounted for about 85 percent (73.6 of the 86.6 Mgal/d) of the pumpage in the final pumping period. Induced infiltration of surface water into the ground-water system accounted for approximately 0.9 percent or 0.8 of the 86.6 Mgal/d. The remaining pumpage was accounted for by (1) a decrease in lateral outflow across the boundaries of the model by approximately 2.6 Mgal/d, (2) an increase in lateral inflow of approximately 10.3 Mgal/d, and (3) water released from storage (approximately 0.4 Mgal/d). The water budget resulted in less than 0.03 percent error in mass balance (table 10).

Table 14a.--Simulated amounts of water released from or taken into aquifer storage, 1891-1983

[Modeled values, in million gallons per day, are reported to hundredths and are not intended to imply accuracy to the precision shown]

	Pumping period										
	1 (1891-1920)	2 (1921-39)	3 (1940-46)	4 (1947-52)	5 (1953-57)	6 (1958-64)	7 (1965-68)	8 (1969-72)	9 (1973-77)	10 (1978-80)	11 (1981-83)
Water released from aquifer storage	0.08	0.13	1.94	1.27	1.79	2.42	5.94	5.25	2.22	1.38	0.38
Water taken into aquifer storage	.00	.00	.00	.00	.00	.00	.00	.00	.01	.03	1.02

Table 14b.--Simulated ground-water discharge to surface water, 1891-1983

[Modeled values, in million gallons per day, are reported to tenths and are not intended to imply accuracy to the precision shown]

Ground-water discharge to surface water	4,767.1	4,762.8	4,755.3	4,750.3	4,745.5	4,733.0	4,724.5	4,708.0	4,702.3	4,700.5	4,702.2
Change in ground-water discharge to surface water since prepumping conditions	8.7	13.0	20.5	25.5	30.3	42.8	51.3	67.8	73.5	75.3	73.6

Table 14c.--Simulated amounts and areas of induced surface-water infiltration to the ground-water system

[Mgal/d is million gallons per day; mi^2 is square miles. Modeled values are not intended to imply accuracy to the precision shown]

Surface-water infiltration to the ground-water system (Mgal/d)	0.00	0.00	0.00	0.00	0.01	0.17	0.34	0.74	0.85	0.89	0.82
Area of surface-water infiltration to the ground-water system (mi^2)	0	0	0	0	77	291	364	515	539	554	533

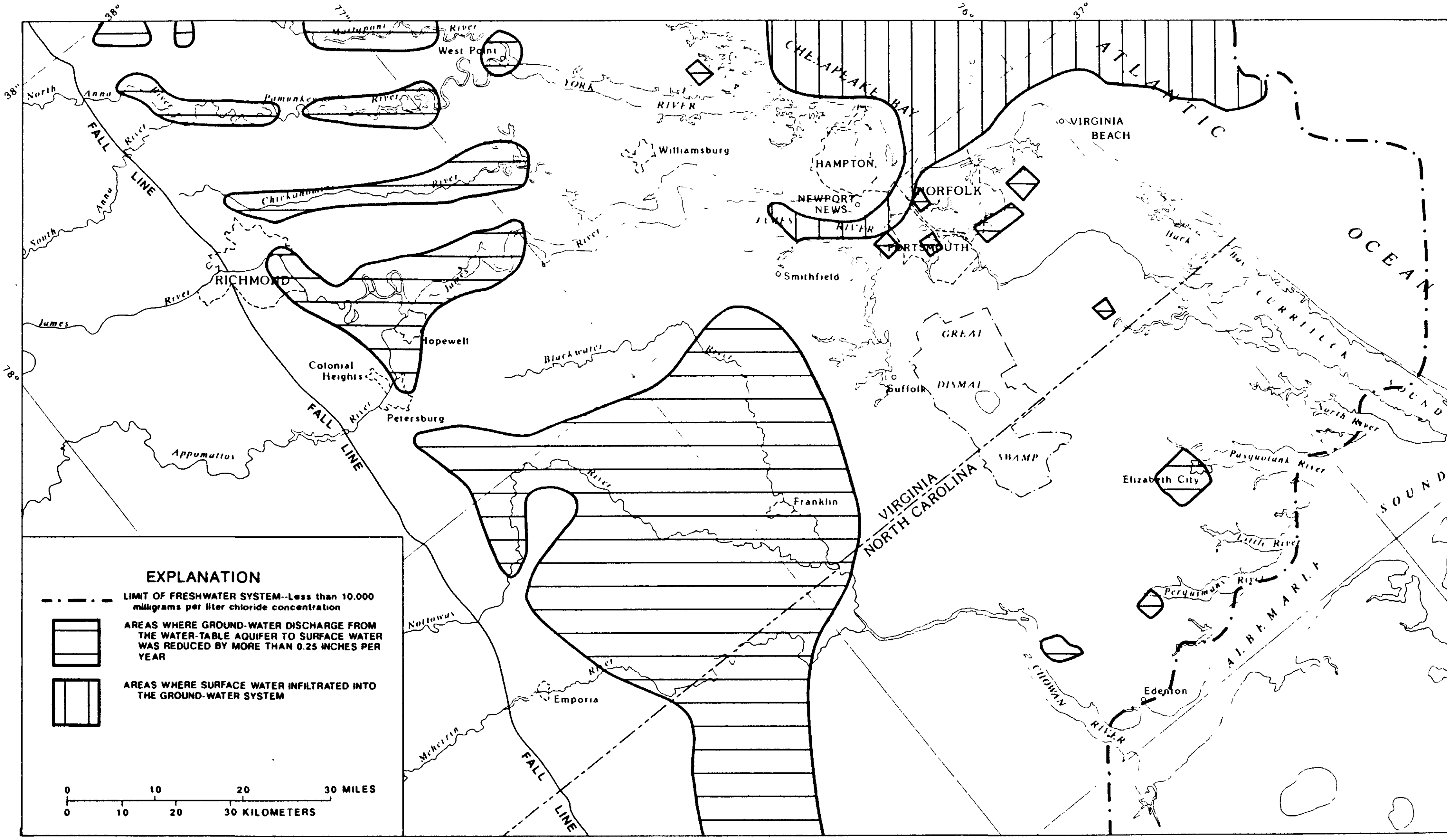

Figure 66.--Simulated areas of reduced discharge to surface water and induced surface-water infiltration, 1983.

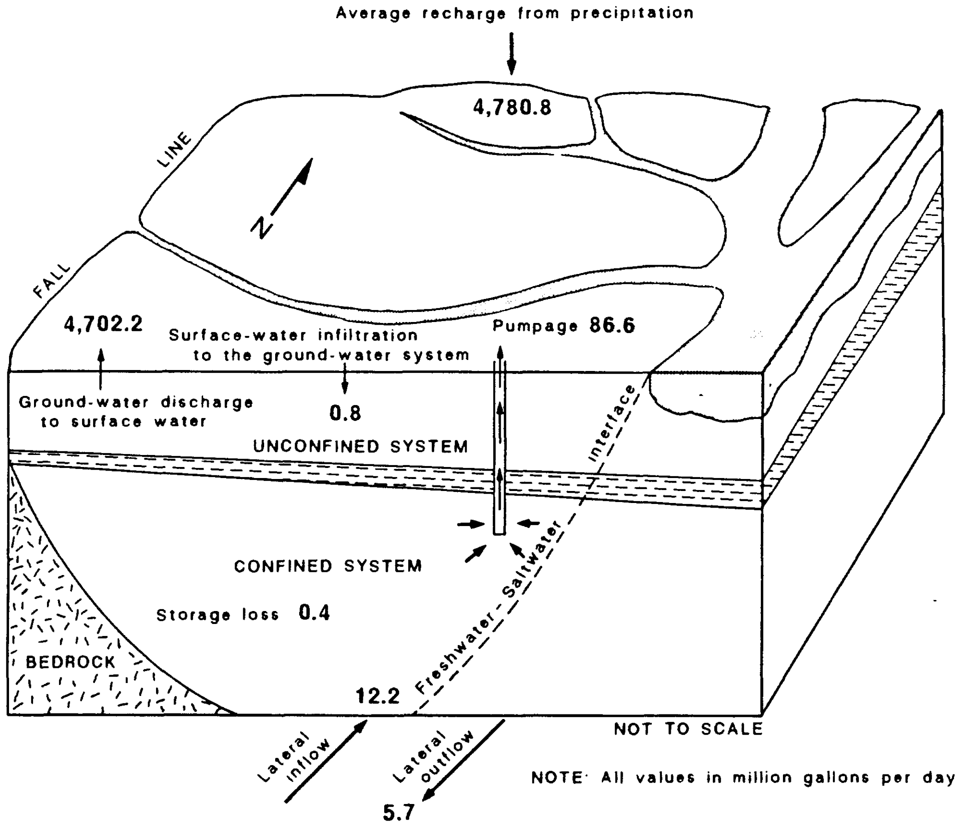

Figure 67.--Simulated ground-water budget, 1983.

Simulated areas of vertical recharge to and discharge from each confined aquifer through the overlying confining unit in 1983 are shown in figures 68 through 74 and table 11. Significant changes occurred since prepumping conditions--areas of recharge to the aquifers increased and areas of discharge decreased because of pumpage. Areas of recharge no longer were confined to the westernmost part of the model area as during prepumping conditions, but occurred throughout most of the model area. Discharge from the aquifers generally occurred under major pumpage centers and along major river valleys in the shallow aquifers (Aquia, Chickahominy-Piney Point, and Yorktown-Eastover). For example, figure 69 indicates that water discharged from the middle Potomac to the upper Potomac aquifer in the Smithfield, Williamsburg, and West Point areas; major pumpage occurred in these areas in the upper Potomac aquifer and induced flow from the lower aquifer.

Simulated vertical ground-water flow can be used to identify potential vertical saltwater contamination from deeper aquifers, assuming solute movement is consistent with fresh ground-water flow. For example, water-quality samples showing elevated chloride concentration that are located in a vertical discharge area would suggest potential movement of saltwater into the overlying aquifer.

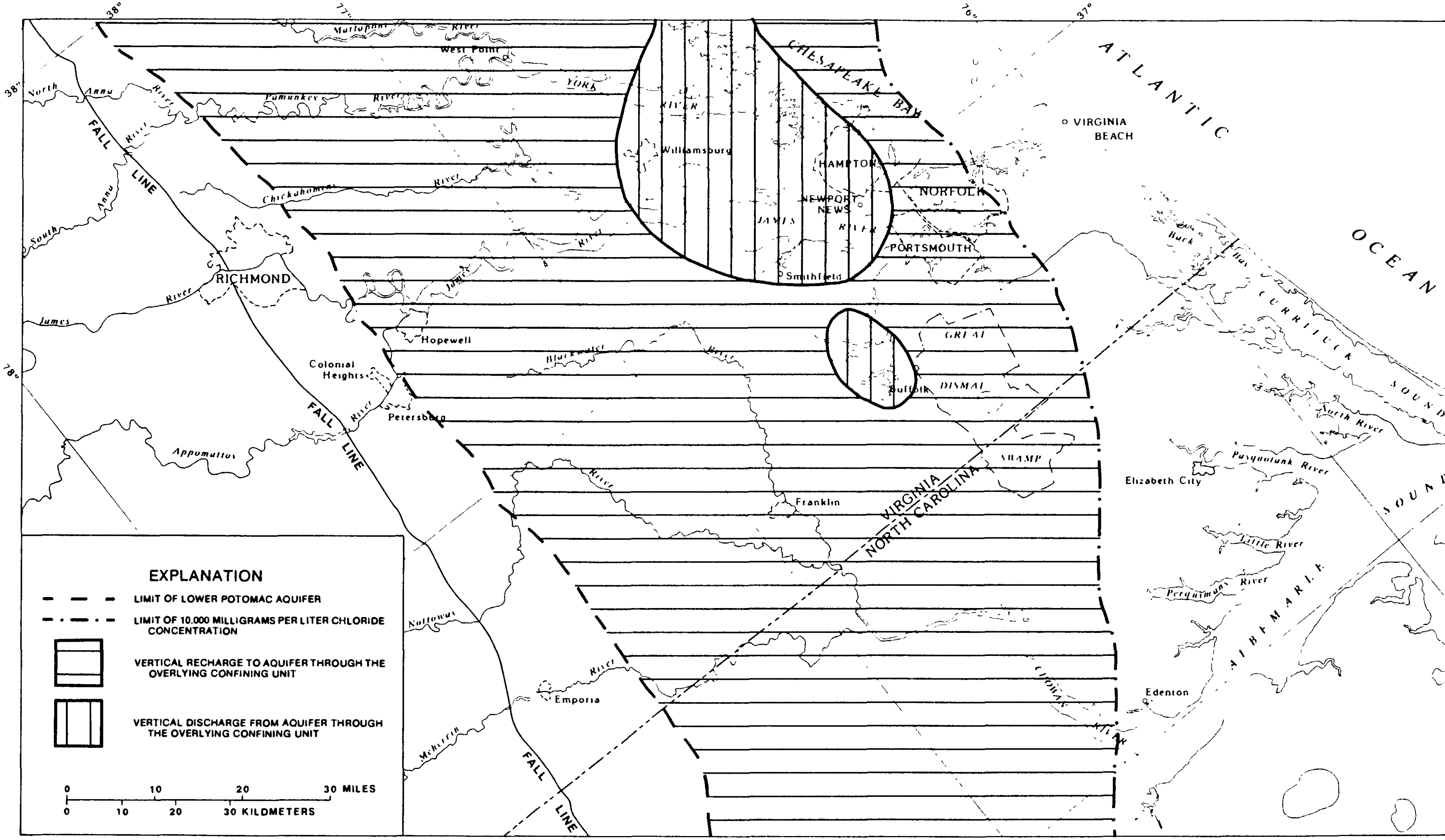

Figure 68.--Simulated areas of vertical recharge to and discharge from the lower Potomac aquifer through the overlying confining unit, 1983.

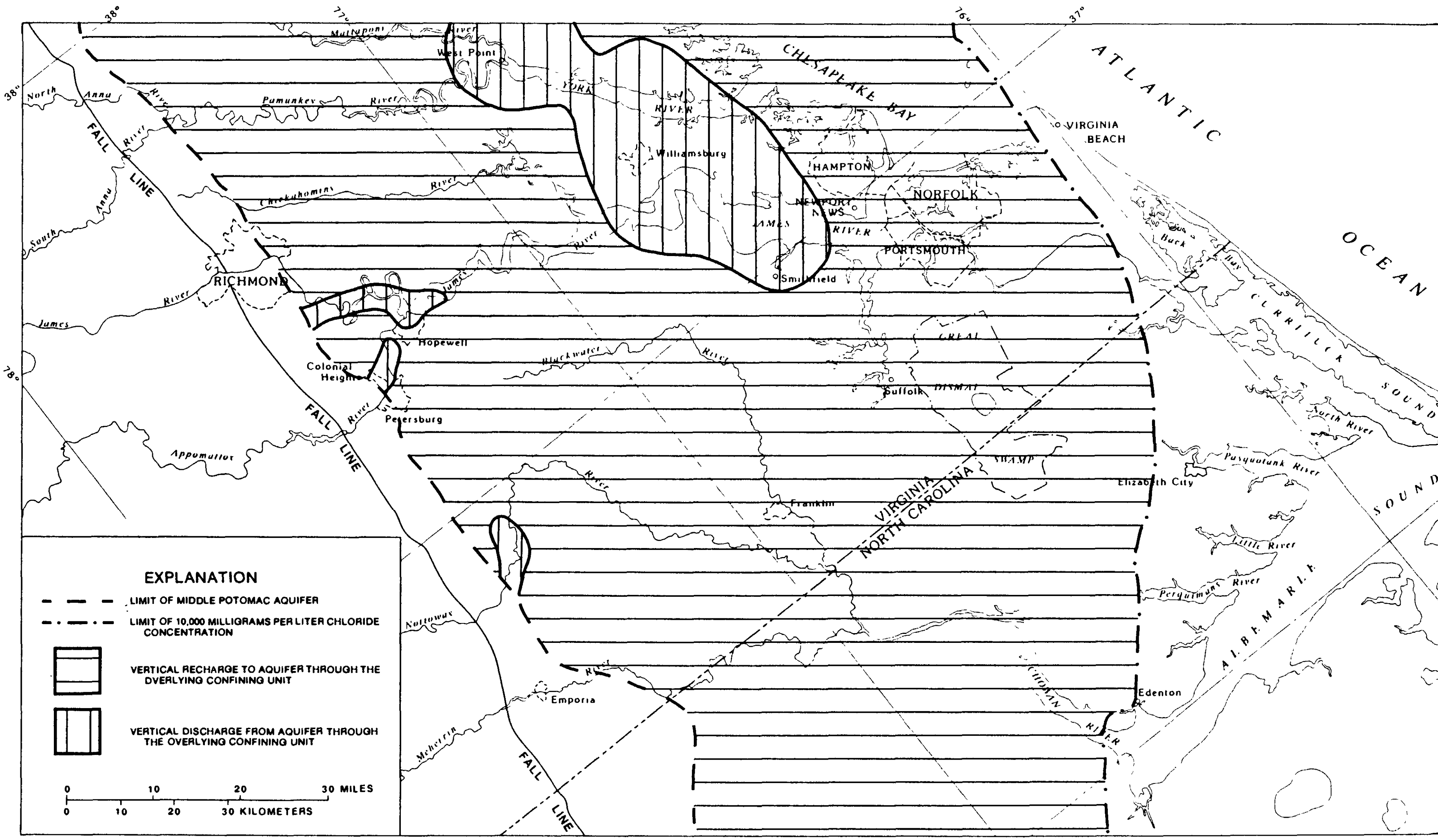

Figure 69.--Simulated areas of vertical recharge to and discharge from the middle Potomac aquifer through the overlying confining unit, 1983.

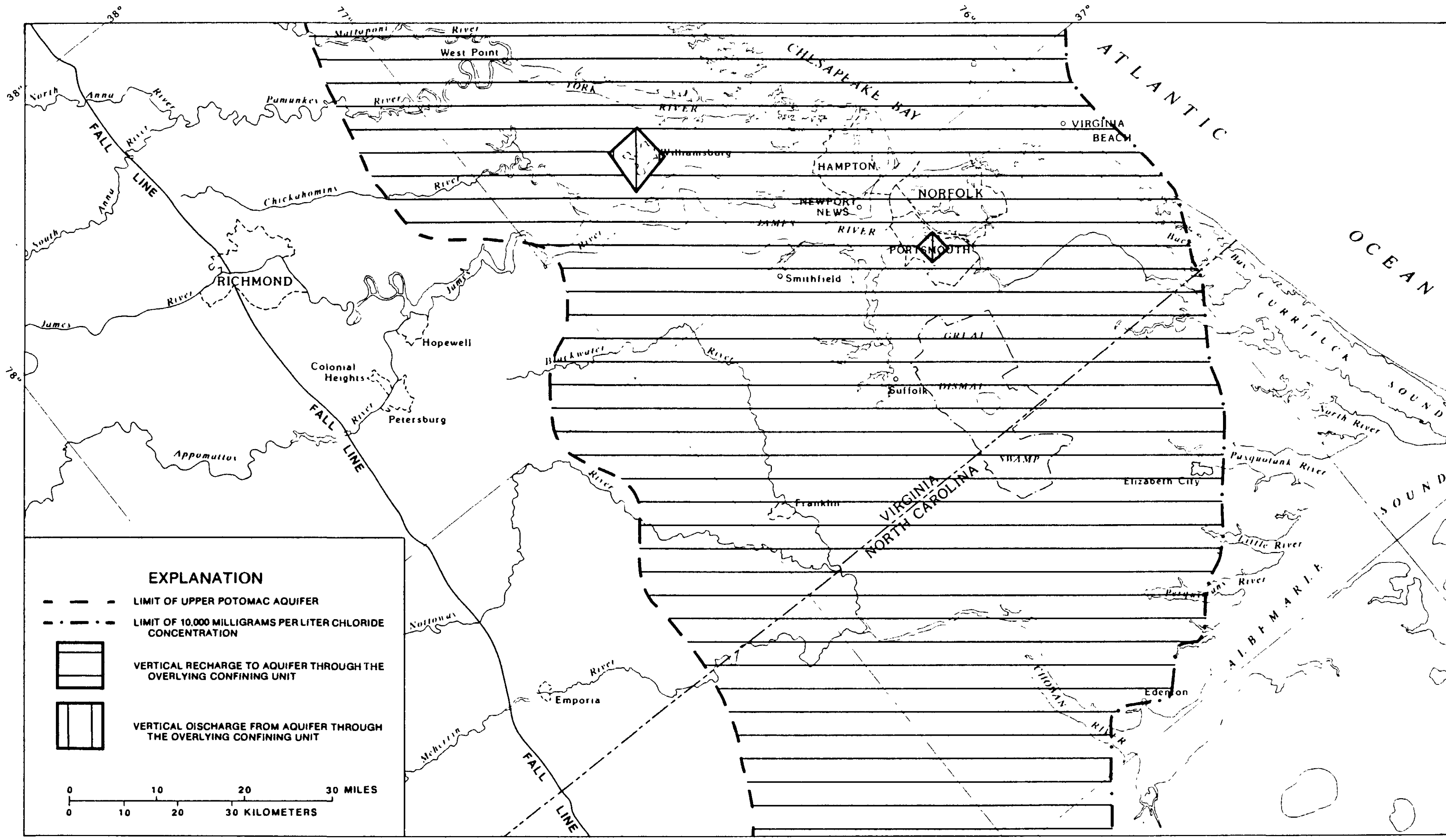

Figure 70.--Simulated areas of vertical recharge to and discharge from the upper Potomac aquifer through the overlying confining unit, 1983.

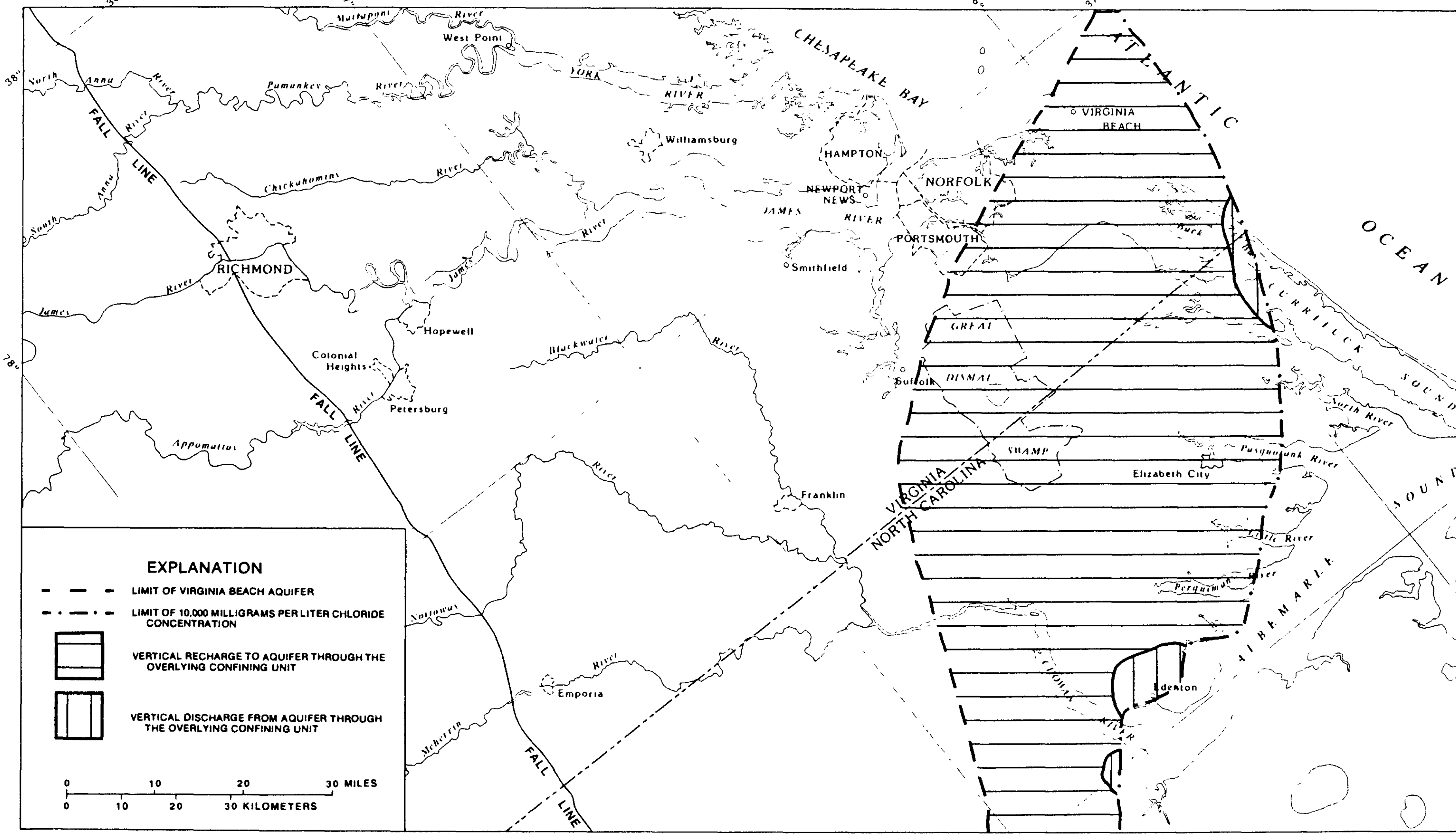

Figure 71.--Simulated areas of vertical recharge to and discharge from the Virginia Beach aquifer through the overlying confining unit, 1983.

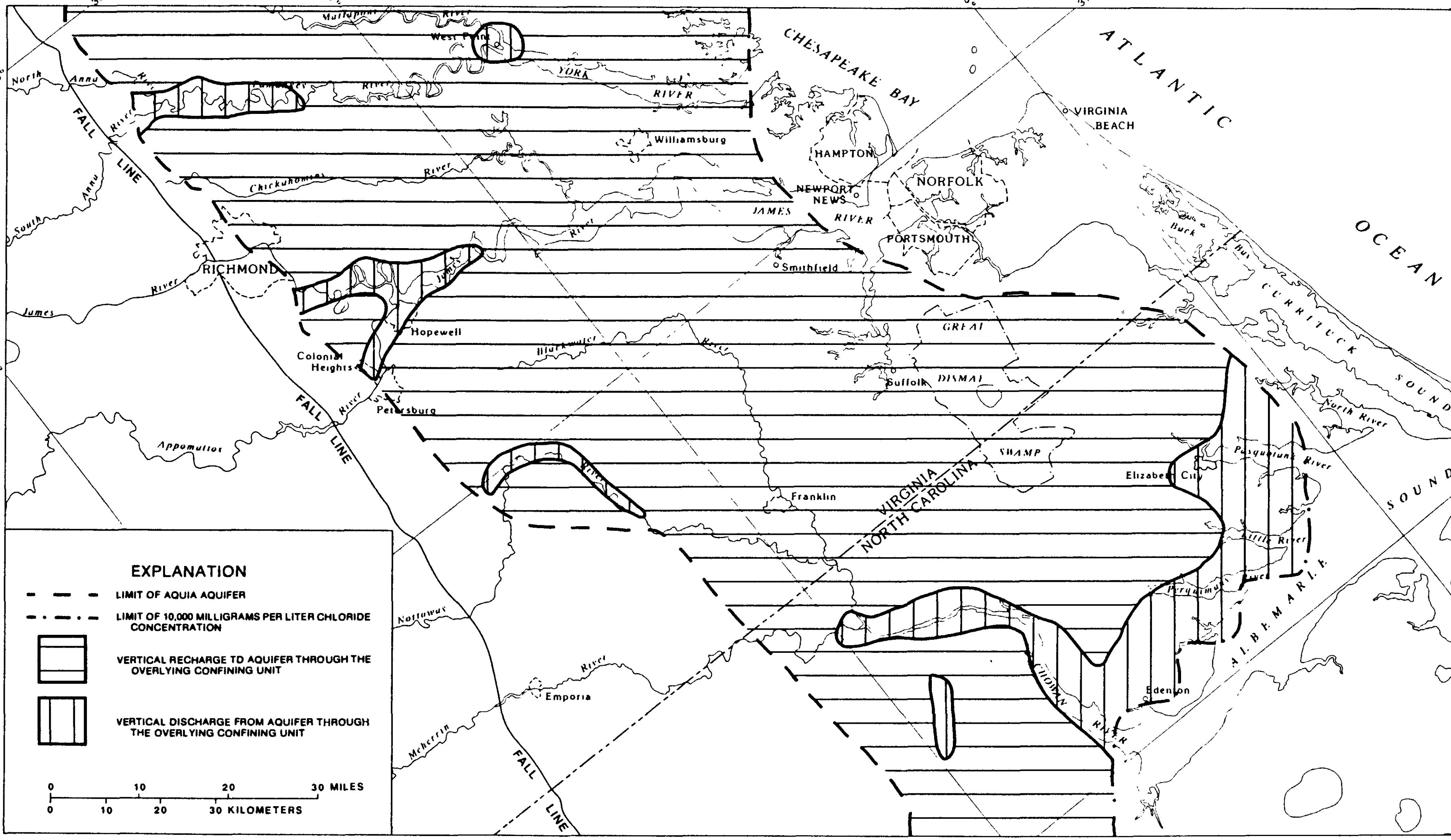

Figure 72.--Simulated areas of vertical recharge to and discharge from the Aquia aquifer through the overlying confining unit, 1983.

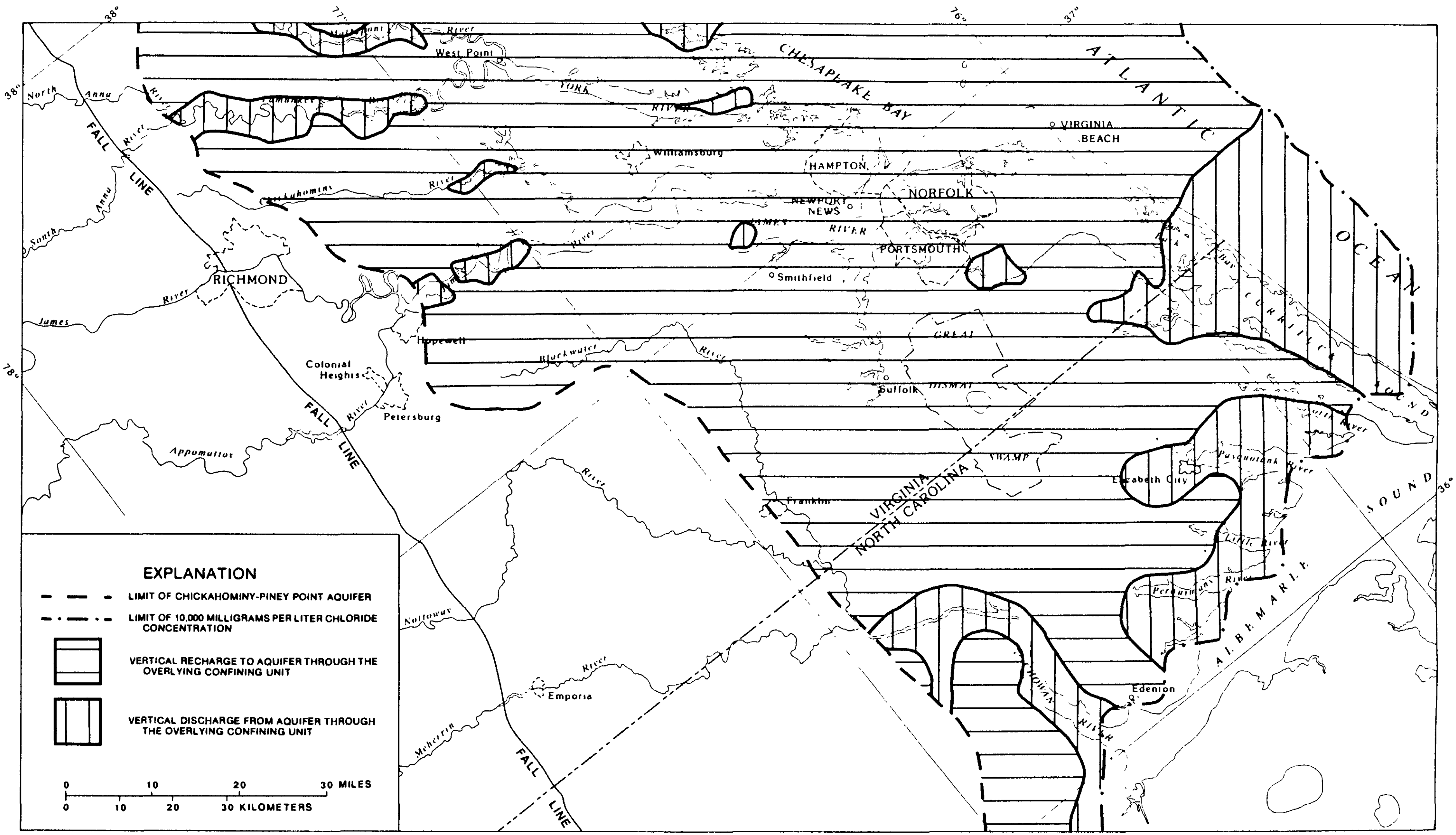

Figure 73.--Simulated areas of vertical recharge to and discharge from the Chickahominy-Piney Point aquifer through the overlying confining unit, 1983.

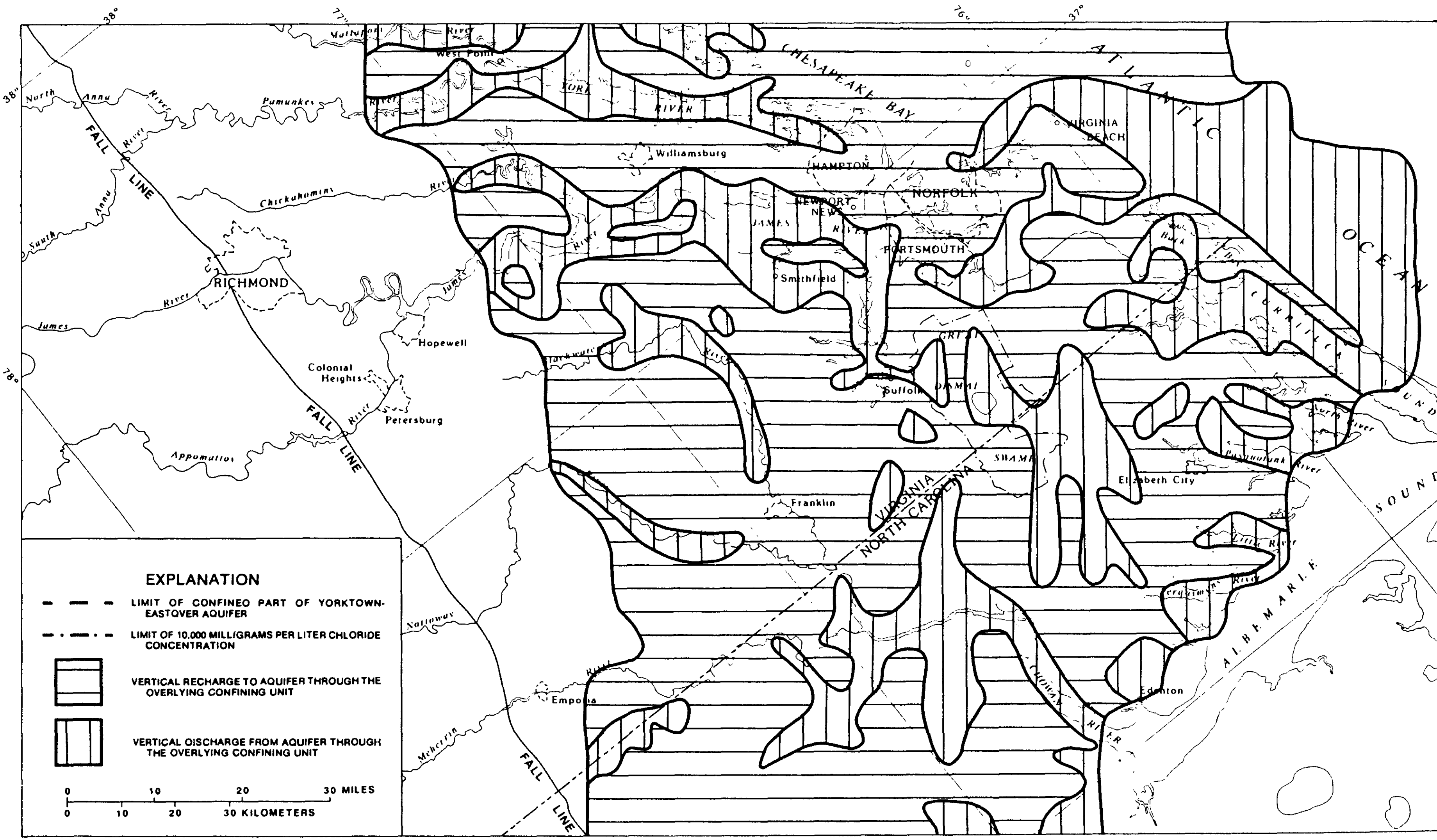

Figure 74.--Simulated areas of vertical recharge to and discharge from the Yorktown-Eastover aquifer through the overlying confining unit, 1983.

Amounts of simulated 1983 vertical recharge to and discharge from each confined aquifer through the overlying confining unit and change in vertical recharge and discharge since prepumping conditions are summarized in table 11. Vertical recharge to aquifers increased and vertical discharge from aquifers decreased, particularly to and from the Potomac aquifers in which most pumpage occurred. Water-budget analysis for individual aquifers indicates that net vertical flow into an aquifer through the overlying and underlying confining units (calculated from table 11) contributed the bulk of pumpage. Net flow across lateral boundaries (calculated from table 9) replaced most of the remaining pumpage. A small percentage of the water was replaced by aquifer storage. For example, net vertical flow into the middle Potomac aquifer in 1983 was 46.5 Mgal/d[2]. Net lateral flow was 2.8 Mgal/d[3]. Total net gain was 49.3 Mgal/d. Pumpage from the middle Potomac aquifer was 49.8 Mgal/d. The small difference was attributed to aquifer storage and roundoff error.

Application of the Model as a Predictive Tool

The use of the transient model as a predictive tool is based on the premise that if historic conditions can be approximated then so can future conditions. It is assumed that the model conceptualization is an accurate representation of the flow system and that the model can be used to project the response of the ground-water flow system to potential injection or increased pumpage in southeastern Virginia. Seven scenarios were designed in cooperation with VWCB. The scenarios were not designed to represent future injection or pumpage rates accurately, but rather to provide insight into regional water levels and ground-water flow. The scenarios also provide examples of the ability of the model to assess the continued reliability of ground water as a resource in southeastern Virginia.

Steady-State-Model Simulations of Increased Pumpage from Emergency-Supply and Industrial Wells

Two pumpage scenarios were run using a steady-state solution to the ground-water flow equation. A steady-state solution means that no change in storage or water levels occurs over time. The steady-state solution, therefore, provided maximum water-level decline that would result from increased pumpage. Both scenarios represented an increase in pumpage above average pumpage conditions in the final pumping period (1981-83).

Scenario 1

Scenario 1 involved increased pumpage of 54.4 Mgal/d (141.0 Mgal/d total) resulting from continuous use of 18 emergency-supply wells, generally used in times of drought or emergency. Approximately 86 percent of the additional pumpage would come from the middle Potomac aquifer (46.9 Mgal/d). The remaining 7.5 Mgal/d would be pumped from the lower Potomac aquifer (1.8 Mgal/d or 3 per

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[2] Calculated from values in table 11b as follows: 64.6 - 5.5 = 59.1 Mgal/d net gain from overlying unit; 13.0 - 0.4 = 12.6 Mgal/d net loss to underlying unit; 59.1 - 12.6 = 46.5 Mgal/d total net gain.

[3] Calculated from values in table 9 as follows: 4.33 - 1.56 = 2.77 Mgal/d net gain across lateral boundaries.

cent) and the upper Potomac aquifer (5.7 Mgal/d or 11 percent). Locations of the emergency-supply wells are shown in figure 75. The wells primarily are located in or near the city of Suffolk. Latitudes, longitudes, State identification codes, design capacity of the wells, and aquifers penetrated by the wells are summarized in table 15.

Modeled water-level decline from simulated 1983 water levels in individual aquifers is shown in figures 76 through 82. Maximum water-level decline in individual aquifers is summarized in table 16. Maximum decline of approximately 204 feet would occur in the middle Potomac aquifer in the Suffolk area. Water-level decline greater than 40 feet would occur throughout most of the aquifer. Water-level decline greater than 20 feet also would occur throughout most of the lower and upper Potomac aquifers.

Although the pumpage would be from the Potomac aquifers, lowered water levels also would occur in the overlying aquifers. Greater than a 50-foot decline would occur in the Williamsburg and Smithfield areas and nearly a 20-foot decline would occur in the town of West Point and city of Franklin in the Aquia aquifer. As indicated in figure 80, the center of maximum water-level decline would not overlie the city of Suffolk as might be expected. This can be explained by relatively thick and impermeable confining-unit sediment separating the Aquia and upper Potomac aquifers in and east of the Suffolk area. The Chickahominy-Piney Point aquifer would be primarily affected along the coast and Chesapeake Bay where original confining-unit sediment was eroded and replaced with more permeable material, allowing for considerable downward flow from the aquifer to underlying units.

Contours of distances between modeled water levels and the tops of the middle and upper Potomac, Aquia, and Chickahominy-Piney Point aquifers are presented in figures 83 through 86. A decline in water level below the top of a confined aquifer would induce unconfined (water-table) conditions and result in dewatering of an aquifer and compaction of aquifer sediment. The contours are accurate only within 50 feet and should be interpreted for trends rather than absolute values. Water levels would be approximately 200 to 350 feet above the top of the middle Potomac aquifer in and near the city of Suffolk where maximum water-level decline would occur. In the same area, water levels would be between 150 and 250 feet above the tops of the upper Potomac and overlying Aquia and Chickahominy-Piney Point aquifers. Water levels would be between 0 and 100 feet above the top of the Chickahominy-Piney Point aquifer in the town of West Point and the top of the middle and upper Potomac, Aquia, and Chickahominy-Piney Point aquifers in and near the city of Franklin.

The modeled ground-water budget is illustrated in figure 87 and summarized in table 17. The modeled values are not intended to imply accuracy to the precision shown. Water-budget sources include recharge from precipitation, surface-water infiltration, and lateral inflow across northern and southern boundaries. Water-budget discharges include pumpage, lateral outflow, and discharge to surface water. Table 18 summarizes lateral flow across northern and southern model boundaries for individual aquifers. The average areal recharge to the water-table aquifer was estimated to be the same as in 1983 (4,780.8 Mgal/d). Of this recharge, about 4,659.4 Mgal/d would discharge to

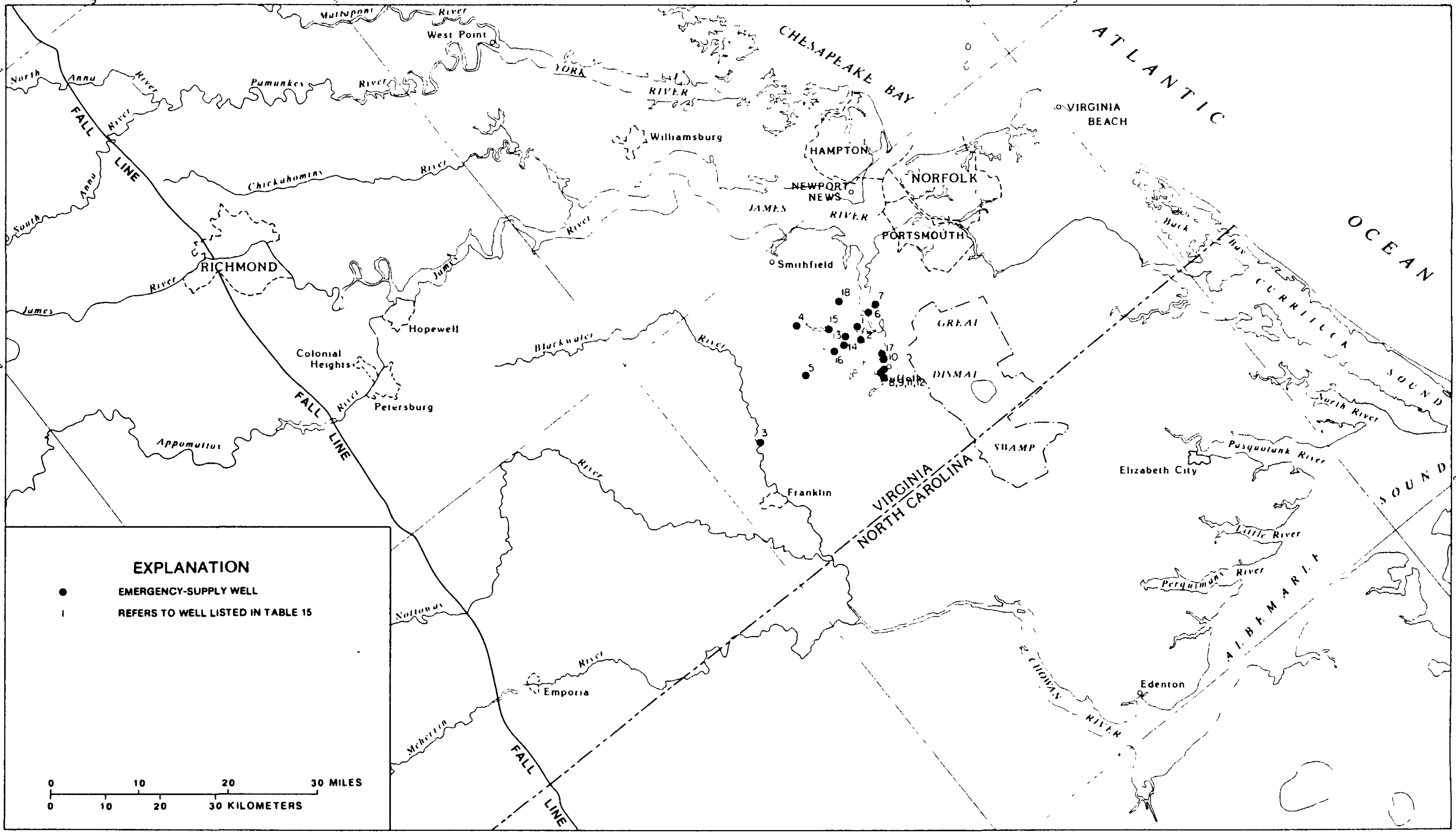


Figure 75.--Location of emergency-supply wells.

Table 15.--Emergency-supply wells simulated in scenario 1

[Mgal/d is million gallons per day]

Well name	Map number[a]	Virginia Water Control Board identification number	Latitude	Longitude	Design capacity (Mgal/d)	Aquifers tapped
Virginia Beach -- Everts	1	161-371	36 48 40	76 35 17	4.04	Middle Potomac
Virginia Beach -- Kings Fork	2	161-372	36 47 27	76 35 56	4.04	Middle Potomac
Virginia Beach -- Burdette	3	187-165	36 45 56	76 53 12	4.04	Lower and middle Potomac
Virginia Beach -- Courthouse	4	146-251	36 52 32	76 40 55	4.04	Middle Potomac
Virginia Beach -- Windsor	5	146-250	36 48 12	76 43 50	4.03	Middle Potomac
Driver #1	6	161-365	36 49 07	76 33 10	4.03	Middle and upper Potomac
Driver #2	7	161-366	36 49 17	76 31 49	4.03	Middle and upper Potomac
Portsmouth #1	8	161-264	36 43 48	76 36 05	2.02	Middle Potomac
Portsmouth #2	9	161-265	36 43 48	76 36 05	2.02	Middle and upper Potomac
Portsmouth #3	10	161-331	36 44 42	76 35 17	3.09	Middle Potomac
Portsmouth #4	11	161-396	36 43 47	76 36 32	3.02	Middle Potomac
Portsmouth #5	12	161-397	36 43 18	76 36 33	3.02	Middle and upper Potomac
Norfolk #1	13	161-200	36 48 37	76 37 09	3.89	Middle and upper Potomac
Norfolk #2	14	161-201	36 48 08	76 37 55	4.32	Middle and upper Potomac
Norfolk #3	15	161-202	36 50 13	76 38 07	3.89	Lower, middle, and upper Potomac
Norfolk #4	16	161-203	36 48 12	76 39 21	3.89	Middle and upper Potomac
Suffolk Farm	17	161-330	36 45 03	76 35 05	3.02	Middle Potomac
Suffolk-Fluoride Well	18	161-380	36 51 47	76 35 05	.72	Middle and upper Potomac

[a]Locations shown on figure 75.

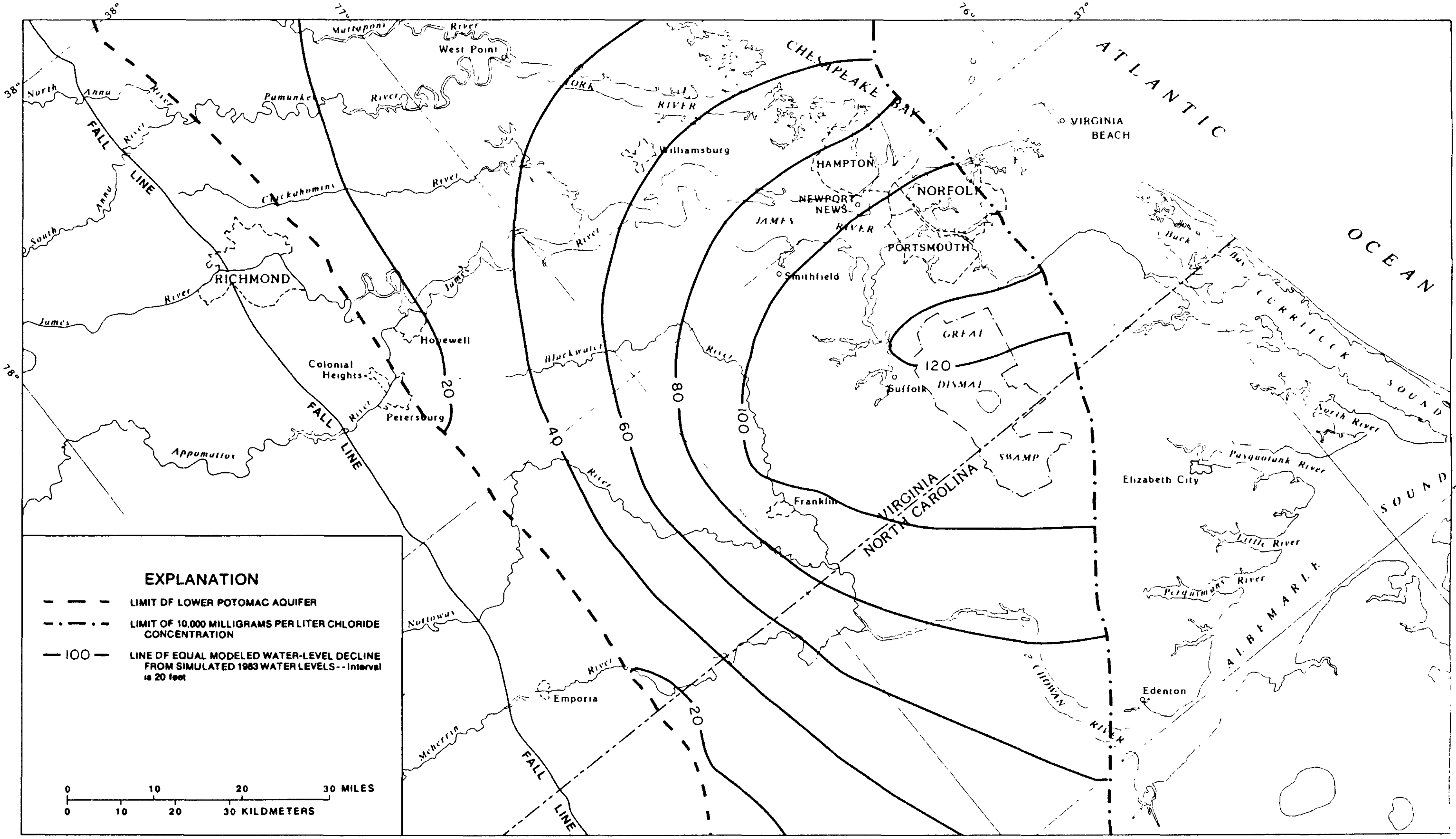


Figure 76.--Modeled water-level decline from simulated 1983 water levels in the lower Potomac aquifer, scenario 1.

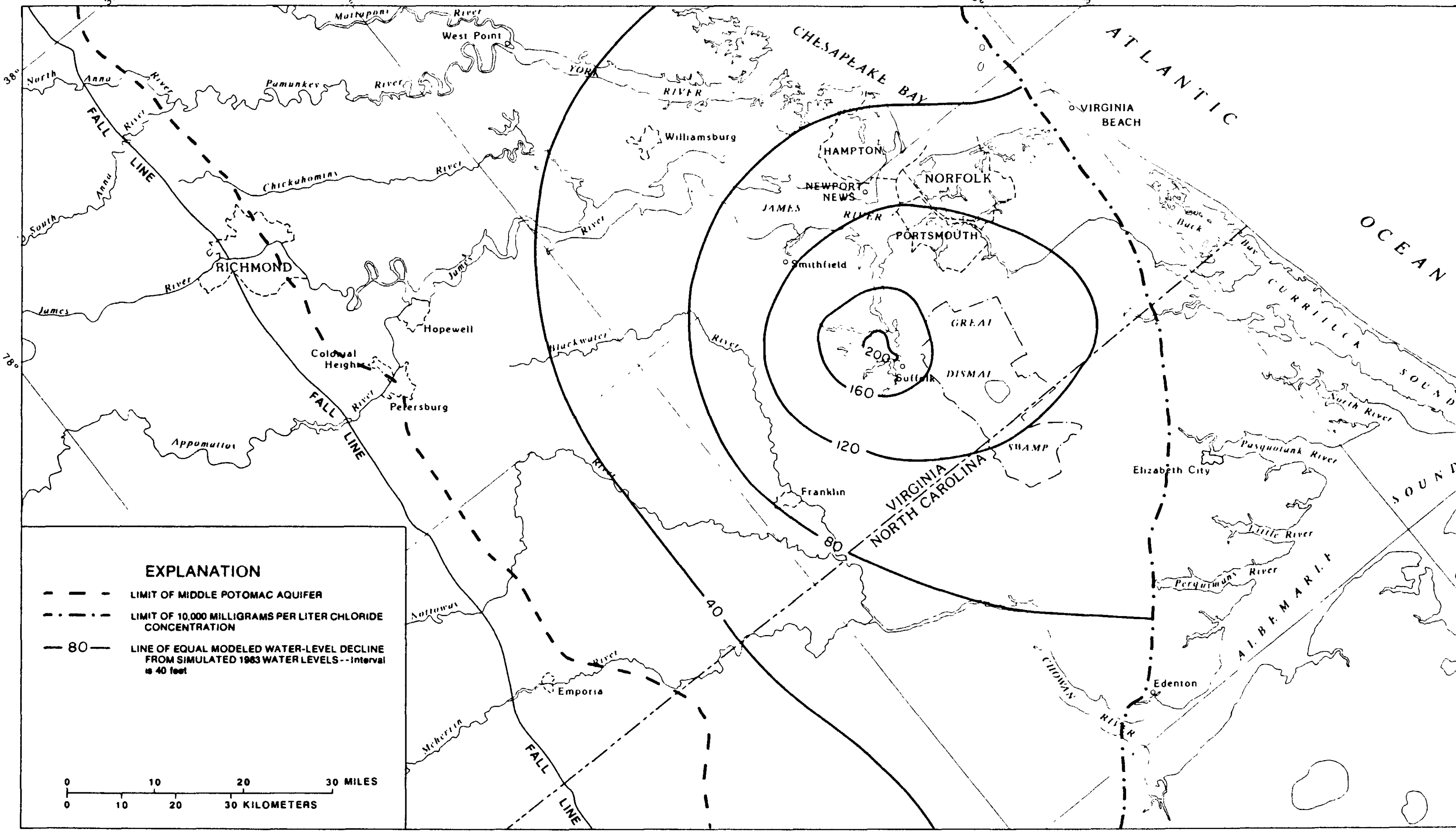


Figure 77.--Modeled water-level decline from simulated 1983 water levels in the middle Potomac aquifer, scenario 1.

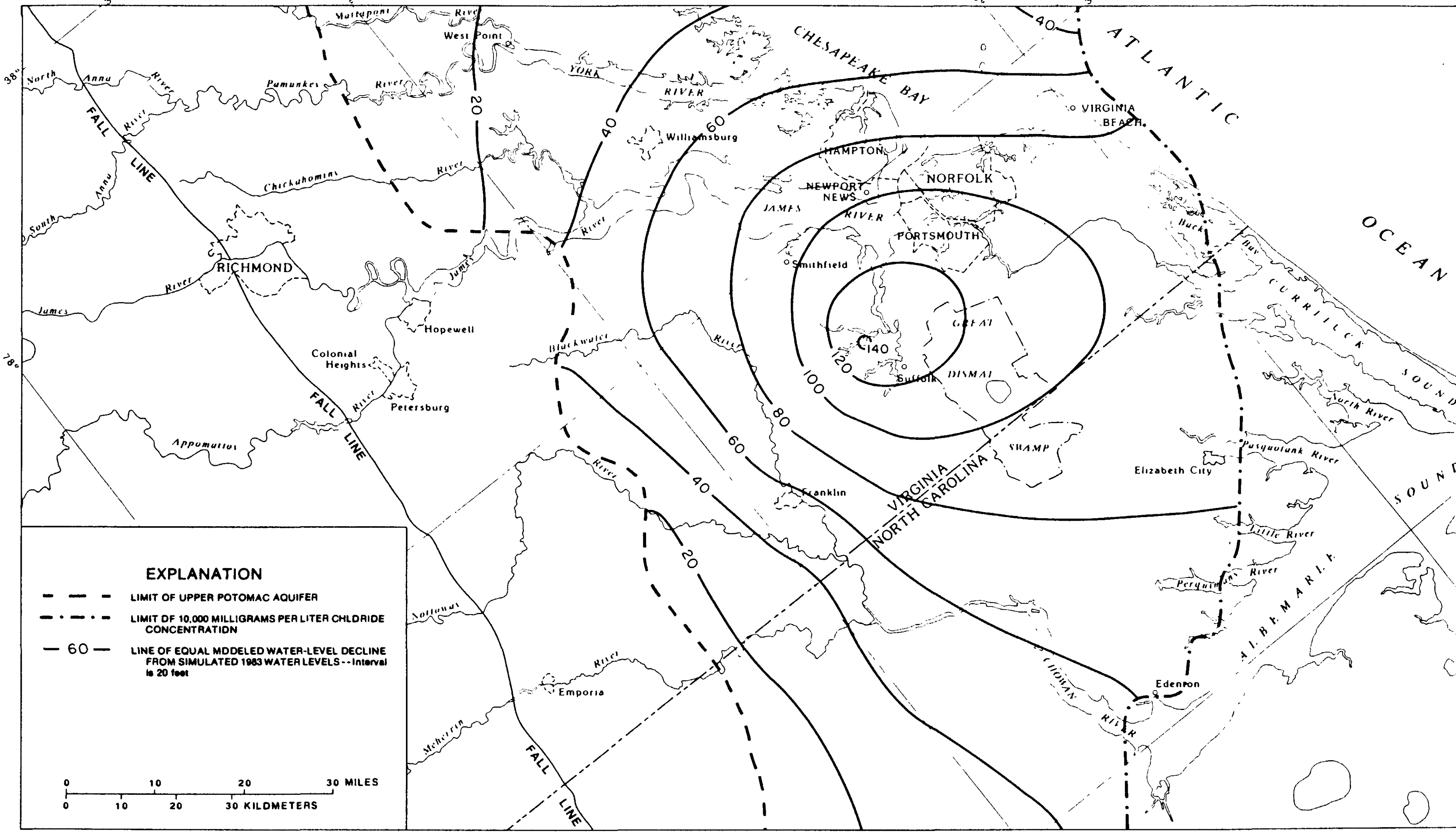


Figure 78.--Modeled water-level decline from simulated 1983 water levels in the upper Potomac aquifer, scenario

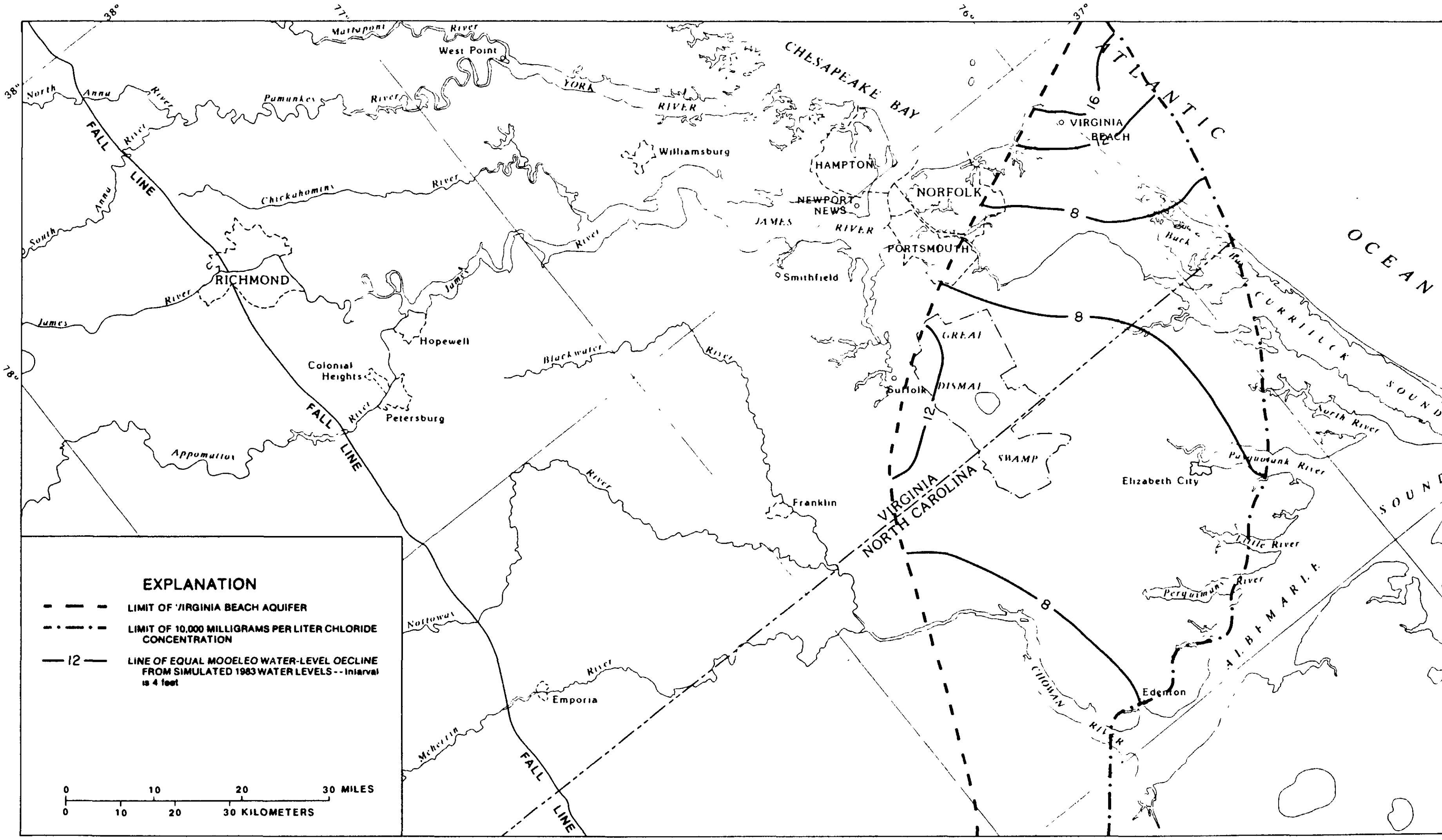


Figure 79.--Modeled water-level decline from simulated 1983 water levels in the Virginia Beach aquifer, scenario 1.

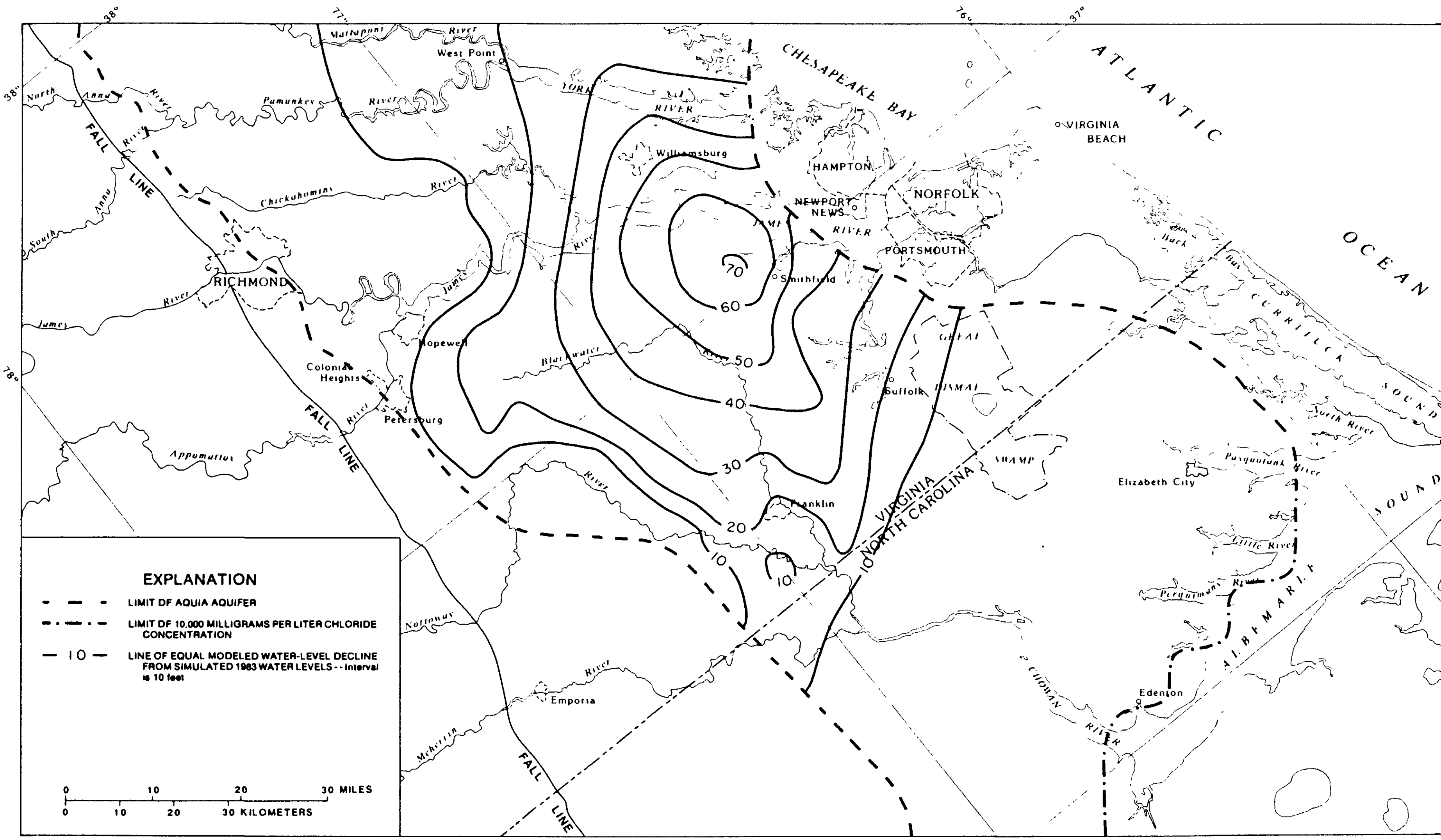


Figure 80.--Modeled water-level decline from simulated 1983 water levels in the Aquia aquifer, scenario 1.

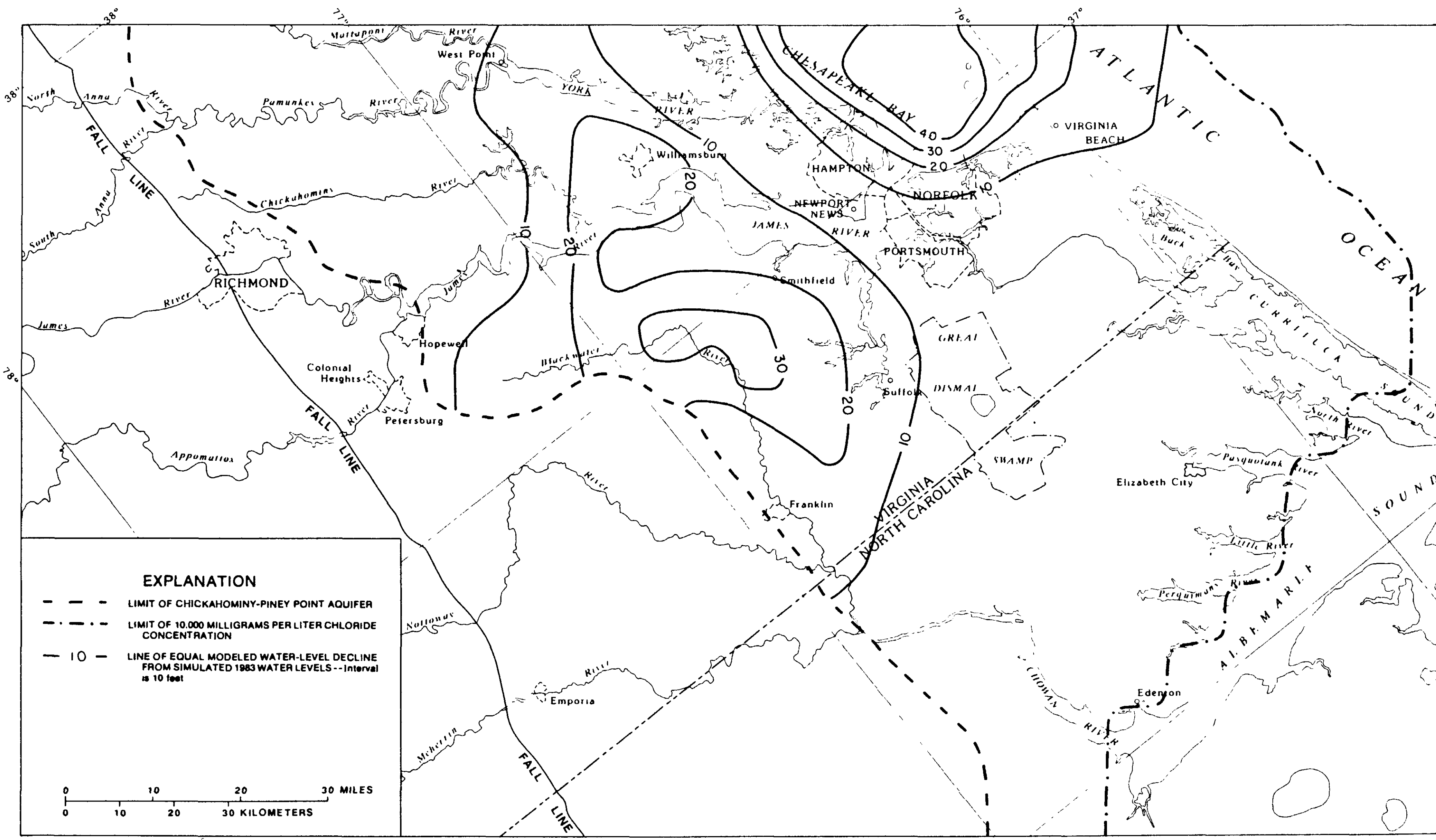


Figure 81.--Modeled water-level decline from simulated 1983 water levels in the Chickahominy-Piney Point aquifer, scenario 1.

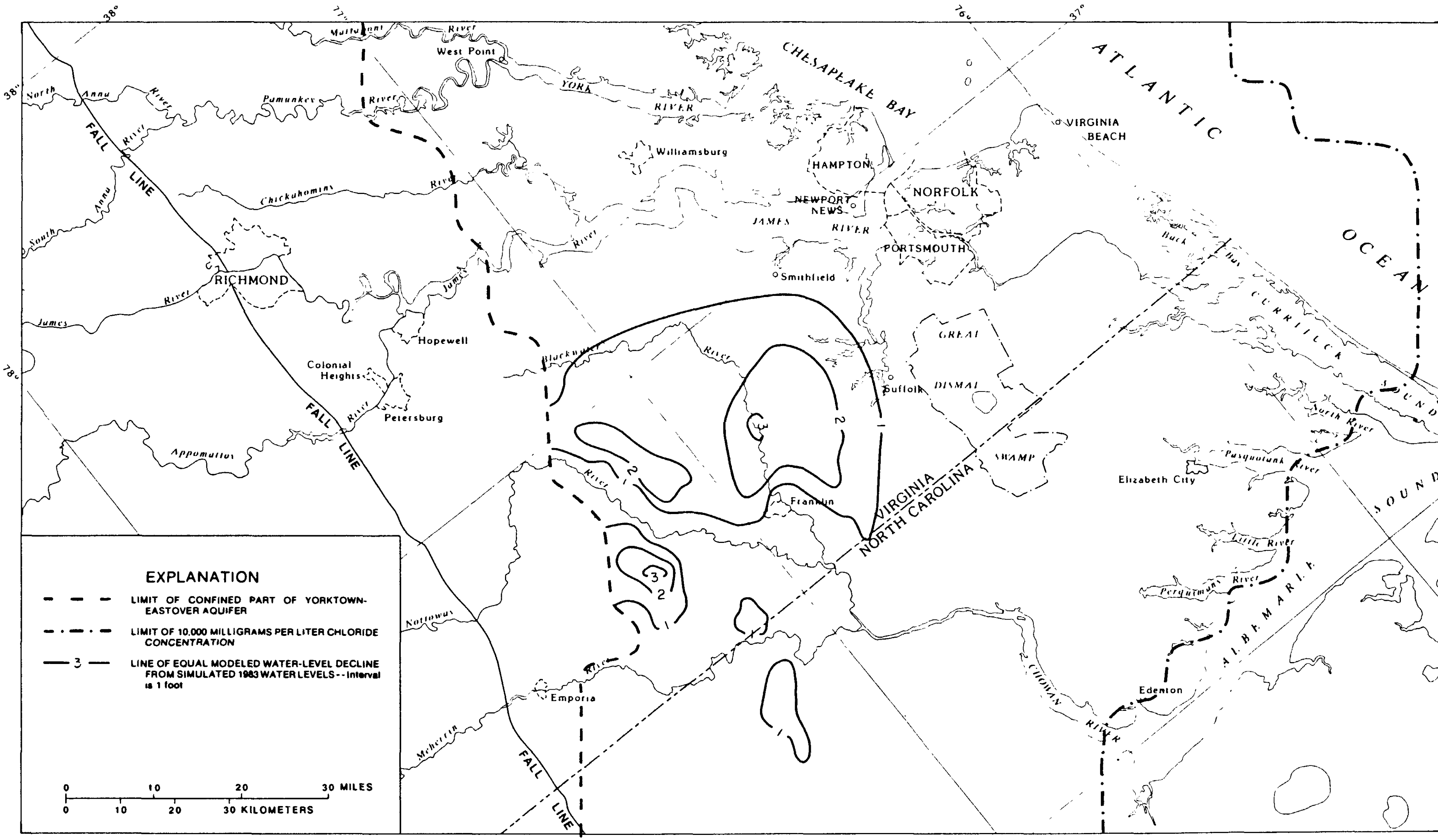


Figure 82.--Modeled water-level decline from simulated 1983 water levels in the Yorktown-Eastover aquifer, scenario 1.

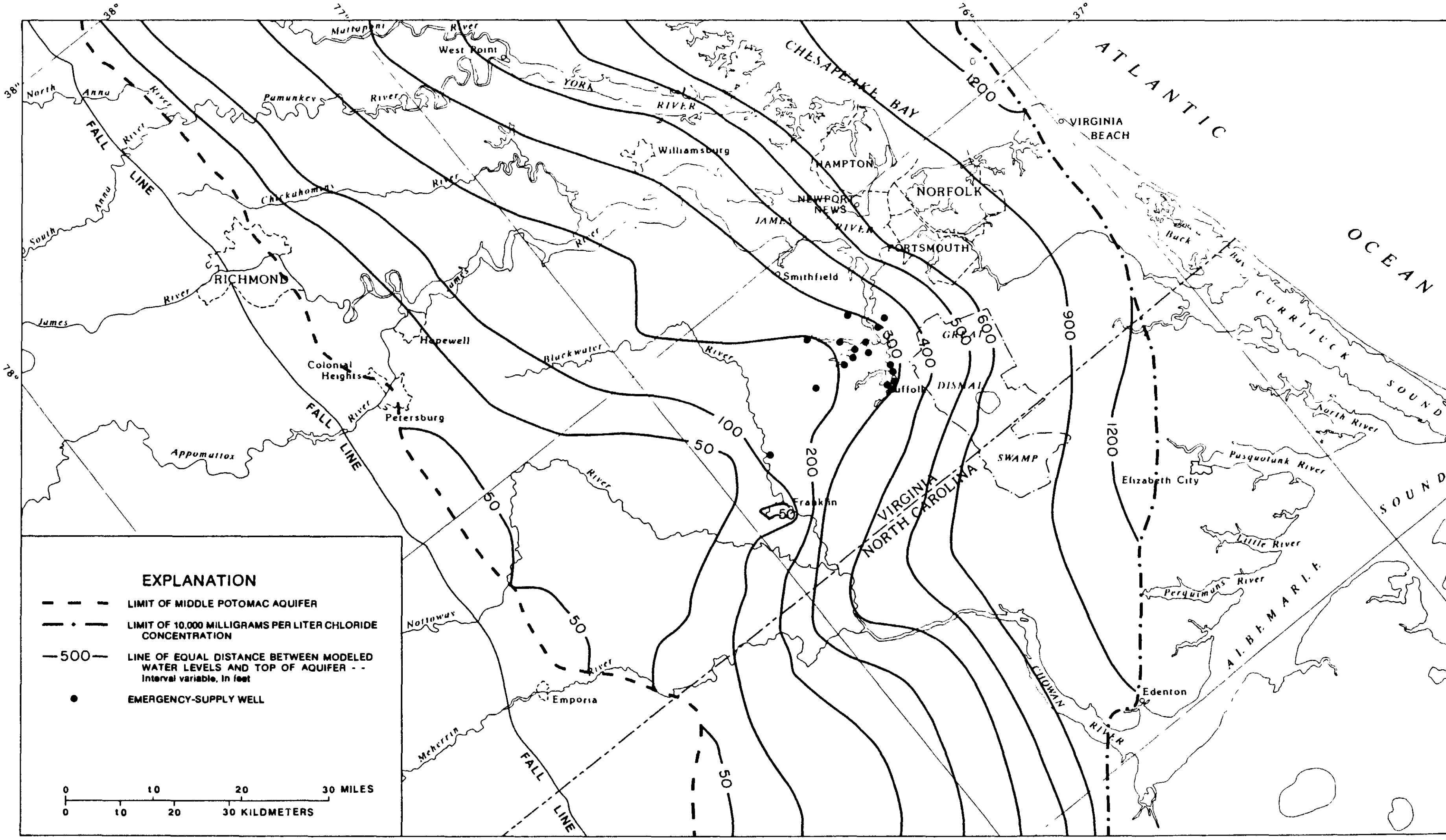


Figure 83.--Distance between modeled water levels and top of the middle Potomac aquifer, scenario 1.

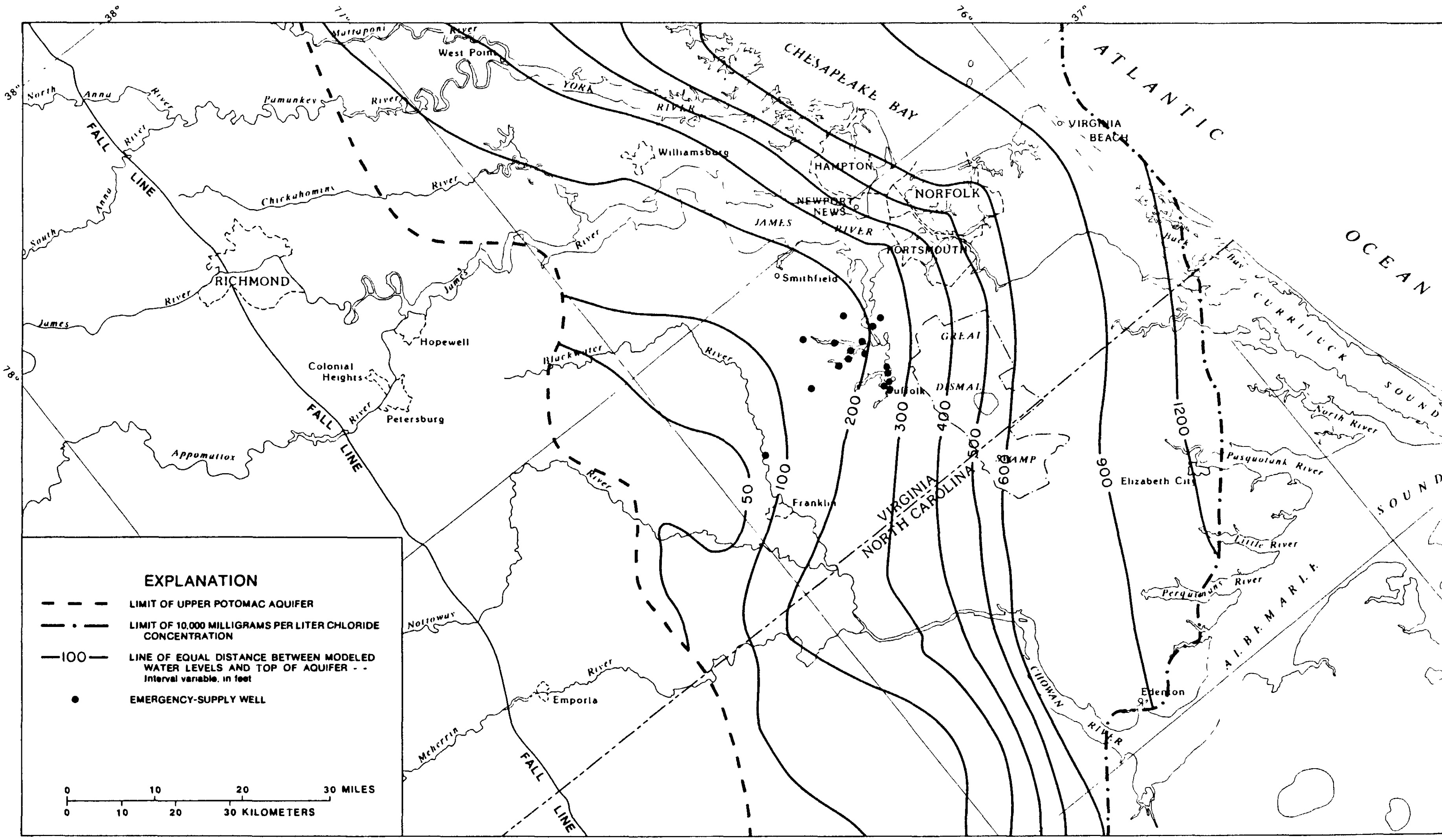


Figure 84.--Distance between modeled water levels and top of the upper Potomac aquifer, scenario 1.

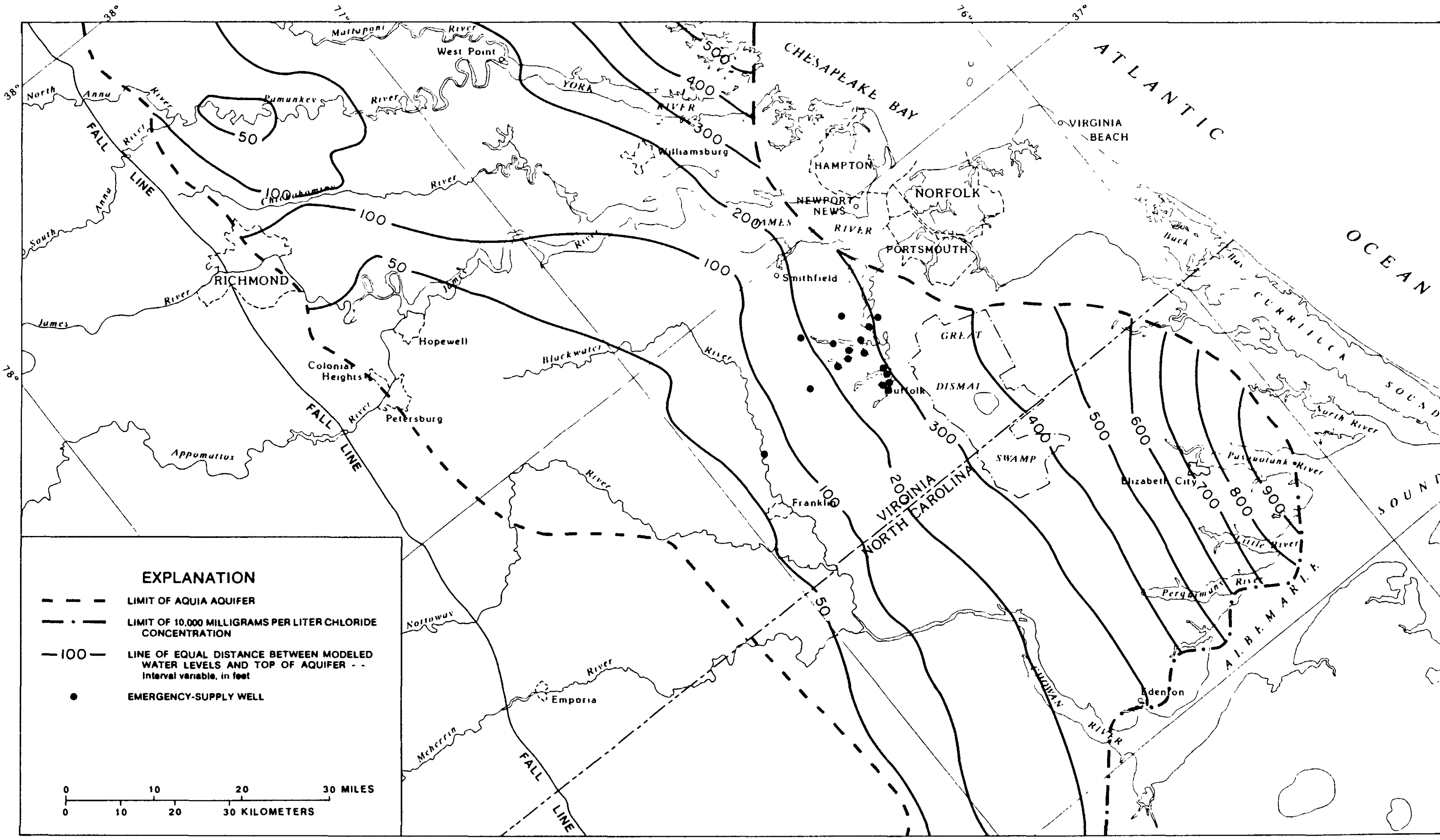


Figure 85.--Distance between modeled water levels and top of the Aquia aquifer, scenario 1.

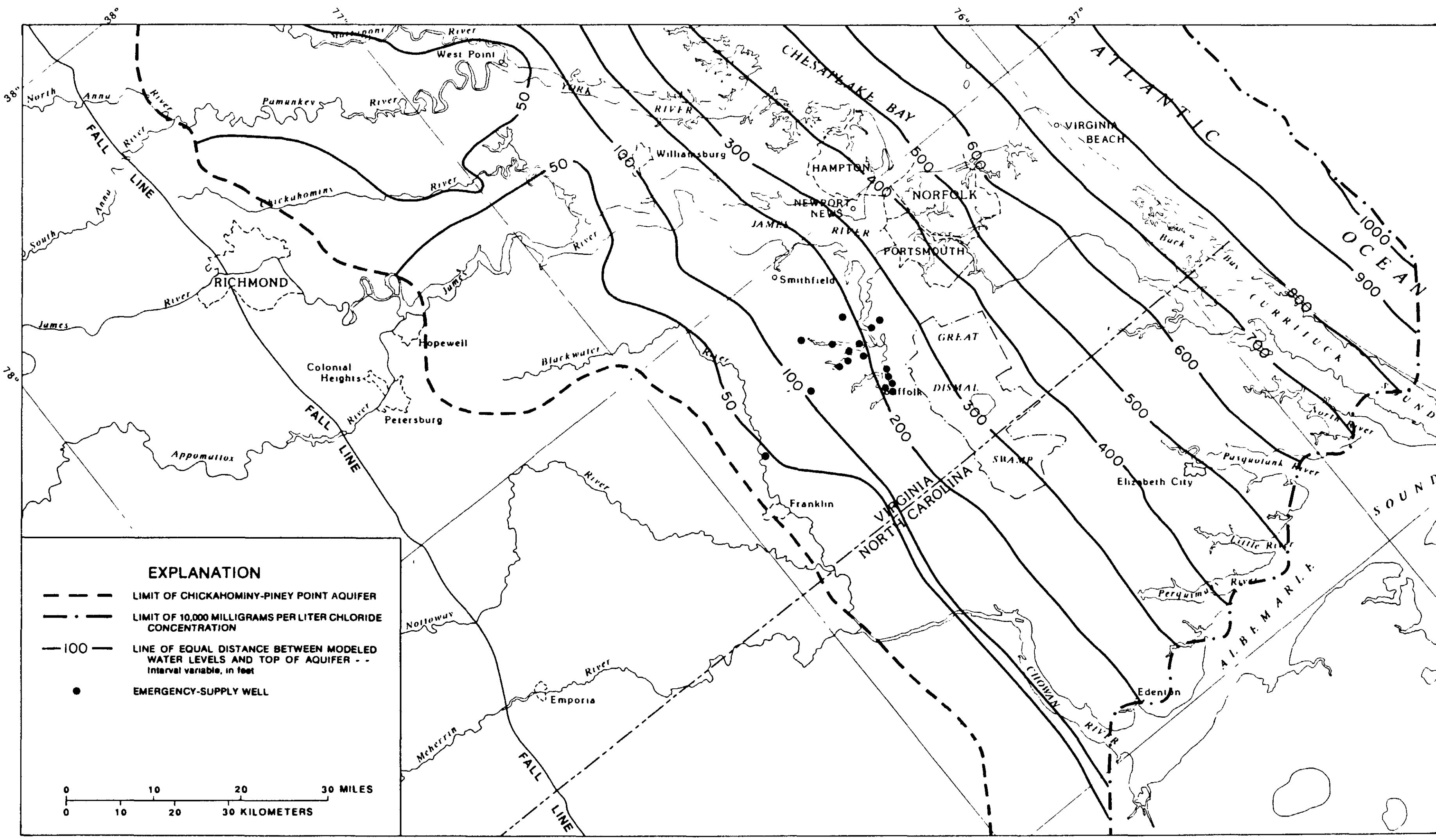


Figure 86.--Distance between modeled water levels and top of the Chickahominy-Piney Point aquifer, scenario 1.

Table 16.--Modeled maximum water-level decline from simulated 1983 water levels for individual aquifers, scenario 1
[Values in feet]

Aquifer	Maximum water-level decline
Yorktown-Eastover	3
Chickahominy-Piney Point	48
Aquia	71
Virginia Beach	20
Upper Potomac	144
Middle Potomac	204
Lower Potomac	121

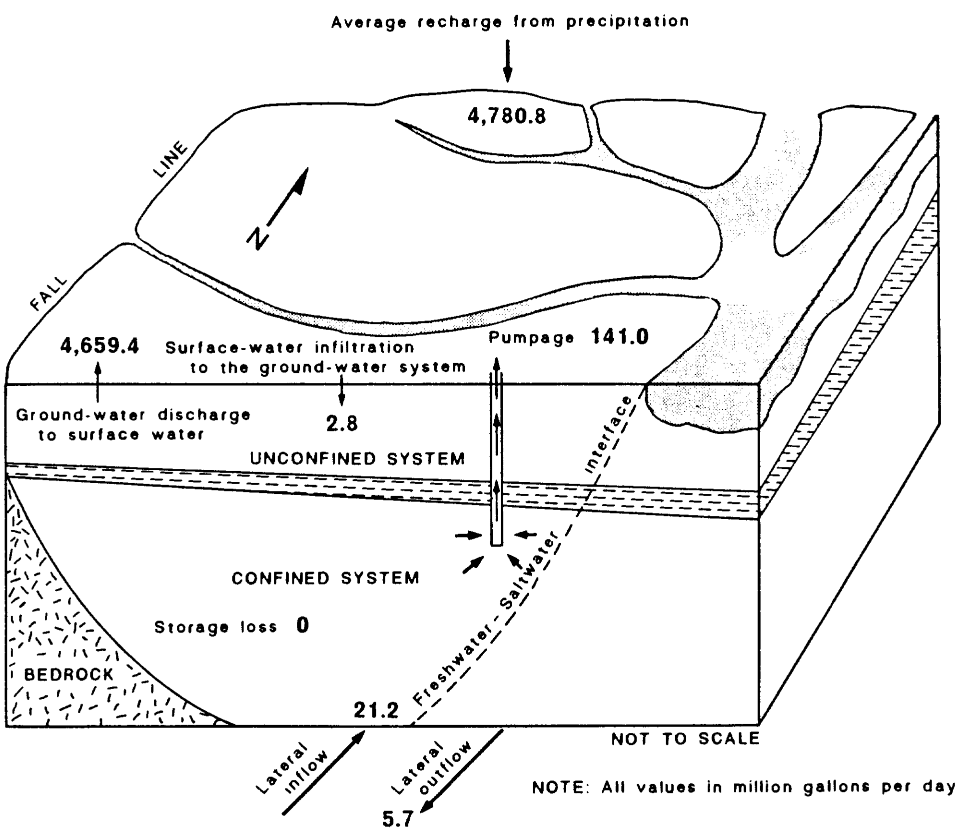


Figure 87.--Modeled ground-water budget, scenario 1.

Table 17.--Modeled ground-water budget, scenario 1
[Modeled values, in million gallons per day, are reported to tenths and are not intended to imply accuracy to the precision shown]

	Scenario 1	Change from 1983	Change from prepumping conditions
Sources			
Water released from aquifer storage	0.0	-0.4	0.0
Lateral boundary inflow	21.2	9.0	19.3
Recharge from precipitation	4,780.8	.0	.0
Surface-water infiltration to the ground-water system	2.8	2.0	2.8
Total	4,804.8	10.6	22.1
Discharges			
Water taken into aquifer storage	.0	1.0	.0
Lateral boundary outflow	5.7	.0	2.6
Ground-water withdrawal from wells	141.0	-54.4	-141.0
Ground-water discharge to surface water	4,659.4	42.8	116.4
Total	4,806.1	-10.6	-22.0

Footnote: The small error between sources and discharges is due to numerical truncation in digital simulation.

Table 18.--Lateral flow across northern and southern boundaries of the model area, scenarios 1 and 2

[Modeled values, in million gallons per day, are reported to hundredths and are not intended to imply accuracy to the precision shown]

Aquifer	Scenario 1		Scenario 2	
	Inflow	Outflow	Inflow	Outflow
Columbia	0.39	0.59	0.39	0.59
Yorktown-Eastover	1.11	1.15	1.09	1.16
Chickahominy-Piney Point	.63	.44	.56	.40
Aquia	.35	.45	.29	.41
Peedee	.00	.00	.00	.00
Virginia Beach	.00	.27	.00	.20
Upper Potomac	6.02	.53	3.86	.69
Middle Potomac	7.87	1.57	5.41	1.54
Lower Potomac	4.86	.65	3.26	.60
Total	21.23	5.65	14.86	5.59

surface water--a decrease of 42.8 Mgal/d from 1983 and decrease of 116.4 Mgal/d from prepumping conditions. Reduced flow to the surface would be because of greater downward movement from the water-table aquifer to the confined system caused by the increased pumpage in the deeper aquifers and would account for 82.5 percent of the pumpage. Approximately 2.8 Mgal/d of surface water would be induced into the ground-water system. Induced surface water would account for 2.0 percent of the pumpage. The area of surface-water infiltration would be about 769 mi^2--an increase of 236 mi^2 since 1983. The additional area primarily would occur along the James River, Chesapeake Bay, and Atlantic Ocean. The remaining pumpage would be accounted for by (1) an increase in lateral inflow across the northern and southern model boundaries by approximately 19.3 Mgal/d and (2) a decrease in lateral outflow across the northern and southern boundaries of the model by approximately 2.6 Mgal/d. The water budget resulted in less than 0.03 percent error in mass balance (table 17).

Areas of modeled vertical recharge to and discharge from each confined aquifer through the overlying confining unit are given in table 19. Area of recharge would increase and area of discharge would decrease from simulated 1983 conditions because of increased pumpage. An exception would occur in the lower Potomac aquifer where the area of discharge to the middle Potomac aquifer would increase by approximately 704 mi^2 because of increased pumpage in the middle Potomac aquifer (fig. 88). This increase could contribute to water-quality degradation in the overlying aquifer because water is generally more saline in the lower Potomac aquifer. Amounts of vertical recharge and discharge for individual aquifers and change in vertical recharge and discharge since simulated 1983 conditions are given in table 19. Vertical recharge would be a major flow component for the aquifers, particularly to the Potomac aquifers

Table 19.--Modeled areas and amounts of vertical recharge to and discharge from each confined aquifer through the overlying confining unit, scenario 1

[mi^2 is square miles; Mgal/d is million gallons per day. Modeled values are not intended to imply accuracy to the precision shown]

Aquifer	Area (mi^2)		Change in area from 1983 (mi^2)		Vertical recharge (Mgal/d)	Vertical discharge (Mgal/d)	Change in vertical recharge and discharge from 1983 (Mgal/d)		Total gain from overlying aquifer (Mgal/d)
	Recharge	Discharge	Recharge	Discharge			Recharge	Discharge	
Yorktown-Eastover	5,164	2,683	606	-606	114.5	32.6	27.5	7.4	34.9
Chickahominy-Piney Point	6,355	677	711	-711	58.7	5.3	21.3	1.6	22.9
Aquia	5,880	217	511	-511	84.5	4.3	28.6	2.1	30.7
Peedee	790	6	89	-89	.8	.0	.5	.0	.5
Virginia Beach	2,459	40	86	-86	5.2	.1	2.9	.0	2.9
Upper Potomac	6,143	16	9	-9	70.7	.1	31.8	.0	31.8
Middle Potomac	7,081	235	481	-481	104.4	3.2	39.8	2.3	42.1
Lower Potomac	4,784	1,473	-704	704	17.6	5.6	4.6	-5.2	-.6

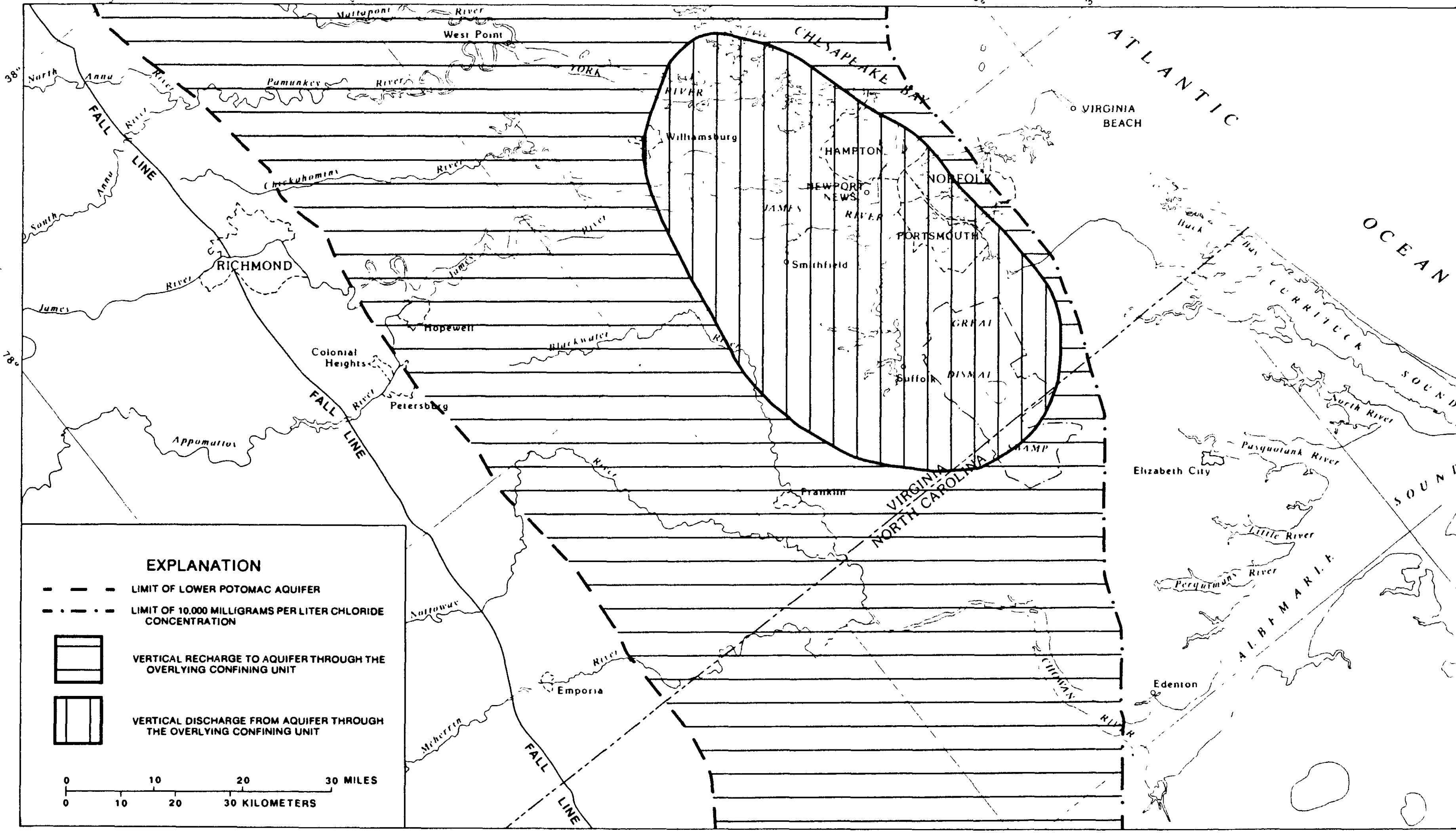


Figure 88.--Modeled areas of vertical recharge to and discharge from the lower Potomac aquifer through the overlying confining unit, scenario 1.

where it would contribute the bulk of water for the increased pumpage.

Scenario 2

Scenario 2 involved continuous use of 51 selected industrial wells at respective permitted limits, increasing pumpage by 19.8 Mgal/d (106.4 Mgal/d total). Approximately 58.2 percent of the additional pumpage would be from the middle Potomac aquifer (11.6 Mgal/d); about 20.6 percent from the upper Potomac aquifer (4.1 Mgal/d); about 15.2 percent from the lower Potomac aquifer (3.0 Mgal/d); and the remaining 6.0 percent from the overlying Virginia Beach, Aquia, Chickahominy-Piney Point, Yorktown-Eastover, and Columbia aquifers (1.2 Mgal/d) (table 20). Locations of the industrial wells are shown in figure 89. Latitudes, longitudes, State identification codes, permitted pumpage, and aquifers penetrated by the wells are summarized in table 21.

Table 20.--Pumpage and modeled maximum water-level decline from simulated 1983 water levels for individual aquifers, scenario 2

[Mgal/d is million gallons per day; ft is feet]

Aquifer	Pumpage (Mgal/d)	Maximum water-level decline (ft)
Yorktown-Eastover	0.58	3
Chickahominy-Piney Point	.04	17
Aquia	.31	28
Virginia Beach	.23	8
Upper Potomac	4.09	45
Middle Potomac	11.55	76
Lower Potomac	3.01	77

Modeled water-level decline from simulated 1983 water levels in individual aquifers is shown in figures 90 through 96. Maximum water-level decline in individual aquifers is given in table 20. Maximum decline of approximately 75 feet would occur in the lower and middle Potomac aquifers in the Franklin area. Water-level decline greater than 10 feet would occur throughout most of these aquifers. Water-level decline greater than 30 feet would occur in the upper Potomac aquifer in the Smithfield, Portsmouth, and Chesapeake areas.

Although the majority of pumpage would be from the lower aquifers, lowered water levels would occur in the overlying aquifers. Water-level decline greater than 20 feet would occur in the Aquia aquifer in and near the Smithfield area. The Chickahominy-Piney Point aquifer primarily would be affected in the southeastern cities of Portsmouth, Chesapeake, and Norfolk (5-15 feet) and along Chesapeake Bay. Minimal water-level decline (1-3 feet) would occur in the Yorktown-Eastover aquifer in southeastern Virginia.

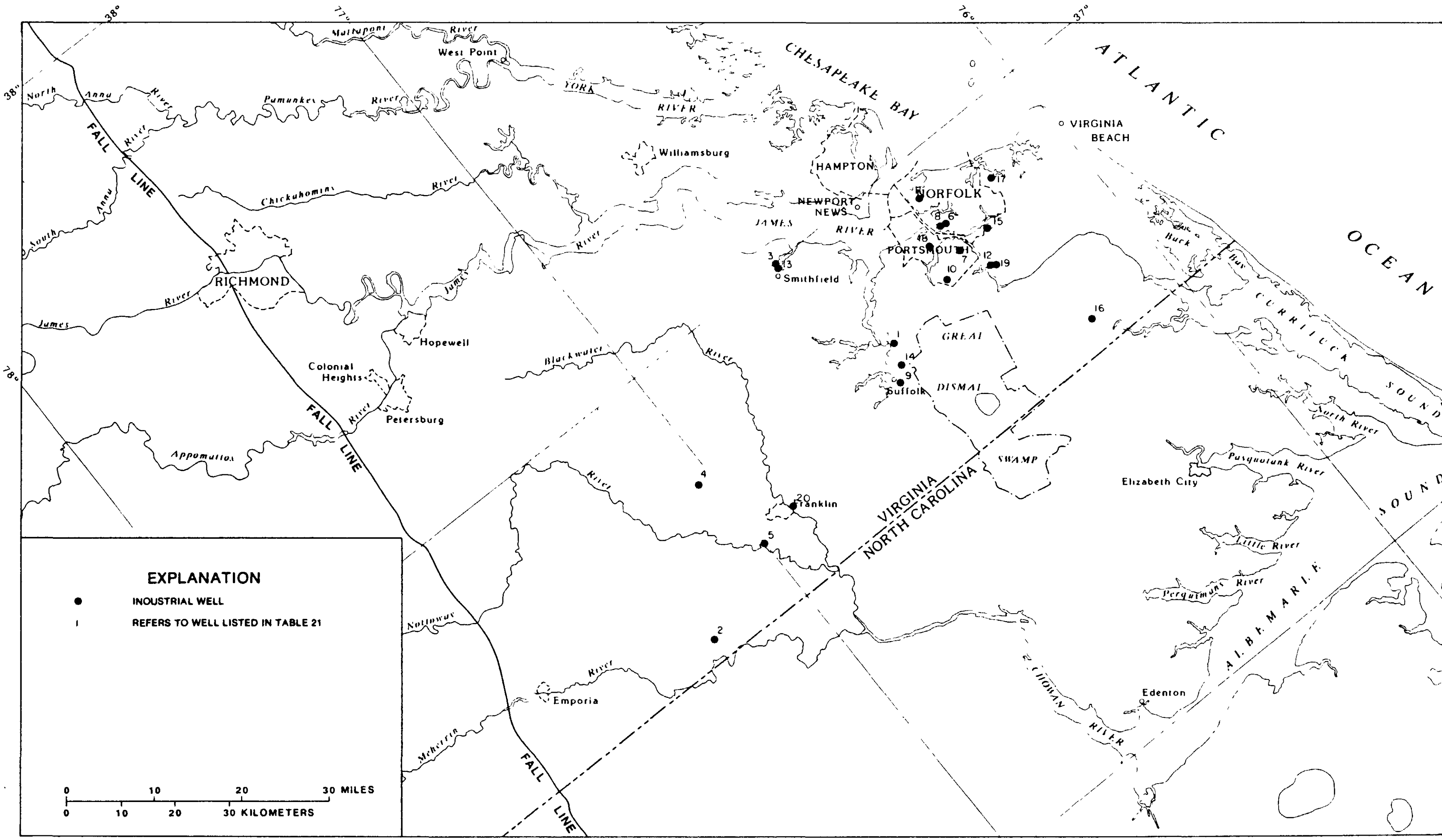


Figure 89.--Location of industrial wells.

Table 21.--Industrial wells simulated in scenario 2
[Mgal/d is million gallons per day]

Name	Map number[a]	Virginia Water Control Board identification number	Latitude			Longitude			Permitted pumpage (Mgal/d)	Aquifers penetrated
Allied Colloids	1	161-004	36	46	42	76	32	29	0.30	Middle and upper Potomac
Boykins Narrow Fab	2	187-005	36	35	08	77	12	15	.45	Middle Potomac
		187-132	36	35	08	77	12	14		
Gwaltney	3	146-109	36	59	43	76	37	51	1.45	Upper Potomac
		146-110	36	59	43	76	37	52		
		146-111	36	59	52	76	37	47		
		146-112	36	59	52	76	37	48		
H.P. Beale	4	187-116	36	47	54	77	02	07	.25	Middle and upper Potomac
		187-135	36	47	54	77	02	07		
		187-136	36	47	54	77	02	07		
		187-143	36	47	55	77	02	03		
Hercules	5	187-001	36	39	01	76	59	57	7.92	Lower and middle Potomac
		187-003	36	39	29	77	00	25		
		187-004	36	39	15	77	00	12		
J.H. Miles	6	217-064	36	51	33	76	18	29	1.00	Upper Potomac
Murro Chemical	7	220-010	36	49	36	76	19	12	.60	Upper Potomac
		220-013	36	49	36	76	19	12		
N & W Railroad	8	217-067	36	52	38	76	19	34	.12	Upper Potomac and Chickahominy-Piney Point
Planters Peanuts	9	161-267	36	43	32	76	34	51	.40	Upper and middle Potomac
		161-268	36	43	15	76	34	59		
Shared Hospital Services	10	220-024	36	48	11	76	22	39	.10	Upper Potomac
Sheller Globe	11	217-021	36	56	02	76	19	07	.19	Yorktown-Eastover
		217-022	36	56	02	76	19	01		
Smith-Douglass	12	234-009	36	46	19	76	17	30	.12	Yorktown-Eastover
		234-010	36	46	18	76	17	31		
		234-149	36	46	18	76	17	31		
Smithfield Packing	13	146-115	36	59	37	76	37	56	2.81	Upper Potomac and Aquia
		146-116	36	59	32	76	37	54		
		146-119	36	59	28	76	37	58		
		146-198	36	59	30	76	37	59		
Smithfield Pk.Plant	14	161-241	36	44	29	76	33	33		Middle Potomac
Southland Corp.	15	234-078	36	49	58	76	14	42	.13	Yorktown-Eastover
Tidewater Chemical	16	234-015	36	36	27	76	12	07	.23	Virginia Beach
		234-076	36	46	18	76	17	31		
		234-079	36	36	27	76	12	07		
Tidewater Linen	17	228-300	36	53	15	76	10	41	.06	Columbia
Virginia Chemical	18	220-001	36	51	45	76	20	44	1.81	Upper Potomac, Aquia, and Yorktown-Eastover
		220-002	36	51	49	76	20	50		
		220-003	36	51	49	76	20	39		
		220-009	36	51	39	76	20	34		
Weaver Fertilizer	19	234-081	36	46	17	76	17	52	.06	Yorktown-Eastover
Union Camp Corp.	20	146-197	36	39	25	76	53	58	43.32	Middle and lower Potomac
		146-129	36	39	12	76	53	50		
		146-131	36	38	48	76	53	42		
		146-122	36	40	49	76	54	53		
		146-124	36	40	24	76	54	40		
		146-126	36	40	02	76	54	37		
		146-127	36	39	41	76	54	20		
		146-128	36	39	26	76	54	02		
		146-133	36	41	52	76	54	39		

[a]Locations shown on figure 89.

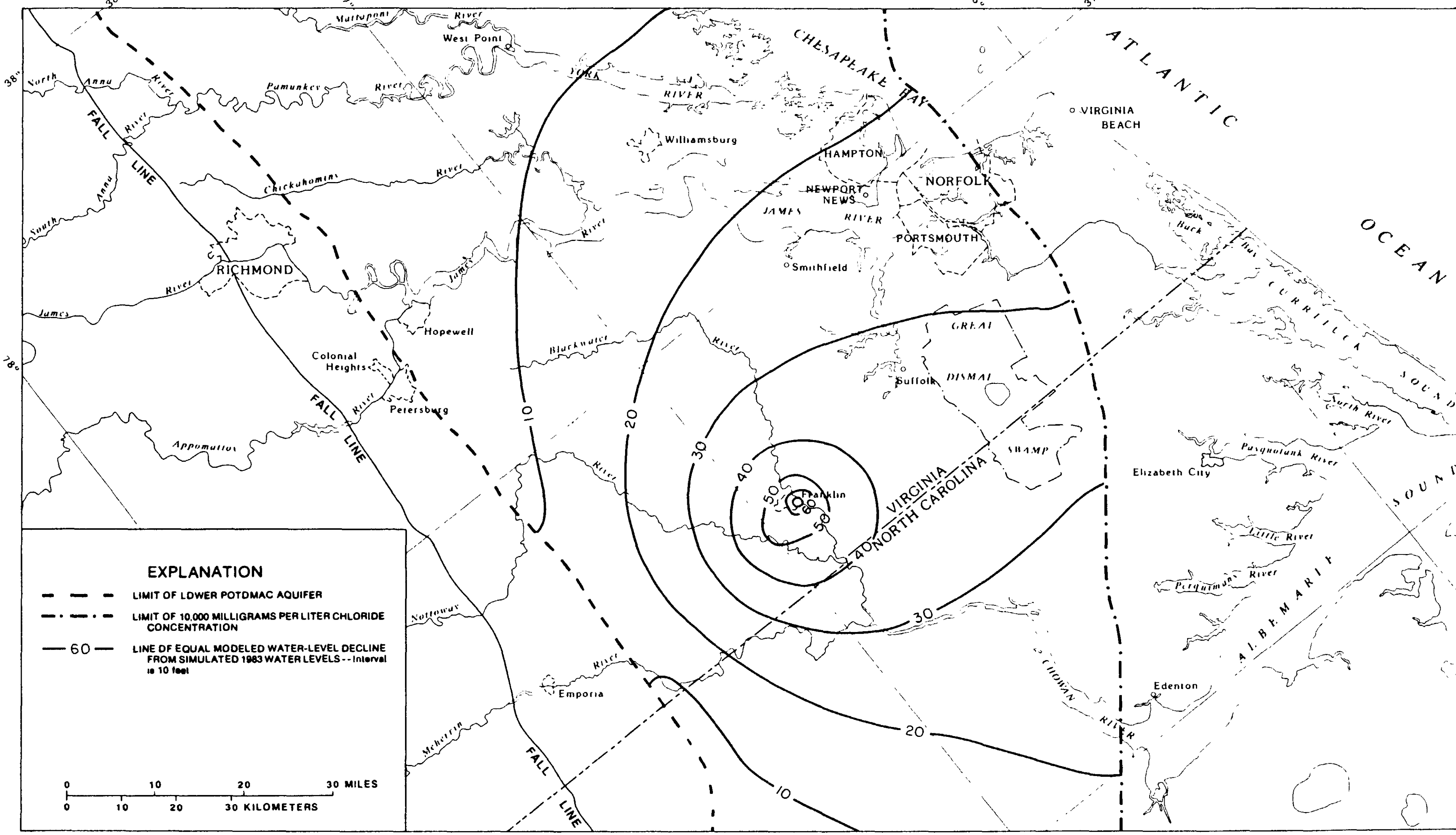


Figure 90.--Modeled water-level decline from simulated 1983 water levels in the lower Potomac aquifer, scenario 2.

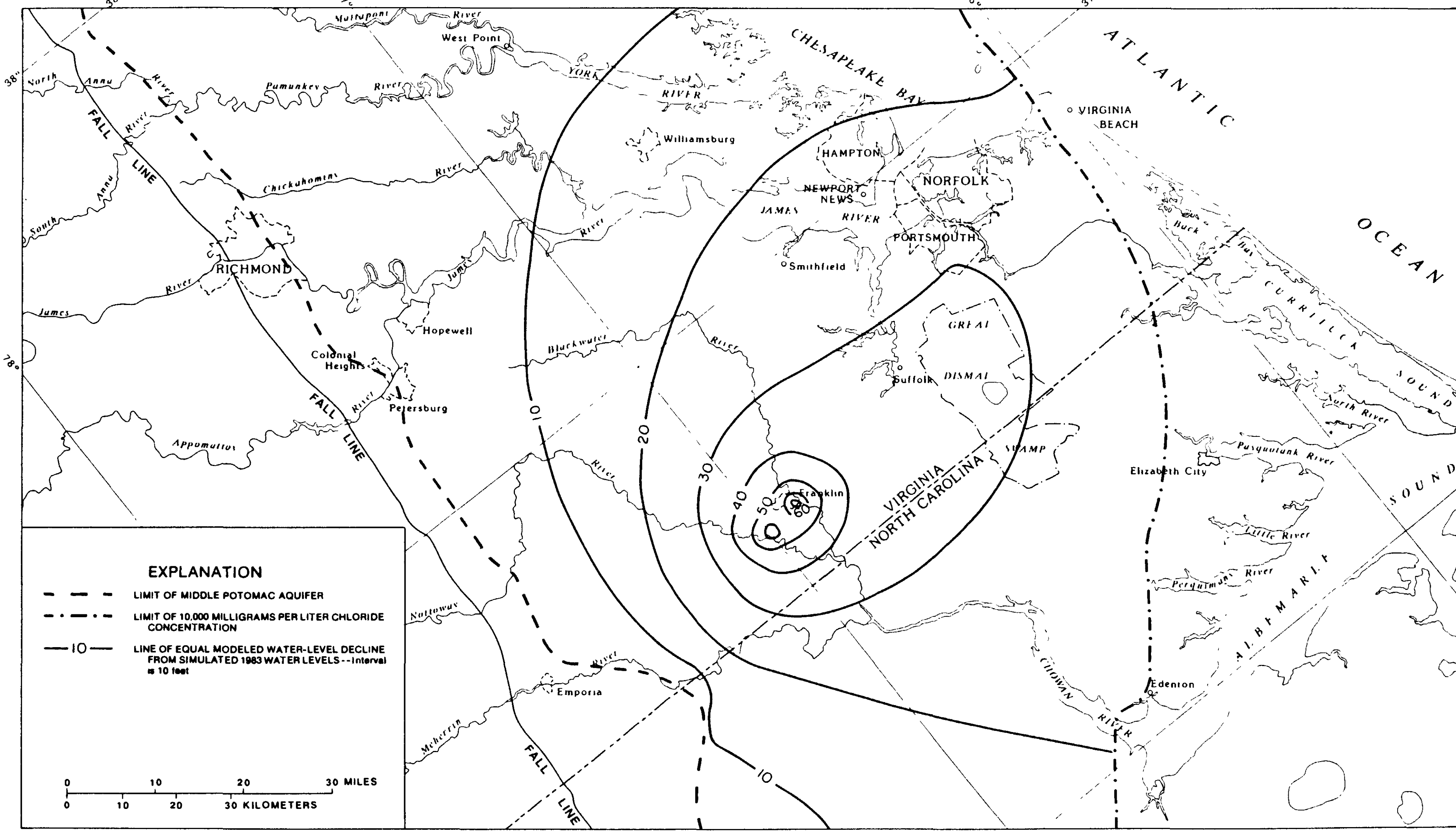


Figure 91.--Modeled water-level decline from simulated 1983 water levels in the middle Potomac aquifer, scenario 2.

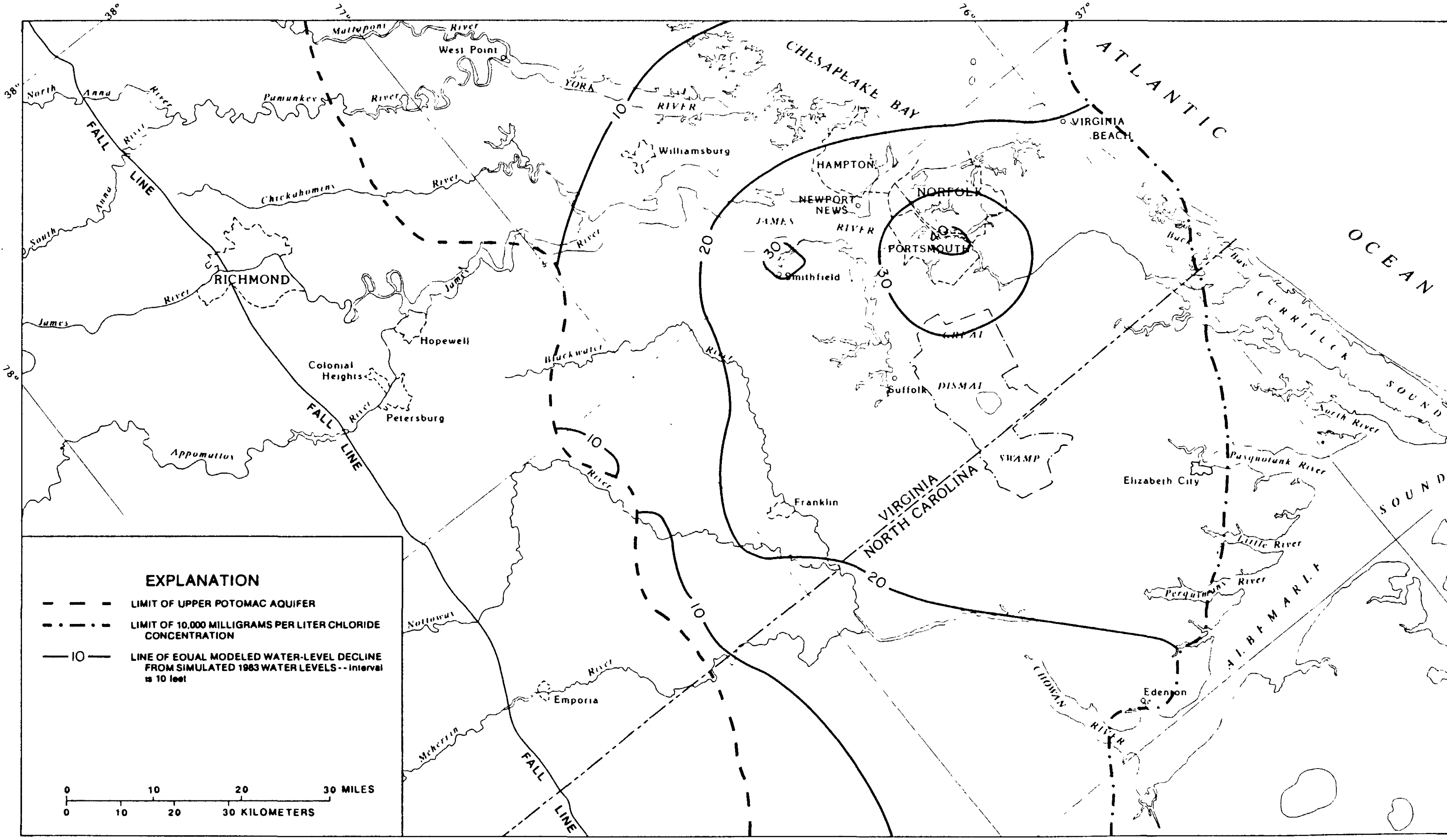


Figure 92.--Modeled water-level decline from simulated 1983 water levels in the upper Potomac aquifer, scenario 2.

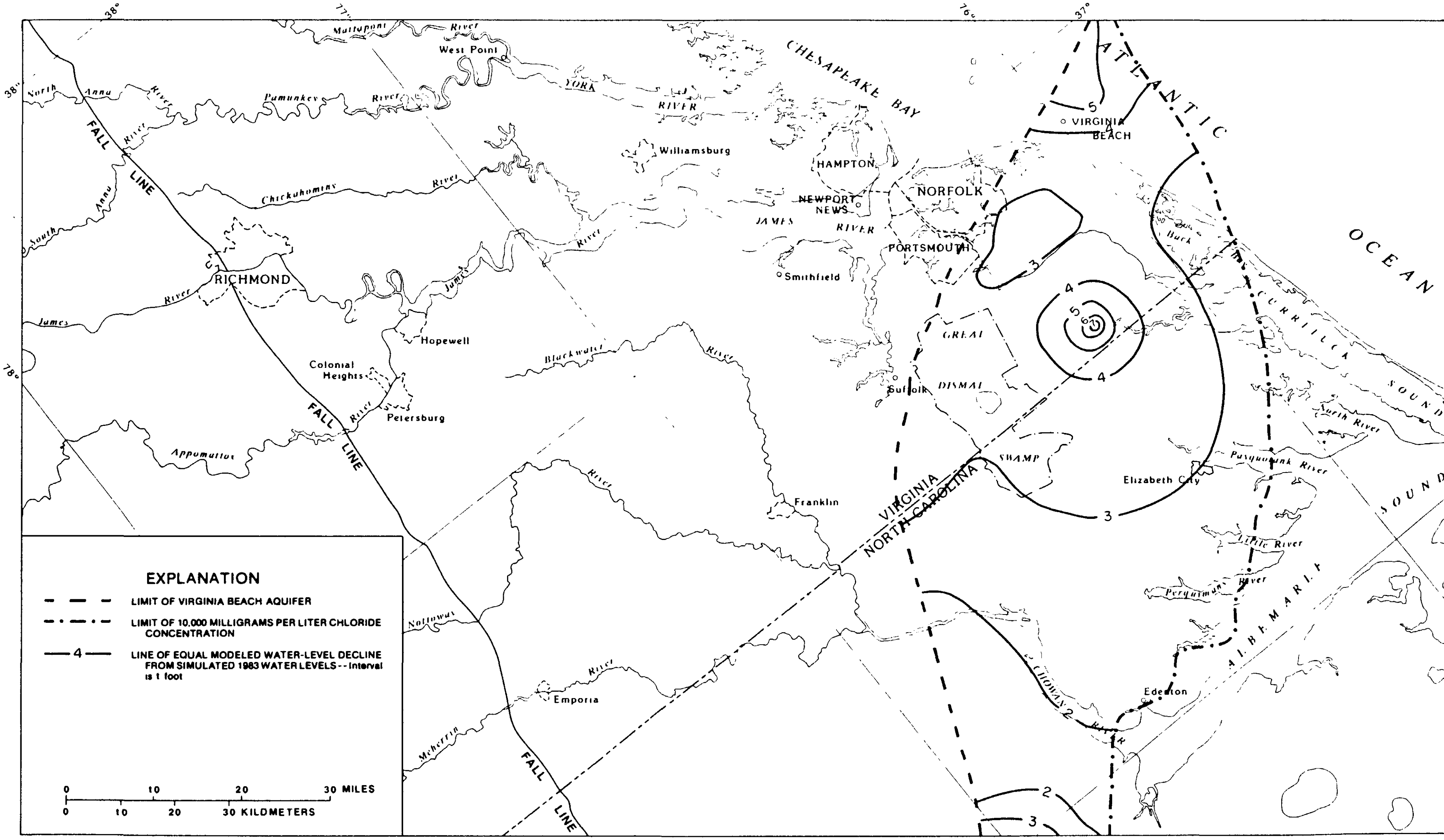


Figure 93.--Modeled water-level decline from simulated 1983 water levels in the Virginia Beach aquifer, scenario 2.

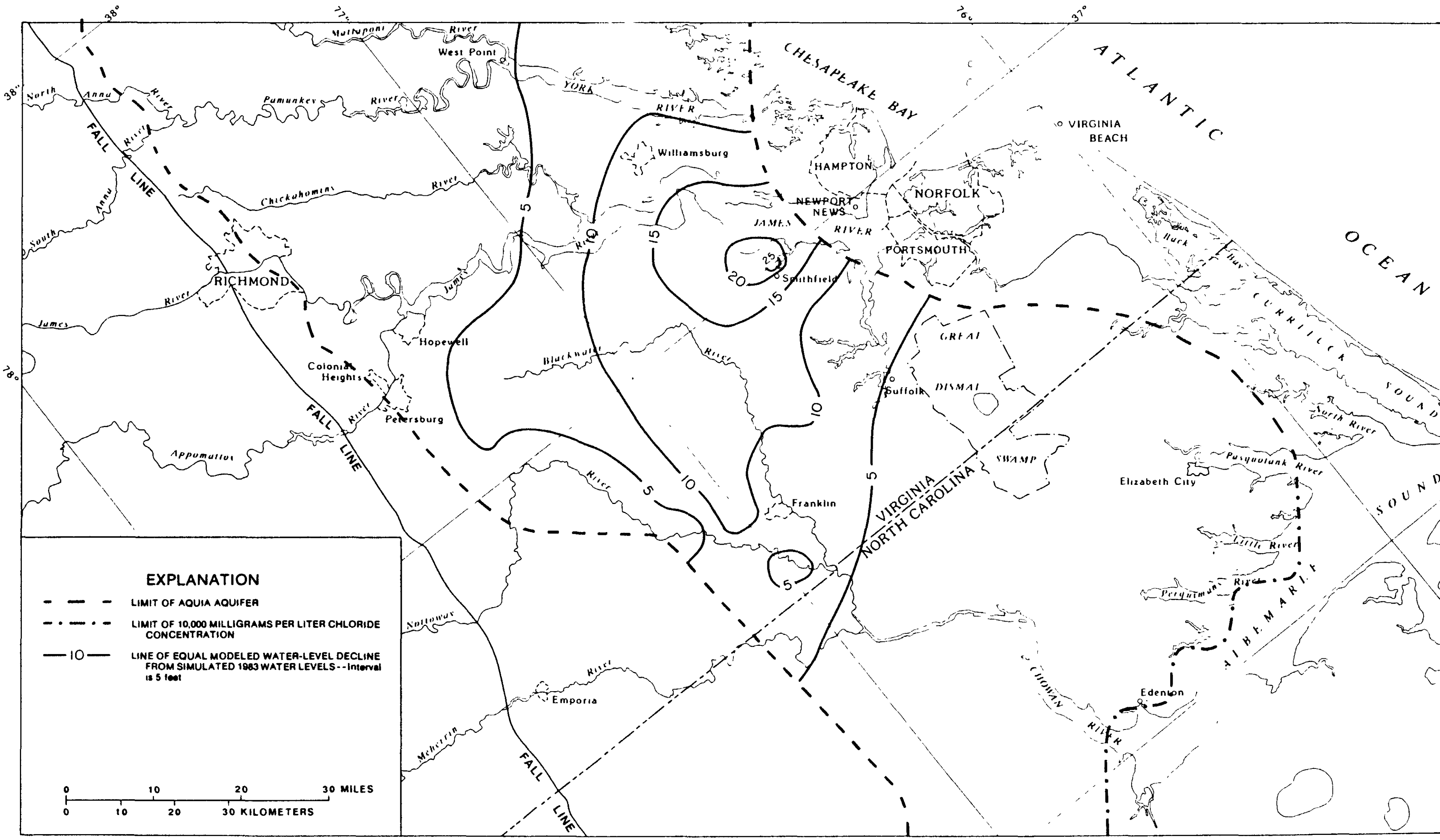


Figure 94.--Modeled water-level decline from simulated 1983 water levels in the Aquia aquifer, scenario 2.

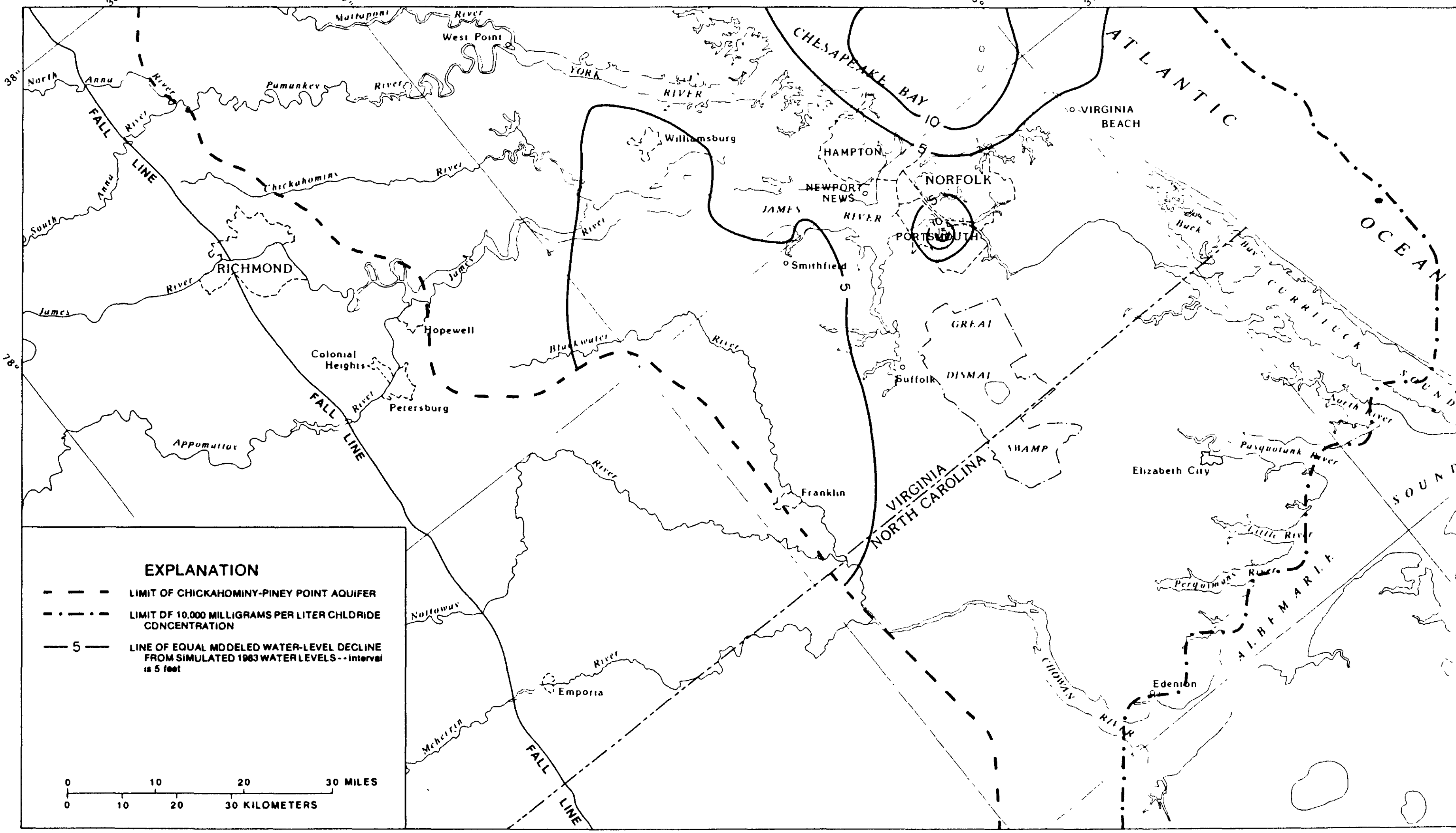


Figure 95.--Modeled water-level decline from simulated 1983 water levels in the Chickahominy-Piney Point aquifer, scenario 2.

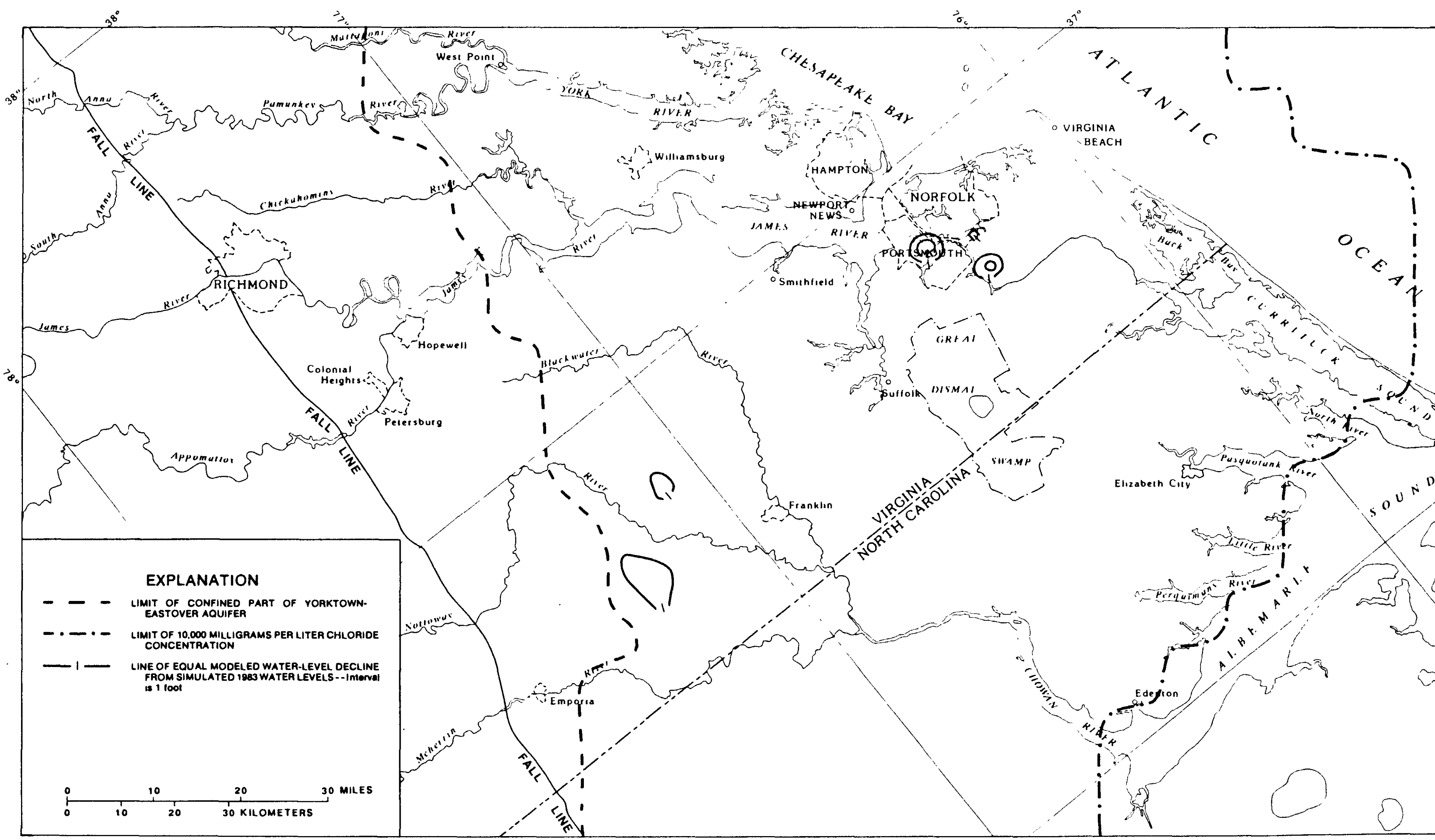


Figure 96.--Modeled water-level decline from simulated 1983 water levels in the Yorktown-Eastover aquifer, scenario 2.

Contours of distances between modeled water levels and the tops of the middle and upper Potomac, Aquia, and Chickahominy-Piney Point aquifers are presented in figures 97 through 100. As indicated in scenario 1, these maps are accurate only within 50 feet and should be interpreted for trends rather than absolute values. Water levels would remain well above the tops of the aquifers except in the West Point and Franklin areas where water levels would be between 0 and 100 feet above the aquifer tops.

The modeled ground-water budget is illustrated in figure 101 and summarized in table 22. Modeled values presented in the text, figures, and tables are not intended to imply accuracy to the precision shown. Water-budget sources include recharge from precipitation, surface-water infiltration, and lateral inflow across northern and southern boundaries. Water-budget discharges include pumpage, lateral outflow, and discharge to surface water. Table 18 summarizes lateral flow across northern and southern boundaries for individual aquifers. The average areal recharge to the water-table aquifer was estimated to be the same as in 1983 (4,780.8 Mgal/d). Of this recharge, about 4,686.1 Mgal/d would discharge to surface water--a decrease of 16.1 Mgal/d from 1983 and decrease of 89.7 Mgal/d since prepumping conditions. Reduced flow to the surface would be because of greater downward movement from the water-table aquifer to the confined system caused by the increased pumpage in the deeper aquifers and would account for 84.2 percent of the pumpage. Approximately 1.3 Mgal/d of surface water would be induced into the ground-water system. Induced surface-water infiltration would account for 1.2 percent of the pumpage. The area of surface-water infiltration to the ground-water system would be about 637 mi^2--an increase of about 104 mi^2 since 1983. The additional area primarily would occur along the James River, Chesapeake Bay, and Atlantic Ocean. The remaining pumpage would be accounted for by (1) an increase in lateral inflow across the northern and southern model boundaries by approximately 13.0 Mgal/d and (2) a decrease in lateral outflow across the northern and southern boundaries of the model by approximately 2.7 Mgal/d. The water budget resulted in less than 0.03 percent error in mass balance (table 22).

Areas of modeled vertical recharge to and discharge from each confined aquifer through the overlying confining unit are given in table 23. Area of recharge would increase and area of discharge would decrease from simulated 1983 conditions because of increased pumpage. As seen in scenario 1, an exception would occur in the lower Potomac aquifer where the area of discharge to the middle Potomac aquifer would increase (approximately 95 mi^2) (fig. 102), allowing discharge of saline water into the overlying aquifer. Area of discharge from the middle Potomac to the upper Potomac aquifer would decrease; however, its location would shift to the east (fig. 103). A smaller area of discharge would occur north of the James River and a new area would occur nearer to the cities of Portsmouth and Norfolk. This shift in location potentially could contribute to water-quality degradation in the overlying aquifer because water is generally more saline in the eastern parts of the middle Potomac aquifer. Amounts of vertical recharge and discharge for each confined aquifer and change in vertical recharge and discharge since simulated 1983 conditions are given in table 23. Vertical recharge would be a major flow component for the aquifers, contributing the bulk of the increased pumpage.

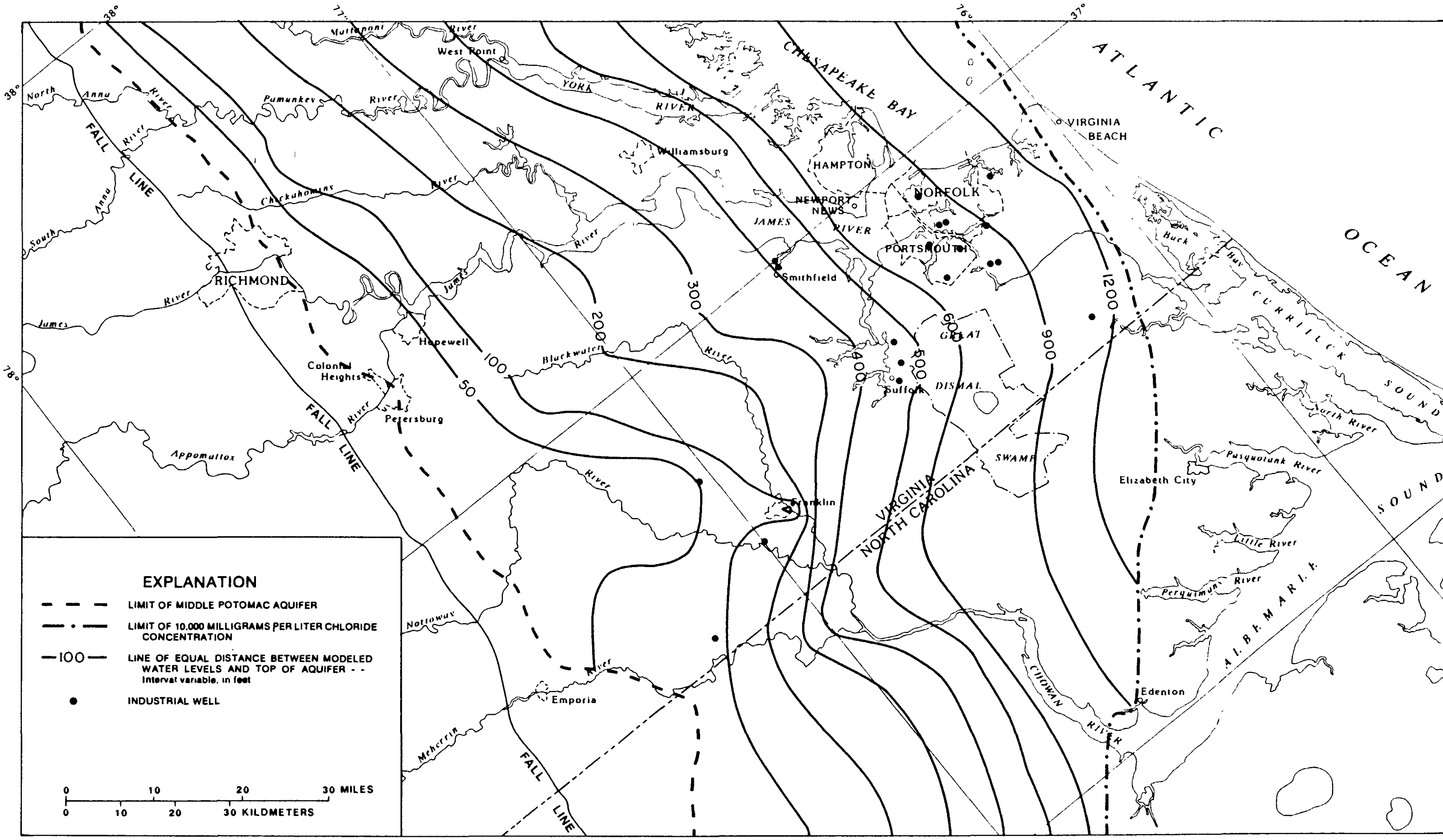


Figure 97.--Distance between modeled water levels and top of the middle Potomac aquifer, scenario 2.

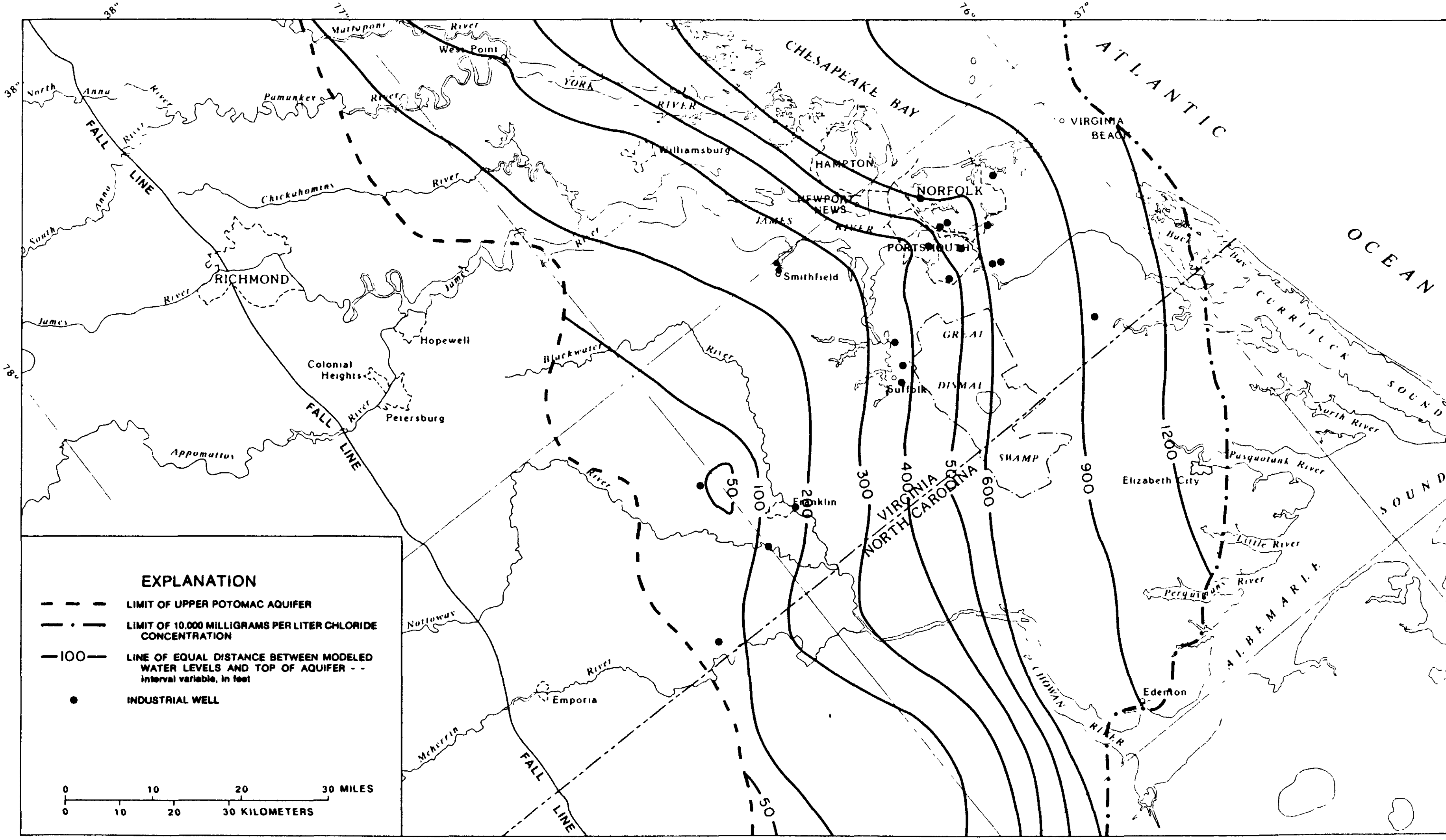


Figure 98.--Distance between modeled water levels and top of the upper Potomac aquifer, scenario 2.

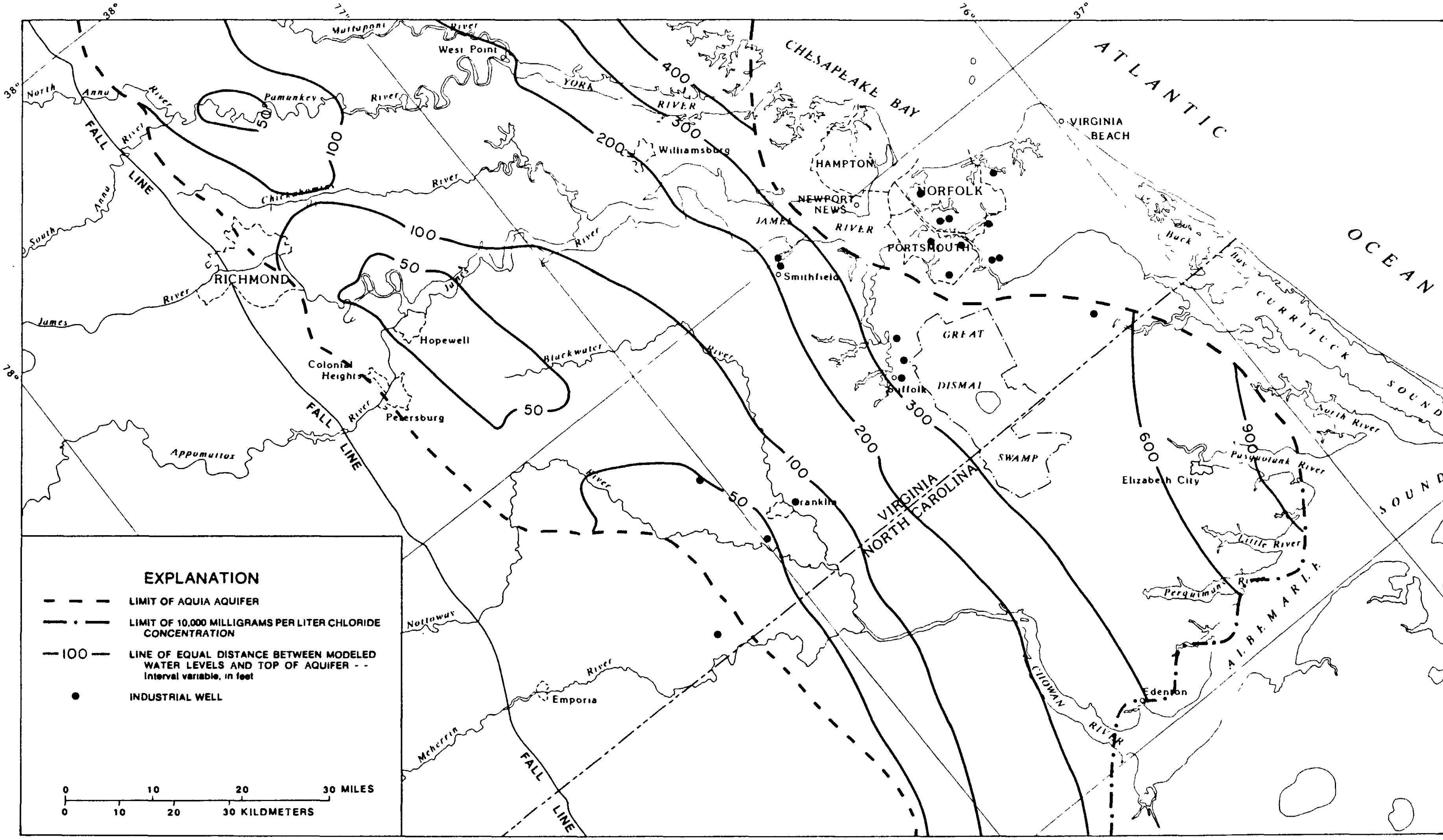


Figure 99.--Distance between modeled water levels and top of the Aquia aquifer, scenario 2.

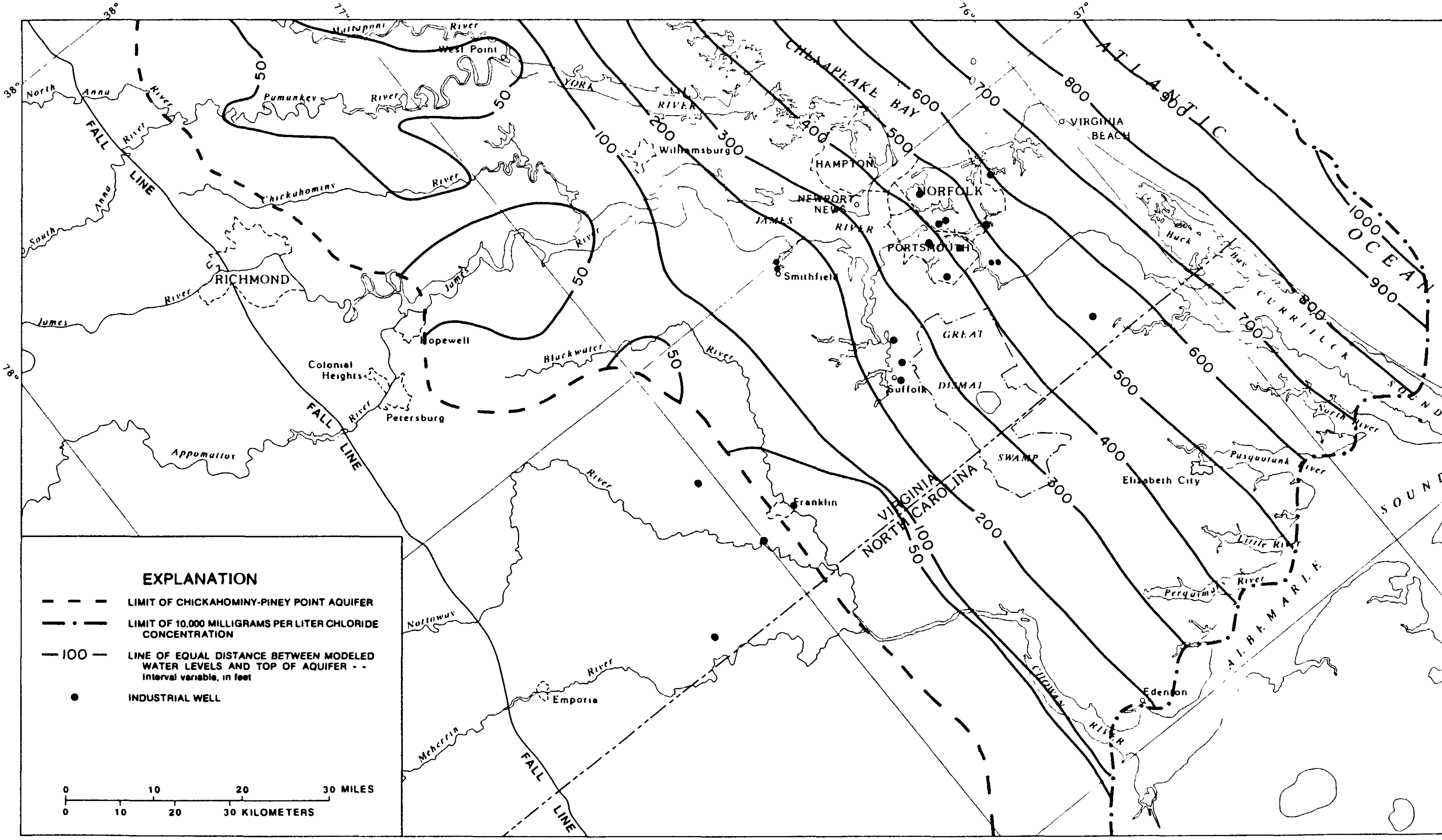


Figure 100.--Distance between modeled water levels and top of the Chickahominy-Piney Point aquifer, scenario 2.

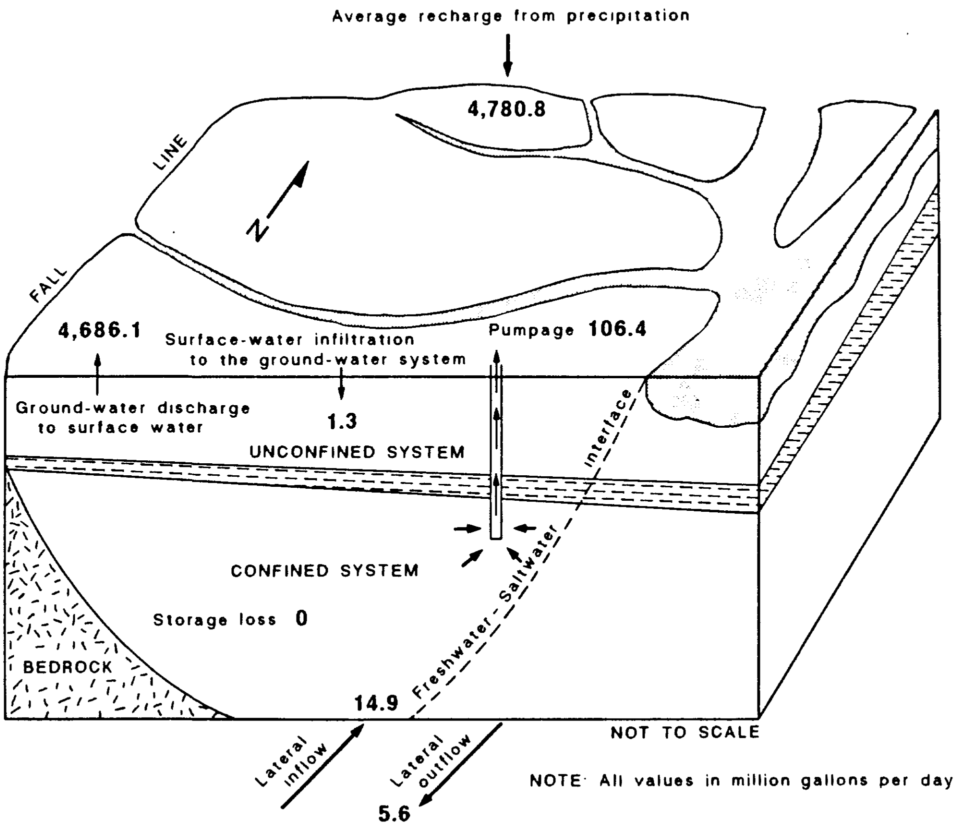


Figure 101.--Modeled ground-water budget, scenario 2.

Table 22.--Modeled ground-water budget, scenario 2
[Modeled values, in million gallons per day, are reported to tenths and are not intended to imply accuracy to the precision shown]

	Scenario 2	Change from 1983	Change from prepumping conditions
Sources			
Water released from aquifer storage	0.0	-0.4	0.0
Lateral boundary inflow	14.9	2.7	13.0
Recharge from precipitation	4,780.8	.0	.0
Surface-water infiltration to the ground-water system	1.3	.5	1.3
Total	4,797.0	2.8	14.3
Discharges			
Water taken into aquifer storage	.0	1.0	.0
Lateral boundary outflow	5.6	.1	2.7
Ground-water withdrawal from wells	106.4	-19.8	-106.4
Ground-water discharge to surface water	4,686.1	16.1	89.7
Total	4,798.1	-2.6	-14.0

Footnote: The small error between sources and discharges is due to numerical truncation in digital simulation.

Table 23.--Modeled areas and amounts of vertical recharge to and discharge from each confined aquifer through the overlying confining unit, scenario 2

[mi^2 is square miles; Mgal/d is million gallons per day. Modeled values are not intended to imply accuracy to the precision shown]

Aquifer	Area (mi^2) Recharge	Area (mi^2) Discharge	Change in area from 1983 (mi^2) Recharge	Change in area from 1983 (mi^2) Discharge	Vertical recharge (Mgal/d)	Vertical discharge (Mgal/d)	Change in vertical recharge and discharge from 1983 (Mgal/d) Recharge	Change in vertical recharge and discharge from 1983 (Mgal/d) Discharge	Total gain from overlying aquifer (Mgal/d)
Yorktown-Eastover	4,818	3,029	260	-260	97.3	37.0	10.3	3.0	13.3
Chickahominy-Piney Point	6,009	1,023	365	-365	43.7	6.4	6.3	.5	6.8
Aquia	5,696	401	327	-327	65.1	5.7	9.2	.7	9.9
Peedee	772	24	71	-71	.5	.0	.2	.0	.2
Virginia Beach	2,429	70	56	-56	3.4	.1	1.1	.0	1.1
Upper Potomac	6,137	22	3	-3	49.4	.2	10.5	-.1	10.4
Middle Potomac	6,606	710	6	-6	76.7	5.5	12.1	.0	12.1
Lower Potomac	5,393	864	-95	95	15.2	.5	2.2	-.1	2.1

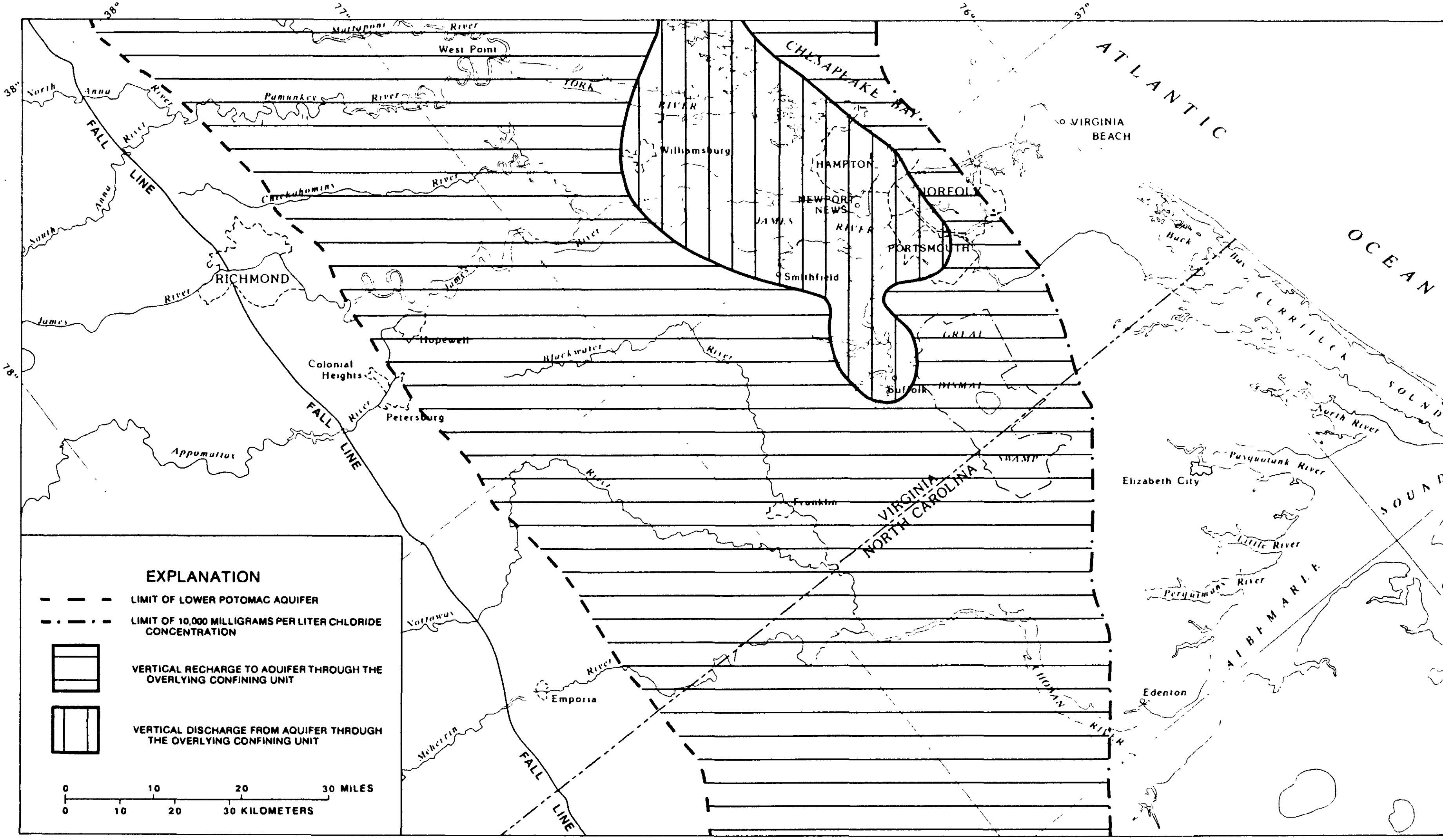


Figure 102.--Modeled areas of vertical recharge to and discharge from the lower Potomac aquifer through the overlying confining unit, scenario 2.

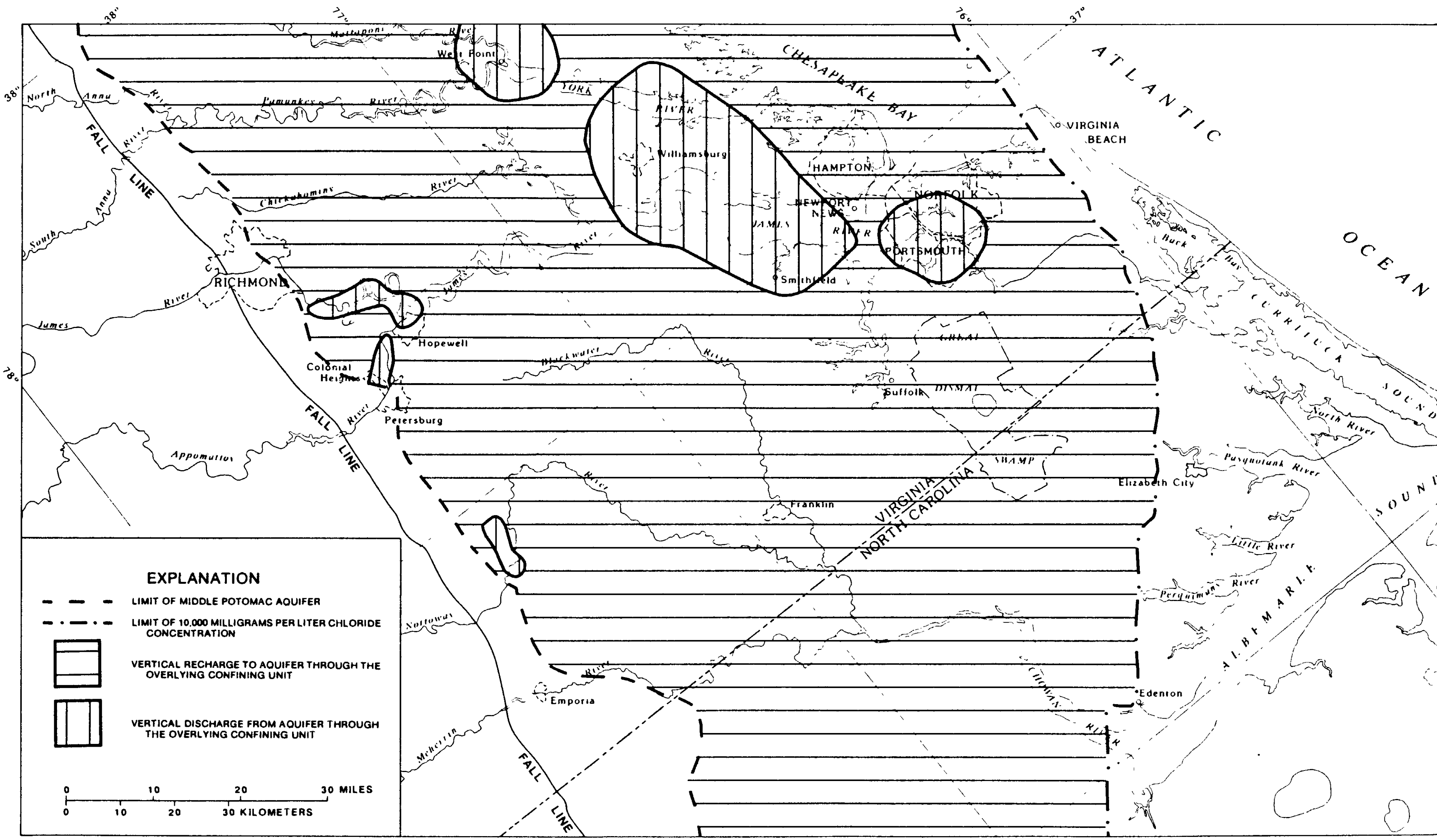


Figure 103.--Modeled areas of vertical recharge to and discharge from the middle Potomac aquifer through the overlying confining unit, scenario 2.

Discussion

Scenarios 1 and 2 indicated that water-level decline throughout southeastern Virginia would be substantial because of increased pumpage. The major consequence of increased pumpage would be considerable interference among ground-water users and would result in increased pumpage costs (costs could involve replacement of burned-out pumps or lowering of pumps). Another consequence would involve potential degradation of water quality from surface-water infiltration and upward flow from deeper aquifers. Induced surface-water infiltration to the ground-water system generally would occur in saltwater areas. Fortunately, these areas are not used heavily for freshwater supply, and the rate of infiltration would be relatively slow. Water quality also could degrade in those confined aquifers underlain by deeper aquifers containing saltwater. This could occur in the eastern part of the study area where water is discharging vertically from the lower Potomac to the middle Potomac aquifer and from the middle Potomac to the upper Potomac aquifer. The model cannot be used to project the degree and rate of water-quality degradation; however, it can be used to identify potential areas where water-quality problems could occur.

One potential consequence of increased scenario pumpage would be compaction of fine-grained materials in the system. The system potentially could move from the elastic (recoverable) to the inelastic range when sediment is subjected to stresses greater than previously experienced. On the basis of subsidence data collected in the cities of Suffolk and Franklin from 1978 to 1987 (which includes significant increases in pumpage in the Suffolk area during 1986 drought conditions), the system most likely would remain in the elastic mode of deformation and compaction consequences would be minimal (D.C. Hayes, U.S. Geological Survey, written commun., 1987).

Water levels would remain well above the tops of confined aquifers throughout most of the model area, indicating that sufficient recharge from the water-table aquifer and lateral boundary flow was available to replace the increased pumpage from the confined aquifers. West Point and Franklin are two areas where water levels could begin to approach the tops of aquifers (modeled water levels were within 100 feet of the tops). If water levels decline below the tops, unconfined (water-table) conditions would occur and would result in dewatering of the aquifers. Dewatering would contribute to compaction of aquifer sediment and subsidence in the areas. Aquifers in the West Point and Franklin areas are more vulnerable to induced unconfined conditions than other areas because the aquifers lie relatively close to the surface (the areas are in the updip parts of the aquifers) and pumpage is heavy.

Transient-Model Simulations of Injection into and Pumpage from Virginia Beach Emergency-Supply Wells

Five scenarios involving injection into and pumpage from five Virginia Beach emergency-supply wells located in the city of Suffolk, Isle of Wight County, and Southampton County were run. The scenarios were run using a transient solution to the ground-water flow equation and represented injection or increased pumpage for 5 years above average pumpage conditions in the final pumping period (1981-83). Several of the scenarios were run using shorter time intervals (months) than used in the transient model simulating 1891-1983 conditions.

Actual monthly pumpage for the final pumping period was not incorporated into the scenario runs; average pumpage for the period was used to represent each month. The shorter periods may not be long enough to minimize the effects of transient storage from confining units (as assumed in the transient model simulating 1891-1983 conditions). Model simulations that include water released from confining-unit storage would result in higher water levels than in model simulations that neglect water released from storage. Confining-unit storage was not simulated in the scenarios involving shorter periods. Modeled results for these scenarios would, therefore, represent maximum water-level change resulting from increases in pumpage or injection.

Locations of these wells are shown in figure 104. Latitudes, longitudes, State identification codes, design capacity of the wells, and aquifers penetrated by the wells are summarized in table 15. The wells primarily penetrate the middle Potomac aquifer. The wells were designed to be pumped during dry periods, allowing for recovery during wetter periods. Scenario 3 approximates this original well design and involves pumping the wells for 3 dry months each year for 5 years. Scenarios 4 through 7 present other pumpage or injection schemes as described below:

1) Scenario 3: Water was pumped from each well during July, August, and September for 5 years at design capacity (4 Mgal/d). This scenario demonstrates impacts of pumping the wells at design capacity during dry periods, allowing the wells to recover during wetter periods.

2) Scenario 4: Water was injected into each well during January, February, March, and April for 5 years at a rate of 1 Mgal/d. This scenario demonstrates benefits from injection on simulated 1983 water levels in the vicinity of the wells.

3) Scenario 5: Water was injected into each well during January, February, March, and April at a rate of 1 Mgal/d and pumped from the wells during July, August, and September at a rate of 4 Mgal/d for 5 years. This scenario demonstrates impacts of pumping the wells at design capacity during dry periods and improving water-level recovery with injection during wetter periods.

4) Scenario 6: Water was pumped year-round from each well for 5 years at a rate of 1 Mgal/d. The scenario demonstrates impacts of pumping an equal volume of water as in scenario 3 but at a lower rate and over a 1-year period instead of 3 months.

5) Scenario 7: Water was pumped year-round from each well for 5 years at design capacity (4 Mgal/d). This scenario demonstrates impacts of pumping the wells for continuous supply rather than for emergency use (dry periods) only.

Modeled water levels located in the middle Potomac aquifer in a node central to the five Virginia Beach wells (fig. 104) were assessed for the five scenarios. The results are described below, followed by a discussion of benefits derived from injection and impacts from 3-month and year-round pumpage. The modeled results presented in the text, figures, and tables are not

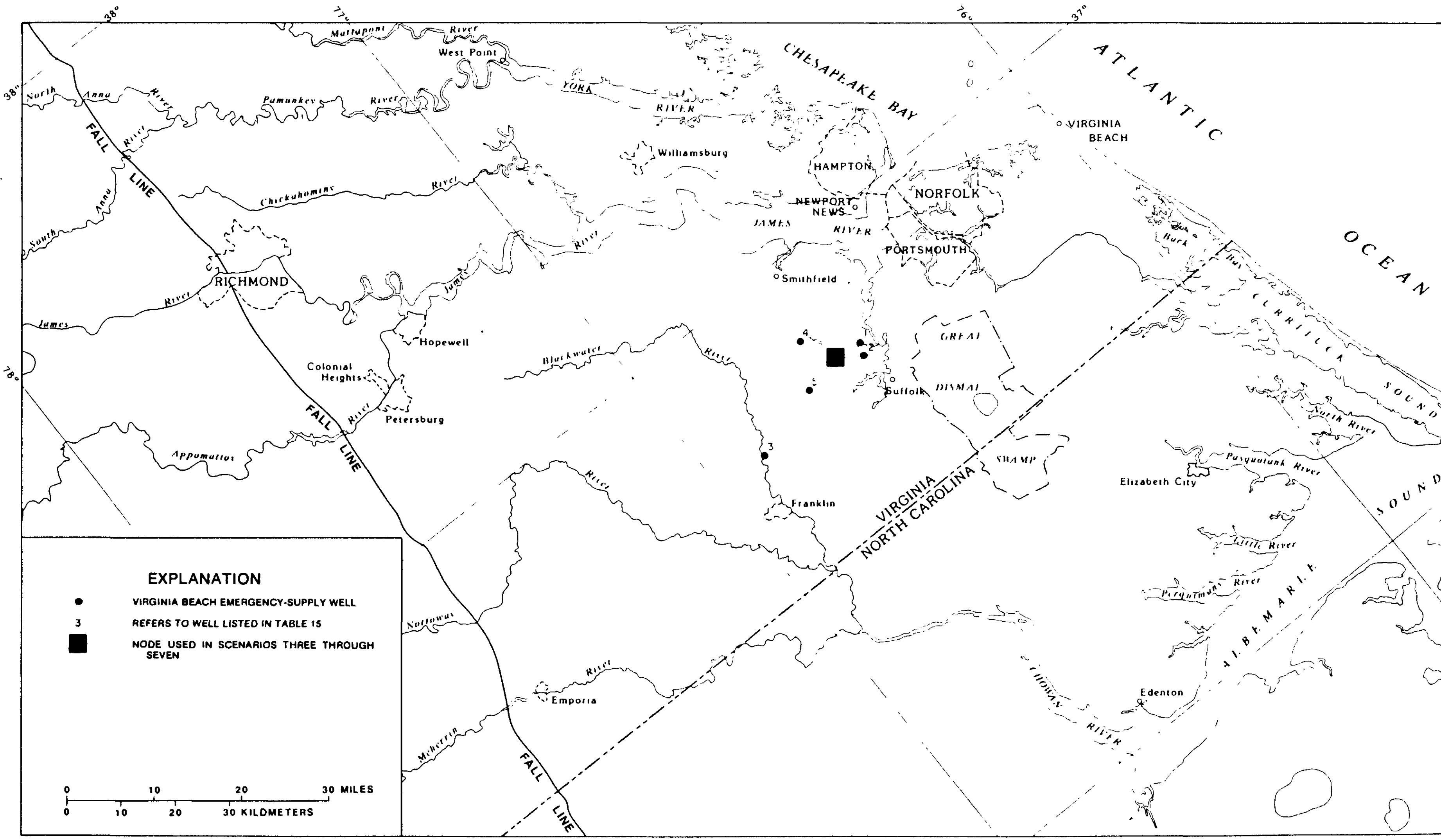


Figure 104.--Location of Virginia Beach emergency-supply wells.

intended to imply accuracy to the precision shown. Water levels in all scenarios would begin to stabilize after the simulated 5-year period, indicating that steady-state conditions were being approached.

Scenario 3

Modeled water levels for scenario 3 are presented in table 24 and figure 105. The projected water level, 78.4 feet below sea level at the end of 1983, would drop to approximately 109.0 feet in September 1984 after 3 months of pumpage. Following 9 months of no increased pumpage (June 1985), the water level would rise to approximately 82.5 feet, resulting in a water-level decline from 1983 of about 4.1 feet. The lowest water level would follow pumpage in the fifth year (September 1988) and equal approximately 113.9 feet, resulting in a maximum 35.5 feet water-level decline during the 5-year period. The 9-month recovery period following this decline extends into a sixth year and was not simulated. Because near steady-state conditions would exist, the water level following recovery (June 1989) would be similar to June 1988--approximately 84.4 feet. Water-level decline after five pumpage/recovery cycles would, therefore, be about 6.0 feet from 1983.

Table 24.--Modeled water levels, scenario 3

[Modeled values, in feet, are reported to tenths and are not intended to imply accuracy to the precision shown; datum is sea level]

	January	February	March	April	May	June	July	August	September	October	November	December
1983												-78.4
1984	-78.4	-78.4	-78.4	-78.4	-78.4	-78.3	-98.1	-105.0	-109.0	-92.1	-87.5	-85.3
1985	-84.1	-83.3	-83.0	-82.8	-82.6	-82.5	-101.8	-108.5	-112.1	-95.0	-90.2	-87.8
1986	-86.4	-85.5	-84.7	-84.1	-83.6	-83.5	-102.8	-109.5	-113.1	-95.9	-91.1	-88.7
1987	-87.3	-86.3	-85.5	-84.8	-84.3	-84.1	-103.5	-110.1	-113.7	-96.5	-91.6	-89.2
1988	-87.7	-86.8	-85.9	-85.3	-84.7	-84.4	-103.7	-110.3	-113.9	-96.7	-91.8	-89.4

Scenario 4

Modeled water levels for scenario 4 are presented in table 25 and figure 106. The projected water level, 78.4 feet below sea level at the end of 1983, would rise to approximately 69.8 feet in April 1984. Following 8 months with no injection, the water level would drop to 76.1 feet, resulting in a gain of 2.3 feet after 1 year. The greatest rise would occur following injection in the fifth year (April 1988), equalling approximately 67.0 feet and resulting in a maximum rise of 11.4 feet from the 1983 water level. The overall increase in water level after 5 years (December 1988) would be 4.6 feet.

Scenario 5

Modeled water levels for scenario 5 are presented in table 26. The projected water level, 78.4 feet below sea level at the end of 1983, would rise

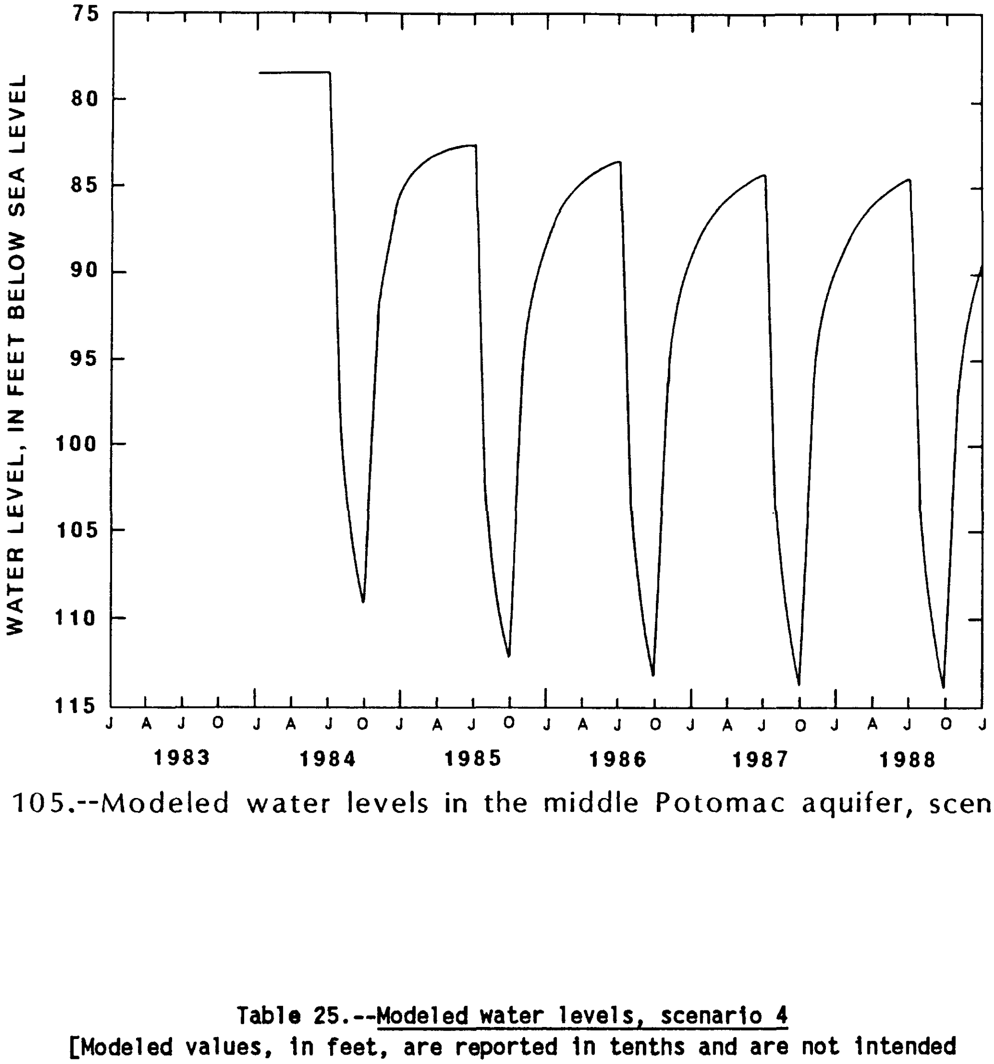


Figure 105.--Modeled water levels in the middle Potomac aquifer, scenario 3.

Table 25.--Modeled water levels, scenario 4
[Modeled values, in feet, are reported in tenths and are not intended to imply accuracy to the precision shown; datum is sea level]

	January	February	March	April	May	June	July	August	September	October	November	December
1983												-78.4
1984	-73.4	-71.7	-70.6	-69.8	-74.1	-75.3	-75.6	-75.8	-75.9	-76.0	-76.1	-76.1
1985	-71.4	-69.9	-68.9	-68.5	-72.9	-74.1	-74.5	-74.6	-74.8	-74.9	-75.0	-75.1
1986	-70.4	-68.9	-68.0	-67.8	-72.2	-73.5	-73.9	-74.1	-74.2	-74.3	-74.4	-74.5
1987	-69.9	-68.4	-67.5	-67.3	-71.7	-73.0	-73.5	-73.7	-73.8	-73.9	-74.0	-74.1
1988	-69.5	-68.0	-67.2	-67.0	-71.4	-72.7	-73.2	-73.4	-73.5	-73.6	-73.7	-73.8

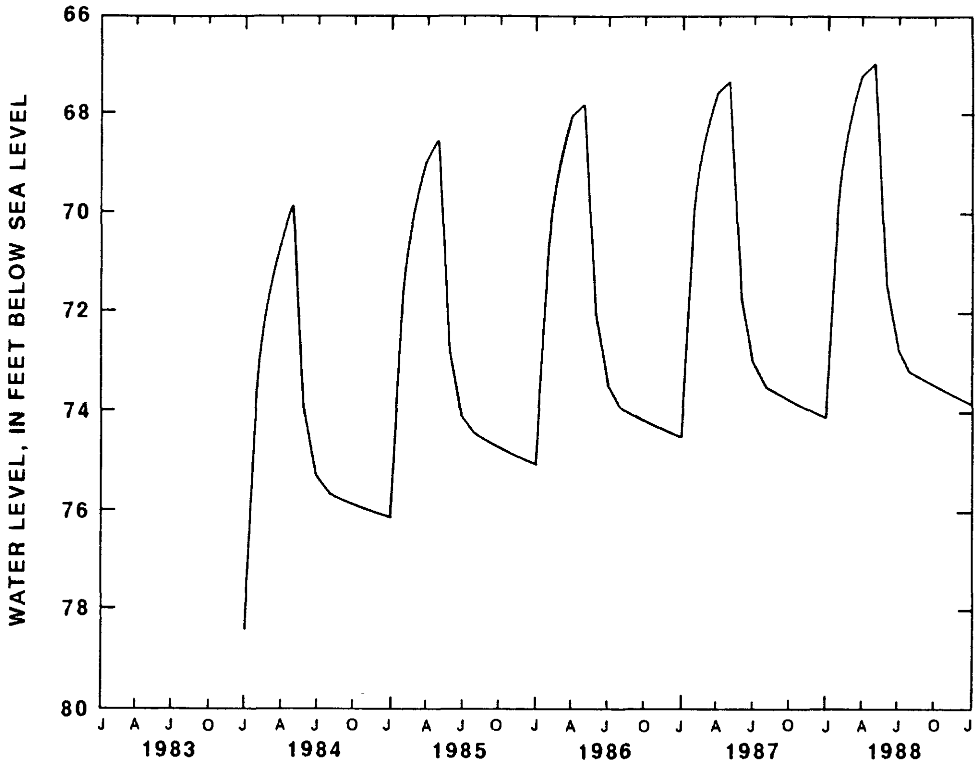


Figure 106.--Modeled water levels in the middle Potomac aquifer, scenario 4.

Table 26.--Modeled water levels, scenario 5
[Modeled values, in feet, are reported in tenths and are not intended imply accuracy to the precision shown; datum is sea level]

	January	February	March	April	May	June	July	August	September	October	November	December
83												-78.4
84	-73.3	-71.7	-70.6	-69.8	-74.1	-75.3	-95.7	-103.0	-107.1	-90.4	-86.0	-83.9
85	-77.8	-75.5	-73.9	-72.8	-76.8	-77.7	-97.9	-105.0	-109.0	-92.1	-87.6	-85.5
86	-79.3	-76.9	-75.2	-73.9	-77.9	-78.8	-98.8	-105.9	-109.9	-93.0	-88.4	-86.2
87	-80.0	-77.5	-75.8	-74.5	-78.4	-79.3	-99.3	-106.4	-110.3	-93.4	-88.8	-86.6
88	-80.3	-77.9	-76.1	-74.8	-78.7	-79.6	-99.6	-106.6	-110.5	-93.6	-89.0	-86.8

to about 69.8 feet in April 1984 following injection and drop to approximately 107.1 feet in September 1984 following pumpage. The water level would then rise to about 77.7 feet after a 9-month recovery period (including 4 months of injection), resulting in an increase of 0.7 feet above the 1983 water level. The lowest water level would follow pumpage in the fifth year (September 1988) and equal about 110.5 feet, resulting in a maximum 32.1 feet water-level decline for the 5-year simulation. The 9-month recovery period following this decline extends into a sixth year and was not simulated. Because near steady-state conditions would exist, the water level following recovery (June 1989) would be similar to June 1988--approximately 79.6 feet. Water-level decline after five pumpage/recovery cycles would, therefore, be about 1.2 feet from 1983.

Scenario 6

Modeled water levels for scenario 6 are presented in figure 107. The projected water level, 78.4 feet at the end of 1983, would drop to about 90.4 feet at the end of 1988, resulting in a total water-level decline of about 12.0 feet over the 5-year period.

Scenario 7

Modeled water levels for scenario 7 are presented in figure 107. The projected water level, 78.4 feet at the end of 1983, would drop to about 137.2 feet at the end of 1988, resulting in a total water-level decline of about 58.8 feet over the 5-year period.

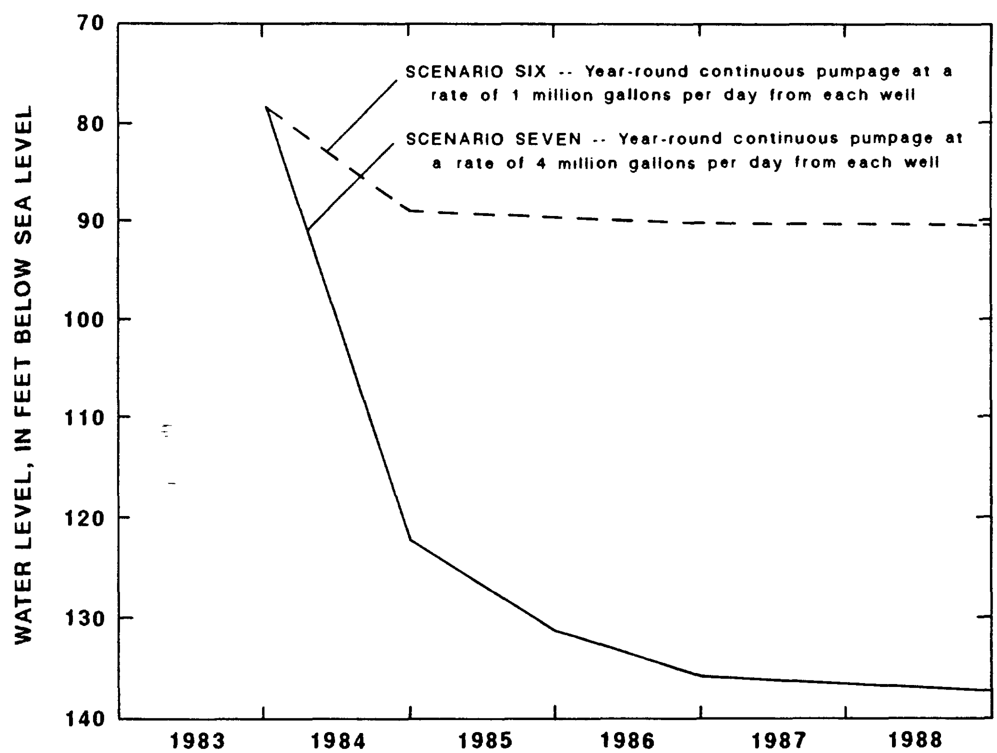


Figure 107.--Modeled water levels in the middle Potomac aquifer, scenarios 6 and 7.

Discussion

Modeled water levels were used to assess benefits derived from injection into and impacts due to 3-month and year-round pumpage from 5 Virginia Beach emergency-supply wells. As discussed previously, modeled results for scenarios 3 through 5 represent maximum water-level changes resulting from increased pumpage or injection because water released from confining-unit storage was not included in the simulations. Increases in water levels because of injection would be minimal, as shown in scenarios 4 and 5. The overall increase above simulated 1983 conditions after 5 years would be 4.6 feet (scenario 4). Improvement in water levels due to 4-month injection during a 9-month recovery period is shown in table 27 and figure 108 (comparison made between scenarios 3 and 5). During the month of maximum water-level decline (September 1988), injection would only increase water levels by 3.4 feet. Water levels after the 9-month recovery period following this decline would only be improved by 4.8 feet (approximated by June 1988 value).

Table 27.--Increase in modeled water levels as a result of injection
[Modeled values, in feet, are reported in tenths and are not intended to imply accuracy to the precision shown; datum is sea level]

	January	February	March	April	May	June	July	August	September	October	November	December
1984	5.1	6.7	7.8	8.6	4.3	3.0	2.4	2.0	1.9	1.7	1.5	1.4
1985	6.3	7.8	9.1	10.0	5.8	4.8	3.9	3.5	3.1	2.9	2.3	2.3
1986	7.1	8.6	9.5	10.2	5.7	4.7	4.0	3.6	3.2	2.9	2.7	2.5
1987	7.3	8.8	9.7	10.3	5.9	4.8	4.2	3.7	3.4	3.1	2.8	2.6
1988	7.4	8.9	9.8	10.5	6.0	4.8	4.1	3.7	3.4	3.1	2.8	2.6

Maximum water-level decline that would result from year-round pumpage at a rate of 1 Mgal/d for 5 years would be approximately 12.0 feet. The water levels generally would be lower (maximum of 7.0 feet) throughout the 5-year period than those resulting from pumping an equivalent volume of water during 3 months of the year at a higher rate of 4 Mgal/d (fig. 109). However, water levels would be approximately 24 feet higher in September each year--the time corresponding to the end of the 3-month pumpage in scenario 3. Year-round pumpage at a lower rate would, therefore, prevent periods of extreme water-level decline during which other users might be adversely affected. It would, however, require facilities for storing the ground water throughout the year if the water were to be used only for dry periods. This could be quite costly.

Water levels would decline by approximately 58.8 feet after 5 years if the wells were pumped year-round at design capacity. Water levels would be significantly lower throughout a 5-year period if the wells were pumped for continuous supply rather than emergency supply (dry periods) only (fig. 110). A 9-month recovery period would, therefore, play an important role in restoring water levels in the area.

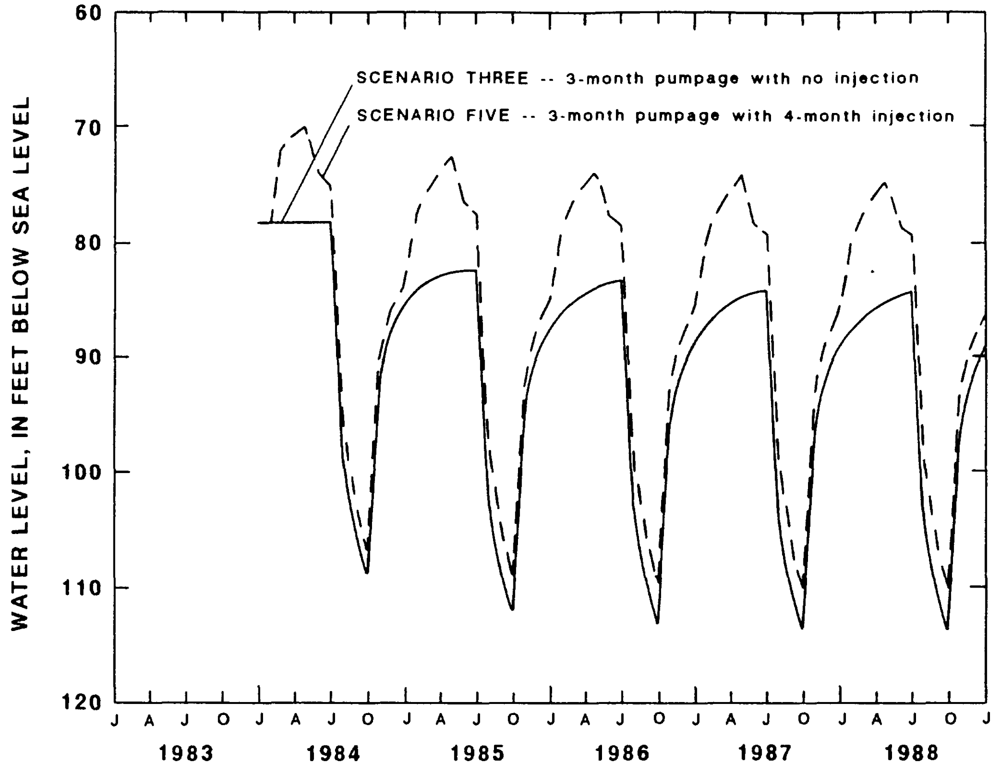


Figure 108.--Comparison between modeled water levels in scenarios 3 and 5.

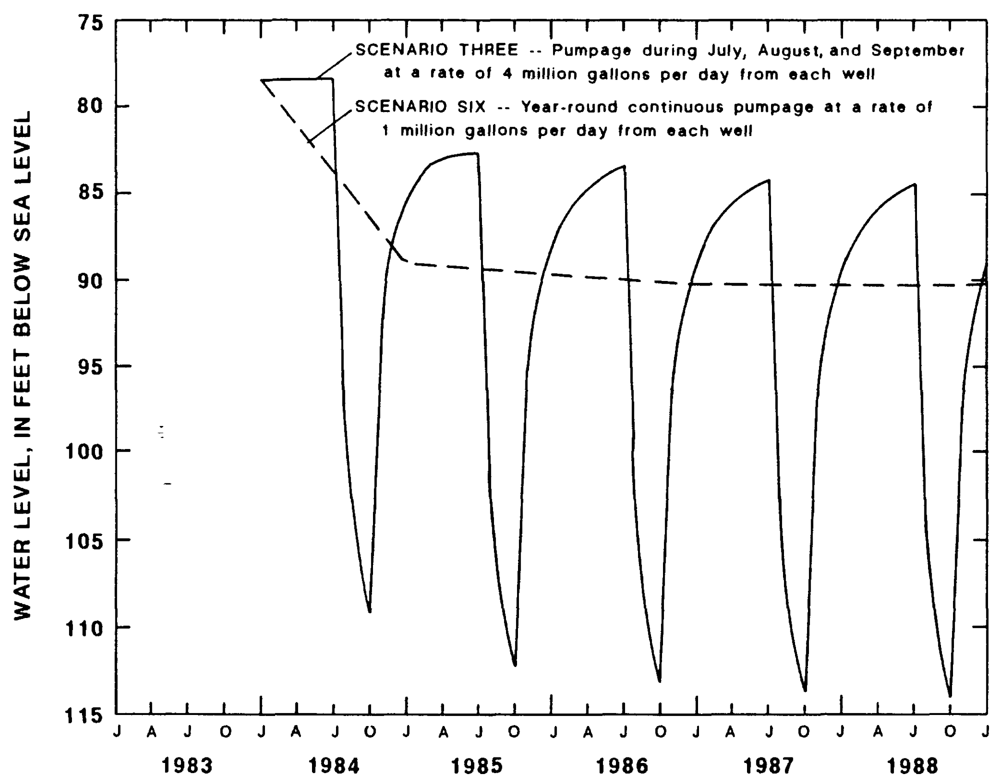


Figure 109.--Comparison between modeled water levels in scenarios 3 and 6.

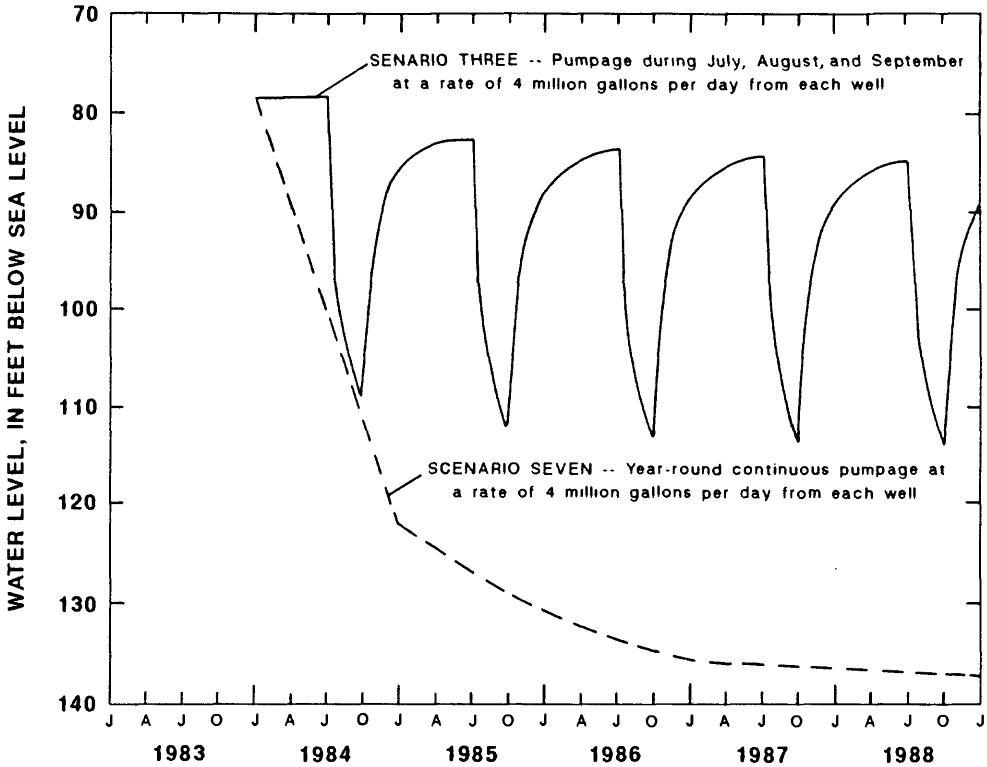


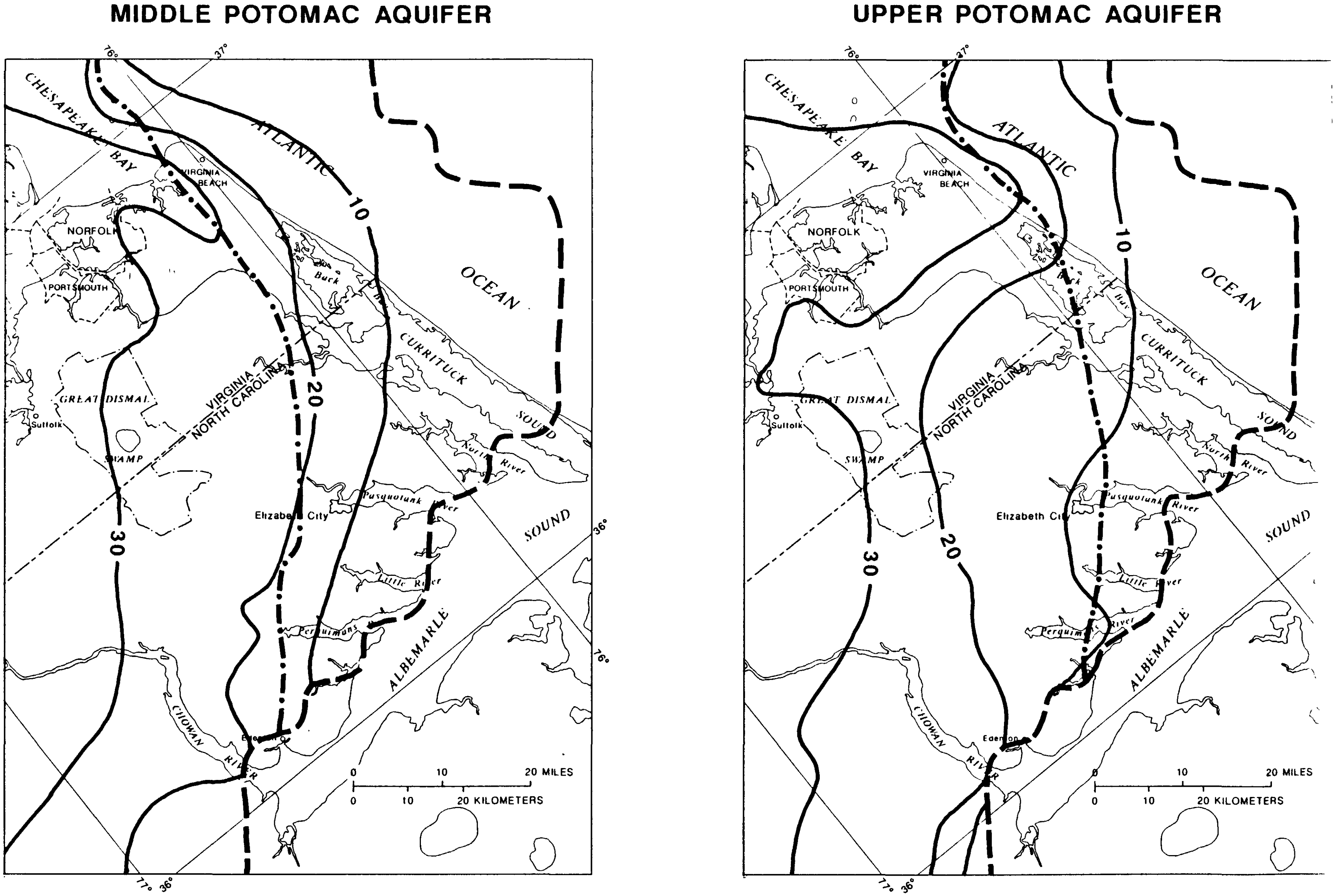
Figure 110.--Comparison between modeled water levels in scenarios 3 and 7.

Sensitivity Analysis

A sensitivity simulation was conducted to test the effect of locating the stationary eastern no-flow boundary at the 10,000 mg/L chloride concentration within each aquifer. The position of this boundary potentially could affect water levels and rates of ground-water flow when pumpage is increased or the spatial distribution of pumpers, particularly in the eastern part of the study area, is changed. In the sensitivity simulation, the extent of the freshwater system was expanded eastward by moving the eastern no-flow boundary in all aquifers seaward to a position representing the 10,000 mg/L chloride concentration in the uppermost confined aquifer (fig. 27). The simulation involved scenario 1 pumping conditions because scenario 1 represents the heaviest pumpage and the largest increases in pumpage near the eastern part of the model that were simulated in this report.

Water levels resulting from the sensitivity simulation were in general agreement with those resulting from scenario 1 throughout all aquifers. Slightly higher water levels did result in the eastern part of the lower, middle, and upper Potomac aquifers in the sensitivity simulation because of the additional flow of water from the east.

Water-level gradients were assessed, and rates of lateral ground-water flow were calculated by means of Darcy's Law on the basis of modeled head gradients and an assumed porosity of 0.4. Figure 111 illustrates rates of lateral ground-water flow in the middle and upper Potomac aquifers in the eastern part of the model area assuming a seaward position of the eastern no-flow boundary. The figure suggests that water would move at a rate of about



EXPLANATION

- ▬ • ▬ • ▬ ORIGINAL PLACEMENT OF EASTERN NO-FLOW BOUNDARY
- ▬ ▬ ▬ SEAWARD PLACEMENT OF EASTERN NO-FLOW BOUNDARY
- —20— LINE OF EQUAL RATE OF LATERAL FLOW -- Interval is 10 feet per year. Values exceeding 30 feet are not shown.

Figure 111.--Modeled rates of lateral flow in the eastern part of the middle and upper Potomac aquifers resulting from sensitivity analysis

10 to 30 ft/yr (feet per year) in the vicinity of the original position of the eastern no-flow boundary, taking about 300 to 900 years to move the distance of one grid block. Effects of saline water within the expanded model area were not considered when calculating rates of lateral flow; however, saline water would impede lateral flow and, therefore, the assumption of freshwater within the expanded area would result in maximum flow rates (P.P. Leahy, U.S. Geological Survey, written commun., 1987). These findings indicate that lateral flow of water in the vicinity of the original eastern no-flow boundary approximated at the 10,000 mg/L chloride concentration within each aquifer would be negligible under scenario 1 pumping conditions, considering the spatial and temporal discretization of the model. The model is, therefore, not sensitive to the stationary no-flow boundary at the 10,000 mg/L chloride concentration for the pumping conditions presented in this report.

Sensitivity analysis also is used to test the response of a calibrated model to changes in hydraulic characteristics. An individual characteristic is increased or decreased within its expected range while all other characteristics remain unchanged and resulting water-level changes are assessed. Significant changes in water levels indicate that a model is sensitive to a particular characteristic. Results from sensitivity analyses done by Harsh and Laczniak (1986) were used as the basis for sensitivity analysis in this study because model conceptualization of the ground-water flow system and model parameters were similar. Many variations to hydraulic characteristics were used in Harsh and Laczniak to test model sensitivity. Variations were made to transmissivity and storage coefficient of confined aquifers and vertical leakance of confining units. The sensitivity analyses showed that simulated water levels were more sensitive to decreases in selected values of transmissivity and vertical leakance than to increases. Analyses also showed that changes to values for transmissivity and vertical leakance in the middle Potomac aquifer and confining unit, respectively, had the greatest effect on water levels throughout the ground-water system. Analyses for storage coefficient showed that the system was sensitive to an increase in storage coefficient by one order of magnitude and insensitive to a decrease of one order of magnitude.

On the basis of Harsh and Laczniak results, values for transmissivity and vertical leakance of the middle Potomac aquifer and confining unit, respectively, were varied to demonstrate the effect of the sensitivity of this model on scenario 1 results. Scenario 1 was selected because pumpage, primarily from the middle Potomac aquifer, significantly affected water levels throughout the ground-water system. No sensitivity analysis was done for storage coefficient because scenario 1 was a steady-state simulation. Table 28 summarizes water levels in five nodes in the middle Potomac aquifer resulting from a 50-percent decrease and increase in transmissivity and vertical leakance. Locations of these five nodes are shown in figure 112. Node 1 is located central to scenario 1 pumpage and the remaining 4 nodes are located at increased distances from the pumpage. Sensitivity analysis showed that the model was more sensitive to changes in transmissivity than to vertical leakance near the pumpage. For example, in node 1, a 50-percent reduction in transmissivity resulted in a 41.4-percent decrease in water level from scenario 1 results (a decrease of approximately 116.2 feet) and a 50-percent reduction in vertical leakance only resulted in a 11.9-percent decrease in water level (a decrease of about 33.5

Table 28.--Modeled water levels resulting from sensitivity runs at selected nodes in the middle Potomac aquifer

[Modeled values, in feet, are reported in tenths and are not intended to imply accuracy to the precision shown; datum is sea level]

Node 1[a]

	Water level	Difference in water level between scenario I and sensitivity run	Percent increase or decrease in water level
Scenario 1	-280.8		
50-percent decrease in transmissivity	-397.0	-116.2	41.4-percent decrease
50-percent increase in transmissivity	-223.2	57.6	20.5-percent increase
50-percent decrease in vertical leakance	-314.3	-33.5	11.9-percent decrease
50-percent increase in vertical leakance	-267.5	13.3	4.7-percent increase

Node 2[a]

	Water level	Difference in water level between scenario I and sensitivity run	Percent increase or decrease in water level
Scenario 1	-135.5		
50-percent decrease in transmissivity	-163.9	-28.4	21.0-percent decrease
50-percent increase in transmissivity	-115.0	20.5	15.1-percent increase
50-percent decrease in vertical leakance	-164.8	-29.3	21.6-percent decrease
50-percent increase in vertical leakance	-124.2	11.3	8.3-percent increase

Node 3[a]

	Water level	Difference in water level between scenario I and sensitivity run	Percent increase or decrease in water level
Scenario 1	-201.3		
50-percent decrease in transmissivity	-245.8	-44.5	22.1-percent decrease
50-percent increase in transmissivity	-170.4	30.9	15.4-percent increase
50-percent decrease in vertical leakance	-234.0	-32.7	16.2-percent decrease
50-percent increase in vertical leakance	-189.0	12.3	6.1-percent increase

Node 4[a]

	Water level	Difference in water level between scenario I and sensitivity run	Percent increase or decrease in water level
Scenario 1	-83.1		
50-percent decrease in transmissivity	-97.3	-14.2	17.1-percent decrease
50-percent increase in transmissivity	-71.7	11.4	13.7-percent increase
50-percent decrease in vertical leakance	-108.9	-25.8	31.0-percent decrease
50-percent increase in vertical leakance	-73.3	9.8	11.8-percent increase

Node 5[a]

	Water level	Difference in water level between scenario I and sensitivity run	Percent increase or decrease in water level
Scenario 1	-36.1		
50-percent decrease in transmissivity	-38.7	-2.6	7.2-percent decrease
50-percent increase in transmissivity	-32.2	3.9	10.8-percent increase
50-percent decrease in vertical leakance	-58.2	-22.1	61.2-percent decrease
50-percent increase in vertical leakance	-27.8	8.3	23.0-percent increase

[a]Location of node on figure 112.

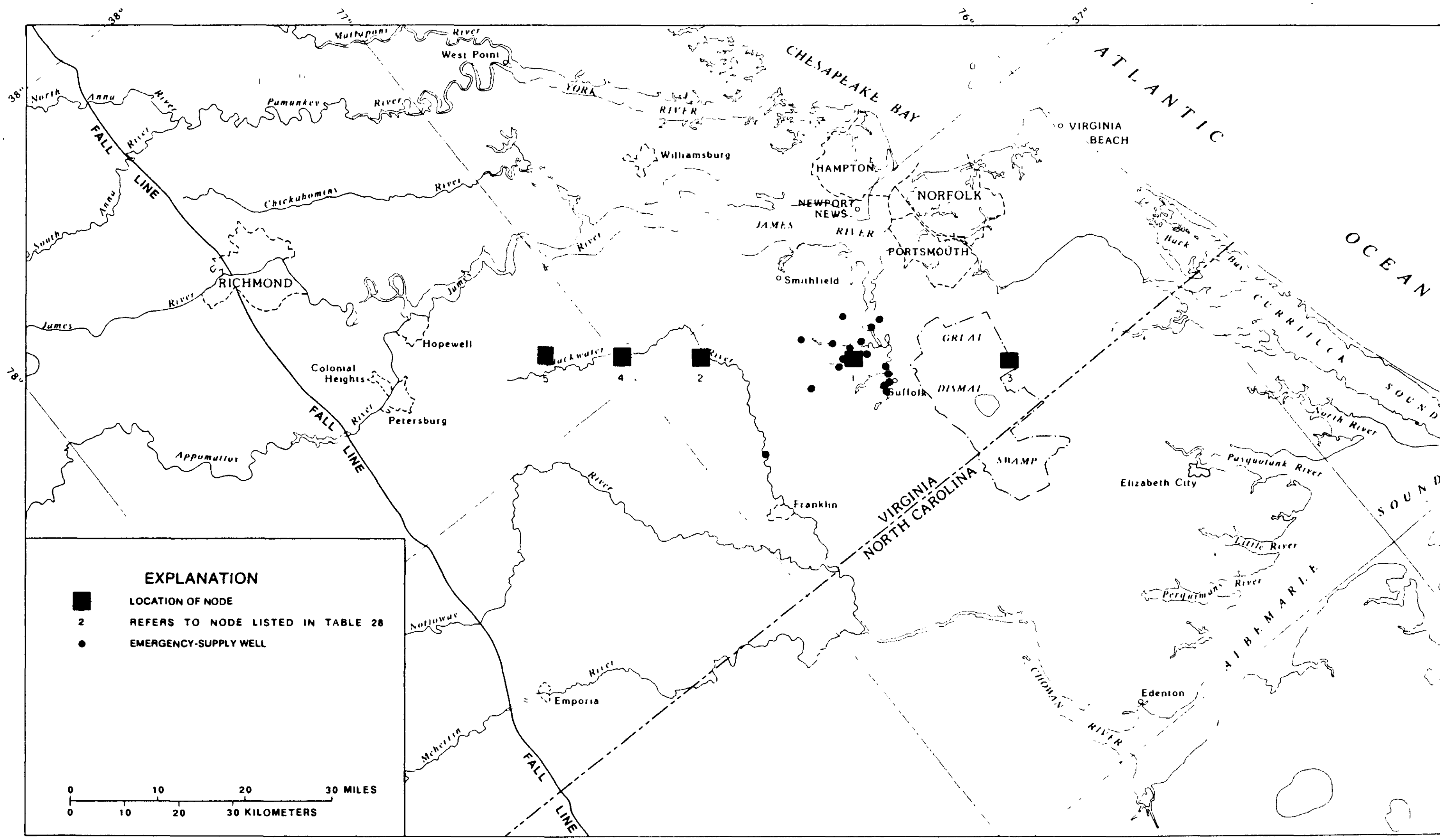


Figure 112.--Location of nodes used in sensitivity analysis.

feet) (table 28). The same trend occurred when the characteristics were increased by 50 percent--a 50-percent increase in transmissivity resulted in a 20.5-percent increase in water level (an increase of approximately 57.6 feet) and a 50-percent increase in vertical leakance only resulted in a 4.7-percent increase in water level (an increase of 13.3 feet).

The model is less sensitive to changes in transmissivity and more sensitive to changes in vertical leakance away from the pumpage center. For example, water levels in nodes 2 and 3, located approximately 20 miles west and east of the pumpage, decreased by about 21 to 22 percent when transmissivity was reduced by 50 percent and decreased by approximately 16 to 22 percent when vertical leakance was reduced by 50 percent (table 28). Approximately 40 miles away from the pumpage (node 5), the model was very sensitive to vertical leakance. Water levels decreased by 61.2 percent with a 50-percent reduction in vertical leakance and only decreased by about 7.2 percent with a 50-percent reduction in transmissivity (table 28). Water levels resulting from the sensitivity analyses for nodes 1, 2, and 5 are presented in figure 113.

As shown in Harsh and Laczniak (1986) and as indicated in table 28 and figure 113, the model generally is more sensitive to decreases than increases in these characteristics. This trend is particularly apparent in node 1 where the model is very sensitive to decreases in transmissivity, and in node 5 where the model is sensitive to decreases in vertical leakance.

Figure 114 and table 29 summarize water-level changes in the lower, middle, and upper Potomac aquifers at node 1 as a result of changes of hydraulic characteristics in the middle Potomac aquifer. Similar trends are seen in these underlying and overlying aquifers--the model is more sensitive to transmissivity than vertical leakance in the area of pumpage and is more sensitive to decreases in hydraulic characteristics than to increases.

Model Limitations

The model incorporated hydrogeologic characteristics of the aquifers and confining units to determine net effects of pumpage on a regional scale. Definition of well interference, water levels, water budgets, and surface-water losses and gains on a smaller scale would require a more refined model with finer grid spacing and shorter time intervals. In addition, data on streambed leakance, baseflows, and pumpage within the water-table aquifer would be necessary to improve accuracy of simulated flow between the ground-water and surface-water systems.

Pumpage primarily occurs in the confined system and, therefore, the model primarily was used to analyze ground-water flow within confined aquifers. Average altitude of surface water was incorporated into the model as an upper boundary condition and used to approximate regional recharge-discharge relations between surface water and the water-table aquifer. Detailed analysis of flow within the water-table aquifer would require better definition of flow between this aquifer and surface water and better definition of pumpage within the water-table aquifer.

The model can be used to identify areas where water levels approach the tops of aquifers; however, it was not developed to simulate an actual conversion from confined to unconfined conditions. If future pumpage increases so

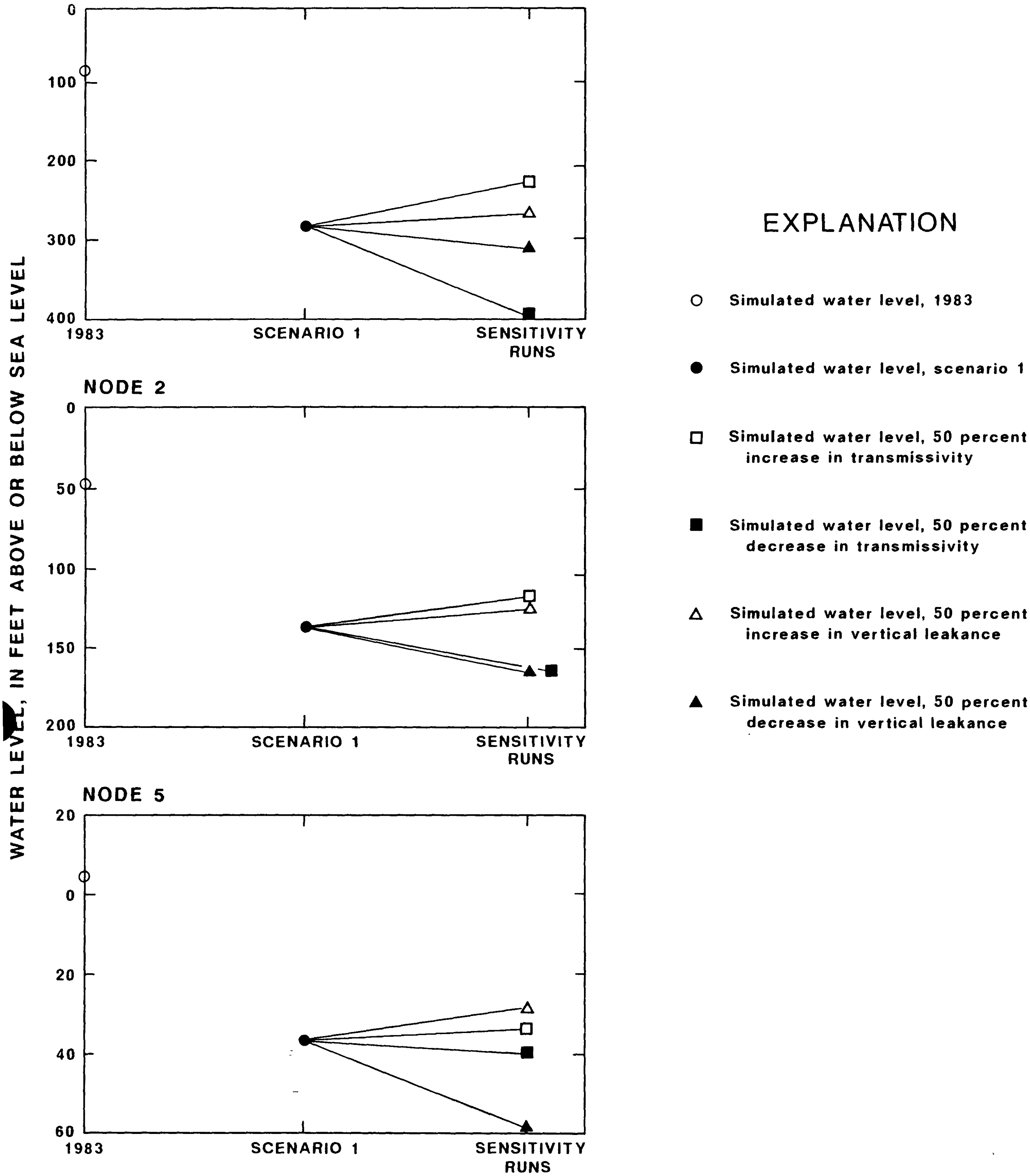


Figure 113.--Modeled water levels resulting from sensitivity analysis in the middle Potomac aquifer at three selected nodes.

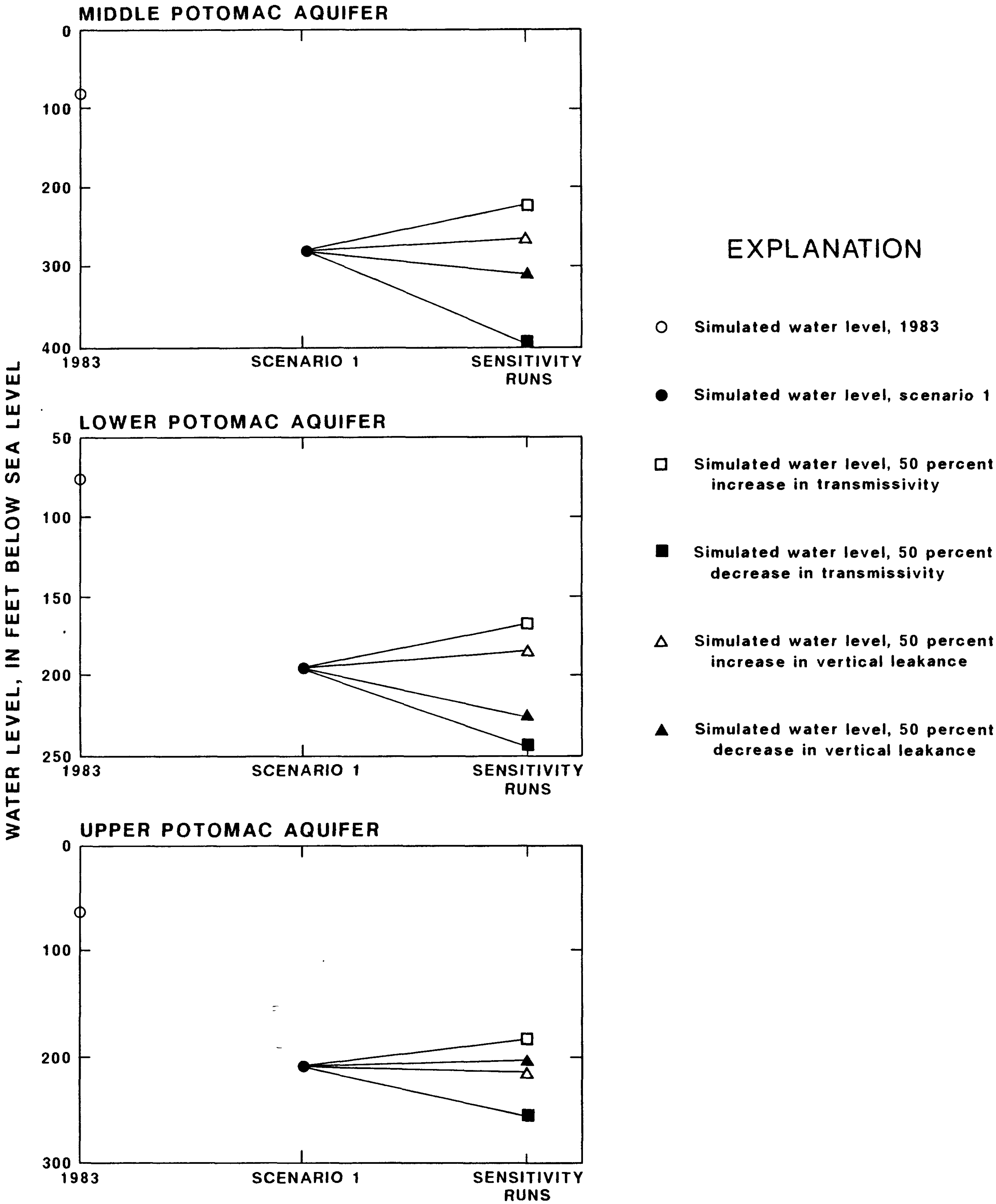


Figure 114.--Modeled water levels resulting from sensitivity analysis in the lower, middle, and upper Potomac aquifers at a node central to pumpage.

Table 29.--Modeled water levels resulting from sensitivity analysis at a representative node in the lower, middle, and upper Potomac aquifers

[Modeled values, in feet, are reported in tenths and are not intended to imply accuracy to the precision shown; datum is sea level]

Middle Potomac aquifer - Node 1[a]

	Water level	Difference in water level between scenario 1 and sensitivity run	Percent increase or decrease in water level
Scenario 1	-280.8		
50-percent decrease in transmissivity	-397.0	-116.2	41.4-percent decrease
50-percent increase in transmissivity	-223.2	57.6	20.5-percent increase
50-percent decrease in vertical leakance	-314.3	-33.5	11.9-percent decrease
50-percent increase in vertical leakance	-267.5	13.3	4.7-percent increase

Lower Potomac aquifer - Node 1

	Water level	Difference in water level between scenario 1 and sensitivity run	Percent increase or decrease in water level
Scenario 1	-195.8		
50-percent decrease in transmissivity	-244.0	-48.2	24.6-percent decrease
50-percent increase in transmissivity	-165.9	29.9	15.3-percent increase
50-percent decrease in vertical leakance	-227.0	-31.2	15.9-percent decrease
50-percent increase in vertical leakance	-183.7	12.1	6.2-percent increase

Upper Potomac aquifer - Node 1

	Water level	Difference in water level between scenario 1 and sensitivity run	Percent increase or decrease in water level
Scenario 1	-209.6		
50-percent decrease in transmissivity	-256.9	-47.3	22.6-percent decrease
50-percent increase in transmissivity	-181.3	28.3	13.5-percent increase
50-percent decrease in vertical leakance	-202.7	6.9	3.3-percent increase
50-percent increase in vertical leakance	-212.9	-3.3	1.6-percent decrease

[a]Location of node on figure 112.

that measured water levels drop below the tops of aquifers, the model would need modification and additional input such as elevations of the bottom of each confined aquifer.

The eastern boundary within each aquifer represents an assumed freshwater-saltwater interface located where the ground water contains concentrations of chloride of 10,000 mg/L. It is assumed to be a stationary no-flow boundary. Variations in salinity and their effects on the ground-water flow system, as well as the potential movement of the freshwater-saltwater interface under natural or pumping conditions, are not considered in this model. Sensitivity analysis showed that a stationary no-flow boundary at the 10,000 mg/L chloride concentration was reasonable for the pumping conditions simulated in this report. However, these assumptions could limit use of the model when pumpage is significantly increased or the spatial distribution of pumpage is changed, particularly in the eastern part of the model. Modifications should be made in the model to (1) include variations in salinity (incorporating density effects) and (2) track the movement of the freshwater-saltwater interface through time. Additional data are necessary to define salinity variations and the movement of the interface, such as time-dependent chloride concentrations and a large-scale pump test in southeastern Virginia. This ground-water flow model provides a foundation for understanding the ground-water flow system in southeastern Virginia; however, because of the nearby presence of saltwater, it is critical that this eastern boundary condition be studied further before the model has unlimited applicability.

The model does not simulate water released from confining-unit storage. Confining-unit storage is assumed negligible because simulation periods are generally long enough (greater than 3 years) to minimize its effect (Harsh and Laczniak, 1986). Modeled results for simulations involving shorter time periods, such as those simulated in scenarios 3 and 5, represent lower water levels than what might actually occur. Simulation of confining-unit storage would require modification to the model based on additional data defining confining-unit characteristics.

SUMMARY AND CONCLUSIONS

Hydrogeology and the ground-water flow system in the Coastal Plain physiographic province of southeastern Virginia were analyzed, and the continued reliability of ground water as a resource was assessed. The study primarily focused on hydrogeologic characteristics of the multiaquifer system, development and refinement of a digital, ground-water flow model, and analysis of future conditions resulting from potential injection or increased pumpage.

Ground water is an important resource in southeastern Virginia. Since the early 1900's, steadily increasing pumpage has resulted in declining water levels, major cones of depression that expand from industrial and population centers, and potential contamination by saltwater encroachment. Commercial, industrial, and municipal withdrawals in southeastern Virginia increased from less than 10 Mgal/d in 1891 to about 55 Mgal/d in 1983. Major pumpage centers are the town of Smithfield and the cities of Franklin, Newport News, and Suffolk.

The Coastal Plain physiographic province of southeastern Virginia is underlain by unconsolidated sediments, dipping and thickening eastward. The sediments primarily consist of sand, clay, silt, and gravel with variable amounts of shell material lying directly upon granitic basement. On the basis of lithologic and hydrologic analysis of the sediments, a hydrogeologic framework consisting of a water-table aquifer and seven confined aquifers and intervening confining units was identified. Values for transmissivity, vertical leakance, and storage which describe the ability of an aquifer to transmit, store, or release water were defined. Transmissivity generally increases eastward (downdip) from the western limit of an aquifer and begins to decrease toward its eastern limit. Transmissivity is highest in the Potomac aquifers. Vertical leakance generally decreases from west to east. Deeper confining units are characterized by relatively low vertical leakance. Relatively high values occur within a confining unit where original sediment was eroded and replaced with more permeable river material.

The ground-water flow system is bounded by granitic basement, the Fall Line to the west, and the freshwater-saltwater interface to the east. Ground-water flow was conceptualized from known hydrogeology and water-level observations beginning in the late 1800's. Under prepumping conditions, assumed to have existed prior to 1891, a hydraulic equilibrium prevailed in the multiaquifer system. Water recharged the water-table aquifer, moved laterally in the direction of decreasing water levels, and ultimately discharged to streams, swamps, Chesapeake Bay, and the Atlantic Ocean. Some water also moved vertically from the water-table aquifer through confining units to recharge the confined system. Downward movement occurred along a narrow band running parallel to the Fall Line and in higher elevations between major river valleys. Lateral movement predominantly occurred within the confined aquifers from the Fall Line toward Chesapeake Bay and the Atlantic Ocean and from interfluves toward major river valleys. The laterally-flowing fresh ground water eventually encountered saltwater beneath the eastern parts of the study area, moved upward through confining units, and ultimately discharged to Chesapeake Bay and the Atlantic Ocean. Vertical flow through the confining units was enhanced by channel incision in Chesapeake Bay and adjoining tributaries where confining units were partially or completely eroded and replaced by more permeable material. Under pumping conditions, pumpage from the confined system lowered water levels, resulting in extensive cones of depression and flow toward major pumpage centers.

To provide a more detailed analysis of water-level decline and ground-water flow, a three-dimensional, digital, ground-water flow model which incorporated hydrogeologic characteristics of the aquifers and confining units was developed for prepumping and pumping conditions. The model area extended into the York-James Peninsula and northern part of North Carolina to include ground-water users affecting flow in southeastern Virginia, such as the town of West Point and the city of Williamsburg. Pumping conditions were simulated from 1891, when estimated pumpage from the model area was less than 10 Mgal/d, through 1983 when estimated pumpage was approximately 87 Mgal/d. The model was used to determine net effects of historic pumpage and potential injection or increased pumpage on regional water levels, ground-water flow, water budgets, and surface-water/ground-water relations.

Model results for prepumping conditions were consistent with known water-level data and the previously conceptualized ground-water flow pattern. Water moved regionally from the Fall Line toward Chesapeake Bay and the Atlantic Ocean and locally to streams, swamps, and bays. Under prepumping conditions, a hydraulic equilibrium prevailed in the multiaquifer system--simulated recharge to the water-table aquifer (about 4,780.8 Mgal/d) approximated ground-water discharge to surface water (about 4,775.8 Mgal/d). The small difference in recharge and discharge was attributed to lateral flow across the northern and southern boundaries of the model area.

Model results for pumping conditions also were consistent with known water-level data, including a significant water-level decline greater than 250 feet that occurred in the lower and middle Potomac aquifers in the Franklin area. Substantial water-level decline (greater than 90 feet) also occurred in these aquifers in the West Point area, with declines of at least 30 feet occurring in most other areas. Water-level decline (greater than 100 feet) occurred in the upper Potomac aquifer in the West Point, Williamsburg, Smithfield, and Suffolk areas. Decline greater than 20 feet occurred throughout most of this aquifer. Greater than a 100-foot decline occurred in the West Point and Williamsburg areas in the Aquia aquifer. The Chickahominy-Piney Point aquifer also was affected in the West Point area (greater than 140 feet) and along Chesapeake Bay (greater than 20 feet).

Water-budget analysis for pumping conditions demonstrated that discharge to surface water no longer approximated recharge to the water-table aquifer, as shown under prepumping conditions. Discharge to surface water was reduced because of increased movement from the water-table aquifer to the confined system to replace pumpage from the deeper aquifers. In 1983, reduced discharge to the surface accounted for about 85.0 percent of the 86.6 Mgal/d withdrawn from the model area. Reduced discharge to the surface was greatest in incised stream valleys in the western part of the model area, in areas of major pumpage centers such as Franklin and West Point, and in areas of pumpage centers in the east that penetrate shallow aquifers.

Water-budget analysis also demonstrated that in some areas surface water recharged the ground-water system because of increased pumpage. Induced infiltration of surface water began in the fifth pumping period (1953-57). It primarily occurred in the Atlantic Ocean and Chesapeake Bay and its major tributaries. The surface-water infiltration is saline and has the potential for degrading the water quality of underlying aquifers; however, this water entered the ground-water system in areas generally not used for freshwater supply. In 1983, surface-water infiltration accounted for approximately 0.9 percent of the 86.6 Mgal/d withdrawn from the model area.

Reduced discharge to the surface and induced infiltration from the surface accounted for approximately 86 percent of the water pumped. The remaining pumpage was accounted for by a decrease in lateral outflow and an increase in lateral inflow across the northern and southern boundaries of the model and water released from storage. Water released from storage was minimal at the end of the model simulation (approximately 0.4 Mgal/d), suggesting that steady-state conditions were being approached. Water levels would, therefore, remain relatively stable if pumpage continued in the model area as simulated in the final pumping period (1981-83).

The model also was used to project the response of the ground-water flow system to potential injection or increased pumpage in southeastern Virginia. Seven scenarios were run, each representing an increase in pumpage or injection above average conditions in the final pumping period (1981-83). The scenarios were not designed to represent future injection or pumpage rates accurately, but rather to provide insight into regional water-level decline and ground-water flow. The scenarios also provide examples of the ability of the model to assess the continued reliability of ground water as a resource in southeastern Virginia.

Scenarios 1 and 2 were run using a steady-state solution to the ground-water flow equation so that no change in storage or water levels would occur over time. The steady-state solutions provided maximum water-level decline resulting from projected increased pumpage. The first scenario involved increased pumpage of 54.4 Mgal/d (141.0 Mgal/d total) resulting from continuous use of 18 emergency-supply wells, generally used in times of drought. Approximately 86 percent of the additional pumpage would come from the middle Potomac aquifer. The second scenario involved continuous use of selected industrial wells at their permitted limit, increasing pumpage by 19.8 Mgal/d (106.4 Mgal/d total). Approximately 79 percent of the additional pumpage would be pumped from the middle and upper Potomac aquifers. In both scenarios, water-level decline from simulated 1983 conditions would be substantial. The major consequence from the increased pumpage would be considerable interference among ground-water users, resulting in increased pumping costs. Another consequence would involve potential water-quality degradation from surface-water infiltration and upward flow of saltwater from deeper aquifers. In both scenarios, water levels would remain well above the tops of aquifers throughout most of the model area, indicating that sufficient recharge from the water-table aquifer and across lateral boundaries was available to replace the increased pumpage from the confined aquifers. West Point and Franklin are two areas where water levels could begin to approach the tops of aquifers (modeled water levels were within 100 feet of the tops). These areas are more vulnerable than other areas because the aquifers lie relatively close to the surface (the areas are in the updip parts of the aquifers) and pumpage is heavy. If water levels declined below the tops, unconfined (water-table) conditions would occur and result in dewatering of aquifers. Dewatering would contribute to compaction of aquifer sediment and subsidence in the area.

Scenarios 3 through 7 involved injection into or pumpage from 5 Virginia Beach emergency-supply wells located in the city of Suffolk, Isle of Wight County, and Southampton County. The scenarios were run using a transient solution to the ground-water flow equation. Water levels were projected for a 5-year period (1984-88). The wells which penetrate the middle Potomac aquifer were originally designed to be pumped during dry periods, allowing for water-level recovery during wetter periods. On the basis of this original well design, scenario 3 involved increased pumpage at a rate of 4 Mgal/d from each well during July, August, and September for 5 years. Scenarios 4 through 7 presented other potential pumpage or injection schemes. Modeled water levels, located in the vicinity of the wells in the middle Potomac aquifer, were used to assess benefits derived from injection and impacts from increased pumpage.

Increased pumpage during 3 months at a rate of 4 Mgal/d followed by 9 months with no increased pumpage would result in a maximum 35.5-foot water-level decline during the 5-year period (1984-88). The water level would rise during the 9-month recovery period following maximum decline to within about 6.0 feet of the simulated 1983 water level. Improvement in water-level recovery due to injection during wetter periods (at a rate of 1 Mgal/d into each well during January, February, March, and April) would be minimal. Injection would only increase water levels during the month of maximum decline by about 3.4 feet. Maximum water-level decline that would result from year-round pumpage at a rate of 1 Mgal/d for 5 years would be approximately 12.0 feet. The water levels would generally be lower throughout the 5-year period (maximum 7.0 feet) than those resulting from pumping an equivalent volume of water during 3 months of the year at a higher rate of 4 Mgal/d. However, water levels would be approximately 24 feet higher in September each year--the time corresponding to the end of 3-month pumpage. Year-round pumpage at a lower rate would, therefore, prevent periods of extreme water-level decline during which other users might be adversely affected. Water levels would decline by approximately 58.8 feet after 5 years if the wells were pumped year-round at design capacity (4 Mgal/d). The water levels would be significantly lower throughout the 5-year period than those resulting from pumping at design capacity only during dry periods. A 9-month recovery period would, therefore, play an important role in restoring water levels in the area.

Use of the model is limited in 5 aspects: (1) The model is adequate in simulating impacts of historic and projected pumpage and injection on a regional scale; simulation of well interference, water levels, and surface-water losses and gains on a smaller scale requires a detailed analysis involving a more refined model with finer grid spacing and shorter time intervals. Additional data on streambed leakance, baseflows, and pumpage within the water-table aquifer are needed to assess local surface-water losses and gains. (2) Pumpage primarily occurs in the confined system and, therefore, the model is used to analyze ground-water flow within the confined aquifers. Detailed analysis of flow within the water-table aquifer requires better definition of flow between this aquifer and surface water and better definition of pumpage within the water-table aquifer. (3) The model can be used to identify areas where water levels approach the tops of aquifers; however, it was not developed to simulate an actual conversion from confined to unconfined conditions. If future pumpage increases so that measured water levels drop below the tops of aquifers, modification of the model is necessary. (4) The model does not simulate water released from confining-unit storage which may be relevant in time periods less than 3 years. (5) The model does not simulate effects of saltwater or the movement of saltwater under natural or pumping conditions.

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