GROUND-WATER RESOURCES

OF THE YORK-JAMES PENINSULA OF VIRGINIA

By Randell J. Laczniak and Andrew A. Meng III

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CONVERSION FACTORS

For the convenience of readers who prefer to use metric International System (SI) units rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	3.785×10^{-3}	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06308	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Transmissivity	
squared foot per day (ft^2/d)	0.09290	meter per day (m/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Specific Capacity	
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]

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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By R.J. Laczniak and A.A. Meng III

ABSTRACT

An unconfined aquifer underlain by six confined aquifers and intervening confining units comprise the hydrogeologic framework of the York-James Peninsula. The three lowermost aquifers--the upper, middle, and lower Potomac aquifers--are the thickest and most productive. These aquifers supplied about 87 percent of the total estimate of ground water withdrawn (39 million gallons per day (Mgal/d)) in 1983. The middle and lower Potomac aquifers, in the western part of the Peninsula, contain water of the best quality for potable supply within York-James Peninsula.

A three dimensional, digital flow model that simulates ground-water flow conditions prior to and throughout the history of ground-water development provides information about the flow of ground water through the multiaquifer system and addresses concerns about the future use of this resource. The model shows that reduction of ground-water flow to and induced flow from surface waters have largely compensated for most of the ground water withdrawals. Model simulation shows that these two flow components accounted for 87 percent of the total water withdrawn (38 Mgal/d) in the final pumping period (1981-83). Most of the surface water that recharges the ground-water flow system was from sources containing salty water (Chesapeake Bay and Atlantic Ocean). This recharge was mainly to parts of aquifers not used for freshwater supply, and rates of recharge were relatively slow, Most of the water withdrawn from confined aquifers was replaced by water flowing through the overlying and underlying confining units.

Four scenarios of increased withdrawal are used to evaluate the availability of ground water for meeting future freshwater supply needs. Results indicate that (1) increased withdrawals are expected to continue to lower water levels throughout the aquifers and that these water-level declines will limit yields from aquifers before available recharge is depleted, (2) the severity of water-level decline could be lessened by locating projected withdrawals away from established pumping centers, (3) the severity of water-level decline could be lessened by using ground water as a supplemental supply, (4) withdrawal from the deeper confined aquifers appears to have a minimal effect on water levels in the Yorktown-Eastover aquifer (uppermost confined aquifer), (5) the distribution and rate of recharge induced from sources containing salty water (surface water or underlying aquifer) depend on the location and quantity of water (surface or underlying aquifer) depend on the location and quantity of water withdrawn, and (6) withdrawal from the Yorktown-Eastover aquifer in York County induces recharge from overlying brackish surface water sources.

INTRODUCTION

Ground water is an important resource of the York-James Peninsula that historically has provided a significant part of the water supplied to the population and industries throughout the peninsula. Since about 1890, the use of ground water has increased steadily. The steady use (withdrawal) of ground water has lowered water levels throughout the aquifers creating cone-like depressions in the water-level surface. These cones of depression have expanded outward from centers of heavy ground-water withdrawal causing interference among ground-water users.

Census projections predict rapid growth of the peninsula's population centers and increases in both industrial and agricultural development. Continued growth and development will increase the demand for freshwater supplies. Any increased use of ground water will further lower water levels, thus causing more interference among ground-water users as cones of depression expand outward, and possibly, accelerate the movement of salty water into the freshwater parts of aquifers. These potentially adverse effects of increased ground-water withdrawal are of major concern to those involved in managing the water resources of the Peninsula. The severity and extent to which these adverse effects will occur are unknown; thus, the reliability of ground water as a source for meeting future water needs is uncertain. In 1982, the U.S. Geological Survey, in cooperation with the Virginia Water Control Board, the cities of Newport News and Williamsburg, and the counties of Charles City, Hanover, James City, New Kent, and York, began a comprehensive study to assess the ground-water resources of the York-James Peninsula.

Purpose and Scope

The purpose of this report is to describe the availability and quality of ground water in the York-James Peninsula. The report presents hydrologic data collected during the study and the results from a digital flow model developed to aid in the assessment of the ground-water resource. Specifically, the report describes (1) the aquifers and confining units composing the ground-water flow system, (2) the flow of ground water through the multiaquifer system, (3) the withdrawal of ground water from aquifers, (4) the quality of water within each aquifer, (5) the hydraulic characteristics of aquifers and confining units, (6) the digital-flow model that simulates ground-water flow, and (7) the effects of increased ground-water withdrawal as projected by model simulations.

Hydrologic data on aquifers and confining units within the York-James Peninsula were collected, compiled, and analyzed. These data were used to develop a digital model to simulate ground-water flow. The digital flow model provided hydrologic information describing the regional response of the multiaquifer system to simulated increases in ground-water withdrawal. The information presented in this report is intended to improve understanding of the ground-water resources of the York-James Peninsula.

Location of Study Area

The study area is located in the central part of the Coastal Plain physiographic province of Virginia and includes most of the landmass commonly referred to as the York-James Peninsula (fig. 1). The study area is bounded

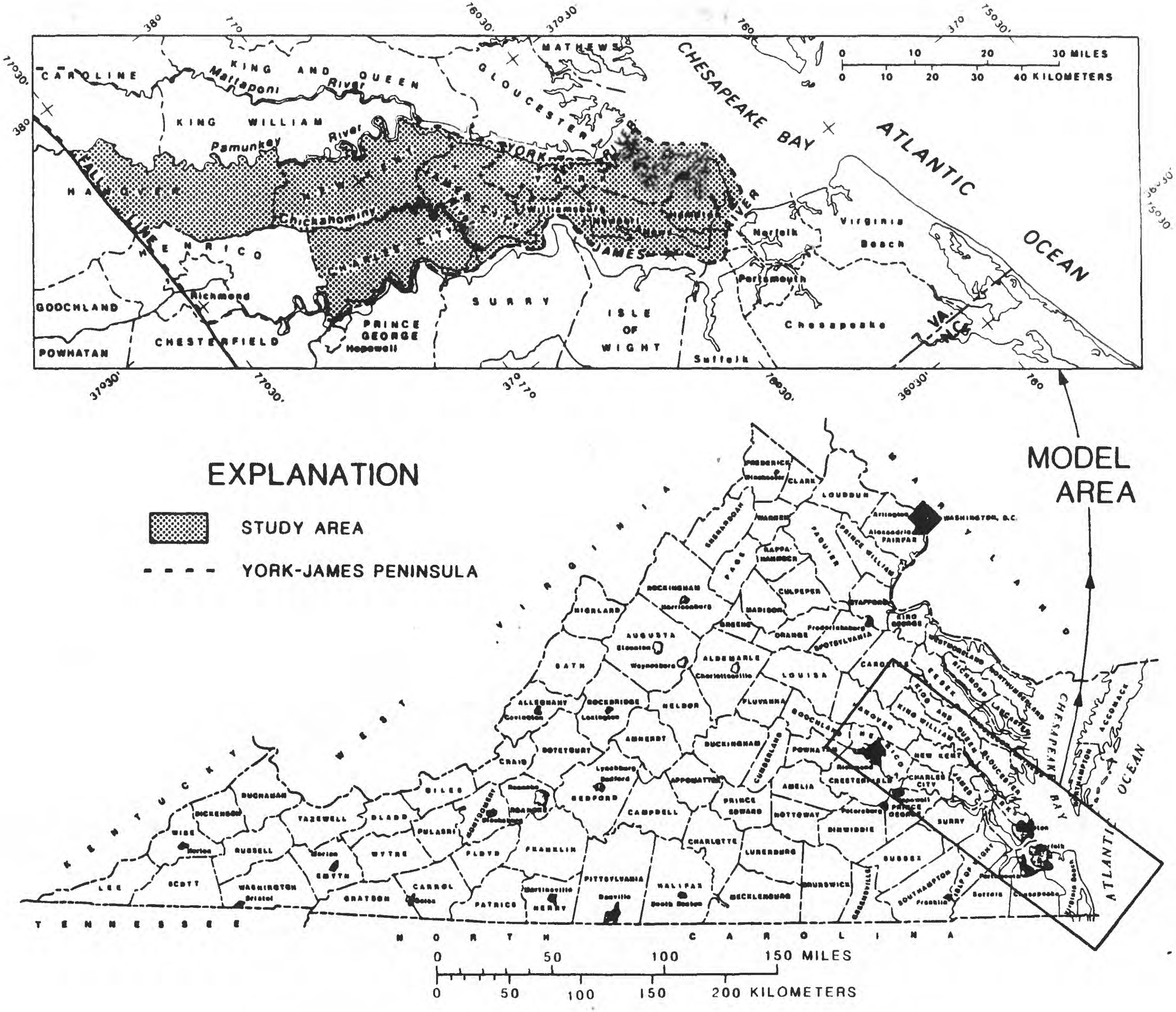


Figure 1. Location of study area and extent of model area.

and drained by the James River on the south and the York and Pamunkey Rivers on the north. Its eastern limit is the Chesapeake Bay, and its western limit is the Fall Line. The study area is about 87 miles in length and ranges from 6 to 25 miles in width; it encompasses about 1,050 square miles and is oriented in a southeasterly direction from the Fall Line. A surrounding area outlined by the inset in figure 1 is also included for model analysis of the ground-water flow system. Collectively, both areas are referred to as the model area in this report.

Previous Investigations

Most reports from previous studies describe particular aspects of the hydrology and geology for various parts of the York-James Peninsula, but only two reports comprehensively address the ground-water resources of the peninsula (Cederstrom, 1957 and Virginia State Water Control Board, 1973). Reports that describe specific hydrogeologic aspects of all or part of the peninsula are county reports by Ellison and Masiello (1979), Harsh (1980), and Wigglesworth, Perry, and Ellison (1984); consultant reports by Leggette, Brashears, and Graham (1966), Geraghty and Miller (1984), and Sirine and Associates, Ltd.(1984); and a drainage basin report by Lichtler and Wait (1974). Bal (1978) developed the first digital flow model to simulate the effects of estimated future withdrawals from the aquifers of Cretaceous age in the Peninsula. Reports that describe particular aspects of the geology of the Peninsula are Roberts (1932), Cederstrom (1945), Cushman and Cederstrom (1945), Bick and Coch (1969), Johnson (1969), Coch (1971), Johnson (1972), Daniels and Onuschak (1974), Johnson (1976), Johnson, Berquist, and Ramsey (1980), Berquist (1983), Peebles (1984), Peebles, Johnson, and Berquist (1984), and Ward (1984).

Regional reports that include the York-James Peninsula as part of their discussion of hydrology or geology are Larson (1981), Mixon, Szabo, and Owens (1982), Kull (1983), and Johnson and Peebles (1985). Reports describing areas directly adjacent to the York-James Peninsula include Cederstrom (1945), Siudyla, Berglund, and Newton (1977), and Siudyla, May, and Hawthorne (1981). Clark and Miller (1912) described the physiography and geology of the peninsula in a comprehensive overview of the Virginia Coastal Plain. Sanford (1913) briefly described the "underground water resources" of the peninsula in a comprehensive hydrogeologic evaluation of the Virginia Coastal Plain. Reports by Meng and Harsh (1984) and Harsh and Laczniak (1986) provide the most recent description of the hydrogeology of the multiaquifer system of the Virginia Coastal Plain.

Methods of Investigation

The report by Meng and Harsh (1984) provided much of the data necessary to develop the hydrogeologic framework described in this study. The digital flow model developed by Harsh and Laczniak (1986) provided the model conceptualization of ground-water flow throughout the peninsula and the means to calculate inflows and outflows of ground water along the northeastern and southwestern limits of the model area. Additional data were collected and compiled to refine the hydrogeologic framework, update ground-water use, characterize the water quality of the aquifers, define the hydraulic characteristics of aquifers and confining units, and develop a digital flow model of the multiaquifer system. Two ground-water research stations (well clusters) were installed to obtain additional hydrologic information. The stations provided: (1) hydrogeologic data to refine identified hydrogeologic units, (2) water-quality data to define lateral and vertical changes in the chemical composition of ground water within the multiaquifer system, (3) vertical hydraulic conductivity values of confining units, and (4) the mineral composition of aquifer and confining-unit sediments.

Acknowledgments

The authors would like to thank the cities of Newport News and Williamsburg; the counties of Charles City, Hanover, James City, New Kent, and York; and the Virginia Water Control Board (VWCB), formerly the Virginia State Water Control Board, for their cooperation and support in this study. Special thanks is also extended to those individuals who represented our cooperators for their assistance to this study. The installation and development of the two research stations by the VWCB provided essential hydrogeologic information. Many industries and municipalities within the Peninsula assisted by providing information to determine the ground-water withdrawal history and future water-supply needs of the peninsula. Local drillers and private consultants allowed access to their files of geophysical logs, well-construction data, and other pertinent hydrogeologic information.

HYDROGEOLOGY

The Coastal Plain physiographic province of Virginia is underlain by layered, sedimentary deposits that generally thicken and dip eastward. These deposits consist of clay, silt, sand, and gravel, with variable amounts of shell material. Except for some local calcareous cementations, this sedimentary section is devoid of consolidated sediments. These local cementations are usually associated with shell beds and form thin, lithified strata referred to as "shell rock" by local drillers. The unconsolidated sediments overlie a hard rock surface, commonly referred to as "basement", which also slopes eastward. This sloping rock surface emerges at the Fall Line, marking the western limit of the onlapping Coastal Plain deposits, and continues westward forming the Piedmont physiographic province. The sediments of the study area attain a thickness of 2,246 feet (Cederstrom, 1957), at the southeastern end of the York-James Peninsula.

The geologic age of the sedimentary section ranges from Early Cretaceous to Holocene and has a highly varied depositional history. About 70 percent of the sedimentary section consists of Cretaceous sediments, with the remainder consisting mostly of Tertiary sediments. The Cretaceous sediments are mainly continental in origin and consist of alternating sand and clay. These sand and clay deposits are laterally discontinuous and highly variable in thickness. The alternating depositional sequences of the Cretaceous section are attributed to fluvial-deltaic processes. Throughout the Early Cretaceous Epoch, large quantities of weathered-rock material were transported out of the western mountainous highlands of the Piedmont and Blue Ridge physiographic provinces by streams and deposited in the lowlands at the edge of the Continental margin. As these sediments accumulated, large delta lobes prograded oceanward. Within the forming deltas, different fluvial environments produced a variety of interfingering continental deposits ranging from carbonaceous clay and silty clay to sand and gravel.

Tertiary sediments of marine origin overlie the Cretaceous deposits. These marine sediments form areally extensive and predictable layered depositional sequences. The uniform depositional patterns of the Tertiary section are the result of generally constant and widespread environmental conditions resulting from the inundation of the Coastal Plain landmass by many transgressions of the sea. The Tertiary marine environments produced deposits ranging from clay to sand with varying amounts of shell.

A thin series of Pleistocene sediments overlie the Tertiary deposits. These sediments formed as a result of fluctuating sea levels during the latest ice age and mostly occur as a series of terrace-type deposits of fluvial or marine origin. As sea levels declined, because of the expansion of the polar ice caps, the Coastal Plain sediments were deeply entrenched and eroded along stream valleys. Streams cut into and through aquifers and confining units near land surface, thus increasing the influence of streams on the ground-water flow system. As sea levels rose, because of the melting of glacial ice, the deeply incised stream valleys were infilled and the headlands were eroded. Deposits range from peat to silty clay and sand to gravel.

A thin veneer of Holocene sediments overlie the Pleistocene deposits in the eastern part of the study area. These sediments are the result of gradually rising sea levels occurring since the Pleistocene. The Holocene sediments occur mostly as fringing estuarine, lagoonal, and tidal deposits, These sediments are hydrologically similar to the underlying Pleistocene deposits and, therefore, are combined in the model analysis. Erosional and depositional processes of the Pleistocene Epoch produced the drowned river valleys and broad, stair-step-like terrace landforms of the York-James Peninsula.

Aquifers and Confining Units

The alternating sand and clay deposits of the Coastal Plain physiographic province of Virginia form a layered series of aquifers and confining units that compose the hydrogeologic framework. Aquifers consist mainly of sand, or interbedded sand and clay, while confining units consist mainly of silt and clay. The hydrogeologic framework was developed from correlation of lithologic and geophysical logs, water-quality analyses, water-level data, and paleontologic and hydraulic analyses of core samples. The locations of control wells are shown in figure 2. The alternating sand and clay deposits form seven confined aquifers, an overlying water-table aquifer, and intervening confining units (table 1). Nomenclature is similar to that presented by Meng and Harsh (1984). Corresponding geologic formations, ages, and hydrogeologic units described by previous investigators also are included in table 1. Only six of the seven confined aquifers listed in table 1 exist within the limits of the study area--the Virginia Beach aquifer, of Late Cretaceous age, is not present and therefore is not discussed in this report. Hydrogeologic descriptions, hydrologic characteristics, and a range of well yields for the aquifers are given in table 2. Hydrogeologic sections, shown in figures 3 and 4, illustrate the relative positions of hydrologic units throughout the peninsula. The areal extents and structure tops of each confined aquifer relative to sea level are shown in figures 5-10. The thicknesses and areal extents of intervening confining units are shown in figures 11-17. The aquifers and confining units of the York-James Peninsula are described briefly below. For a more detailed discussion on hydrogeologic characteristics, depositional patterns and settings, and geophysical log correlations, the reader is referred to Meng and Harsh (1984).

The Columbia aquifer includes Holocene and Pleistocene sediments. It is the uppermost aquifer and is a water-table aquifer throughout its extent. The aquifer is present only in the eastern part of the study area and primarily consists of a thin series of Pleistocene terrace deposits. The thickness of the Columbia aquifer is highly variable and generally ranges between 10 to 40 feet but also attains thicknesses greater than 80 feet in Pleistocene paleochannels. The aquifer consists of interbedded and intermixed sand, silt, and clay, generally overlying a gravelly base.

The Yorktown-Eastover aquifer is the uppermost aquifer of Tertiary age and includes sediments of the Pliocene Yorktown Formation and the Miocene Eastover Formation. It is present throughout the study area, except along stream valleys where the aquifer has been removed by erosion (fig. 5). The thickness of the aquifer is highly variable and generally depends on the elevation of the land surface. Thickness ranges from a featheredge at the updip limit to 160 feet thick at well 59E 5 in the city of Hampton. The lithology of the aquifer is complex, varying from gravelly-to-silty sand, interbedded with silt, clay, and shell. The Yorktown-Eastover aquifer is the water-table aquifer in the western and central parts of the study areas and is overlain by the Yorktown confining unit in the eastern part of the study area. The

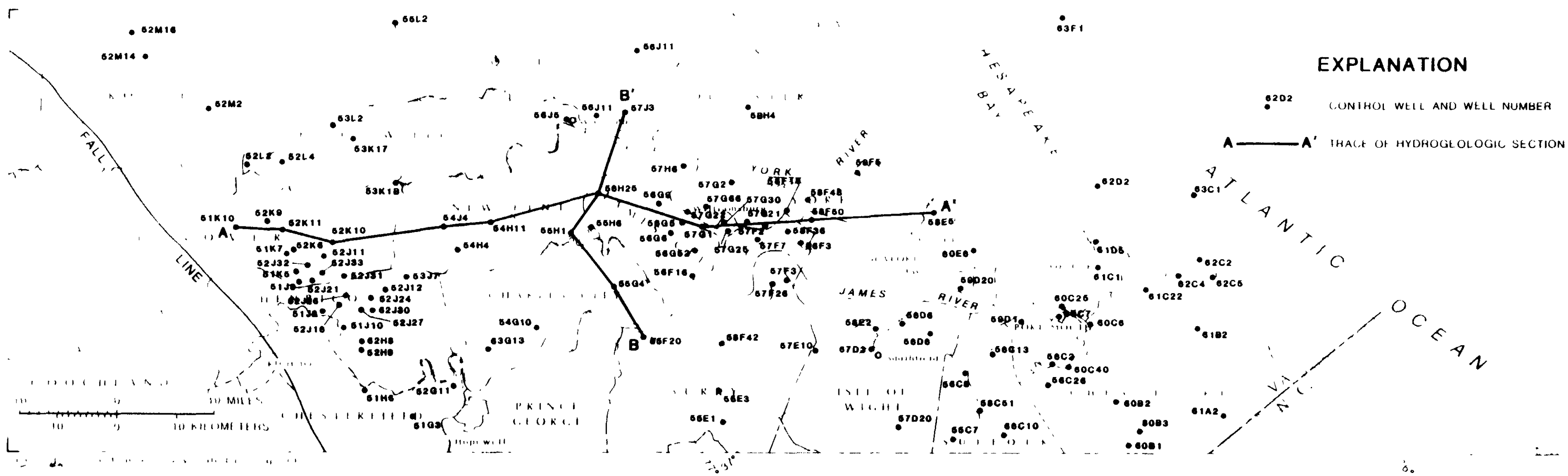


Figure 2. Location of control wells, sampled wells, local well numbers, and lines of hydrogeologic sections.

Table 1.--Hydrogeologic units in the York-James Peninsula

Period	Epoch	Stratigraphic formation	Hydrogeologic Unit: York-James Peninsula Model (this report)	Cederstrom (1957)	Virginia State Water Control Board (1977)	Harsh (1980)	Laczniak and Harsh (1986)
Quaternary	Holocene / Pleistocene	Undifferentiated sediments	Columbia aquifer	Sands of Recent deposits and the Columbia Group	Water-table aquifer	Quaternary aquifer	Columbia aquifer
Tertiary	Pliocene	Yorktown Formation	Yorktown confining unit	Sands and shells of the Yorktown Formation		Yorktown Aquifer	Yorktown confining unit
			Yorktown-Eastover aquifer				Yorktown-Eastover aquifer
	Miocene	Eastover Formation					
		St. Marys Formation	St. Marys confining unit		Confining unit	Confining unit	St. Marys confining unit
		Choptank Formation					St. Marys-Choptank aquifer[2]
		Calvert Formation	Calvert confining unit				Calvert confining unit
	Oligocene	Old Church Formation	Chickahominy-Piney Point aquifer	Basal sands of the Calvert Formation	Upper artesian aquifer	Eocene and Paleocene aquifer	Chickahominy-Piney Point aquifer
	Eocene	Chickahominy Formation		Sands of the Chickahominy Formation			
		Piney Point Formation		Sands of the Nanjemoy Formation			
		Nanjemoy Formation	Nanjemoy-Marlboro confining unit		Confining unit		Nanjemoy-Marlboro confining unit
		Marlboro Clay					
	Paleocene	Aquia Formation	Aquia aquifer	Sands of the Aquia Formation	Principal artesian aquifer		Aquia aquifer
		Brightseat Formation	Upper Potomac confining unit	Sands of the Mattaponi Formation		Confining unit	Brightseat - Upper Potomac confining unit[2]
			Upper Potomac aquifer				Brightseat - Upper Potomac aquifer[2]
Cretaceous	Late Cretaceous	Equivalent of Black Creek Formation of North Carolina	Virginia Beach confining unit[1]	Not present in area	Not present in area	Not present in area	Confining unit 4[1]
			Virginia Beach aquifer[1]				aquifer 4[1]
		Potomac Formation	Upper Potomac confining unit	Sands of the Mattaponi Formation	Principal artesian aquifer	Cretaceous aquifer	Upper Potomac confining unit
			Upper Potomac aquifer				Brightseat - Upper Potomac aquifer
	Early Cretaceous		Middle Potomac confining unit	Sands of the Potomac Group			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 present in model area

[2]Not present in model area

Table 2.--Hydrogeologic descriptions, characteristics, and well yields of aquifers in the York-James Penins

[gal/min is gallons per minute]

Aquifer name and description	Well yield (gal/min) Common range	Well yield (gal/min) May exceed	Hydrologic characteristics
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.	3-30	40	Generally unconfined, semiconfined locally. Most productive in eastern area, very thin to missing in central and western areas. Water is very hard calcium-bicarbonate type. Highly susceptible to contamination from surface pollutants. Elevated 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 area, thin to missing in western area. Water is hard to very hard sodium calcium bicarbonate type. Salty water in lower part of aquifer in eastern area.
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	Important aquifer in central area; yields moderate to abundant supplies to domestic, small industrial, and municipal wells. Water is soft to hard, calcium sodium bicarbonate type and generally suitable for most uses. Aquifer not present in western area.
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	Important aquifer in central area; yields moderate supplies to domestic, small industrial, and municipal wells. Water is soft sodium bicarbonate type, with elevated iron, sulfide, and hardness locally. Aquifer not present in eastern area.
Upper Potomac aquifer: Sand, very fine to medium, micaceous, lignitic, and clayey; interbedded with silty clays; confined, restricted to central and eastern areas. Shallow, estuarine and marginal marine in origin, sediments result of first major marine inundation of Cretaceous deltas.	20-400	1,000	Multiaquifer unit. Restricted to subsurface, yields largest supply of water in study area. Water is soft sodium chloride bicarbonate type with elevated chlorides in eastern area.
Middle Potomac aquifer: Sand, fine to coarse, occasional gravels; interbedded with silty clays; generally confined, unconfined in outcrop areas of northwestern Coastal Plain and major stream valleys near Fall Line. Fluvial in origin, sediments result of deltaic deposition.	20-160	700	Multiaquifer unit. Yields second largest supply of water in study area. Water is moderately hard, sodium chloride bicarbonate type, with elevated chlorides in eastern area.
Lower Potomac aquifer: Sand, medium to very coarse, and gravels, clayey; generally confined, unconfined only in northwestern area of Coastal Plain. Fluvial in origin, sediments result of deltaic deposition.	100-800	1,500	Multiaquifer unit. Yields third largest supply of water. Water is soft to very hard, and of a sodium bicarbonate to sodium chloride type, with elevated chlorides and dissolved solids in eastern area. Thickest of all aquifers.

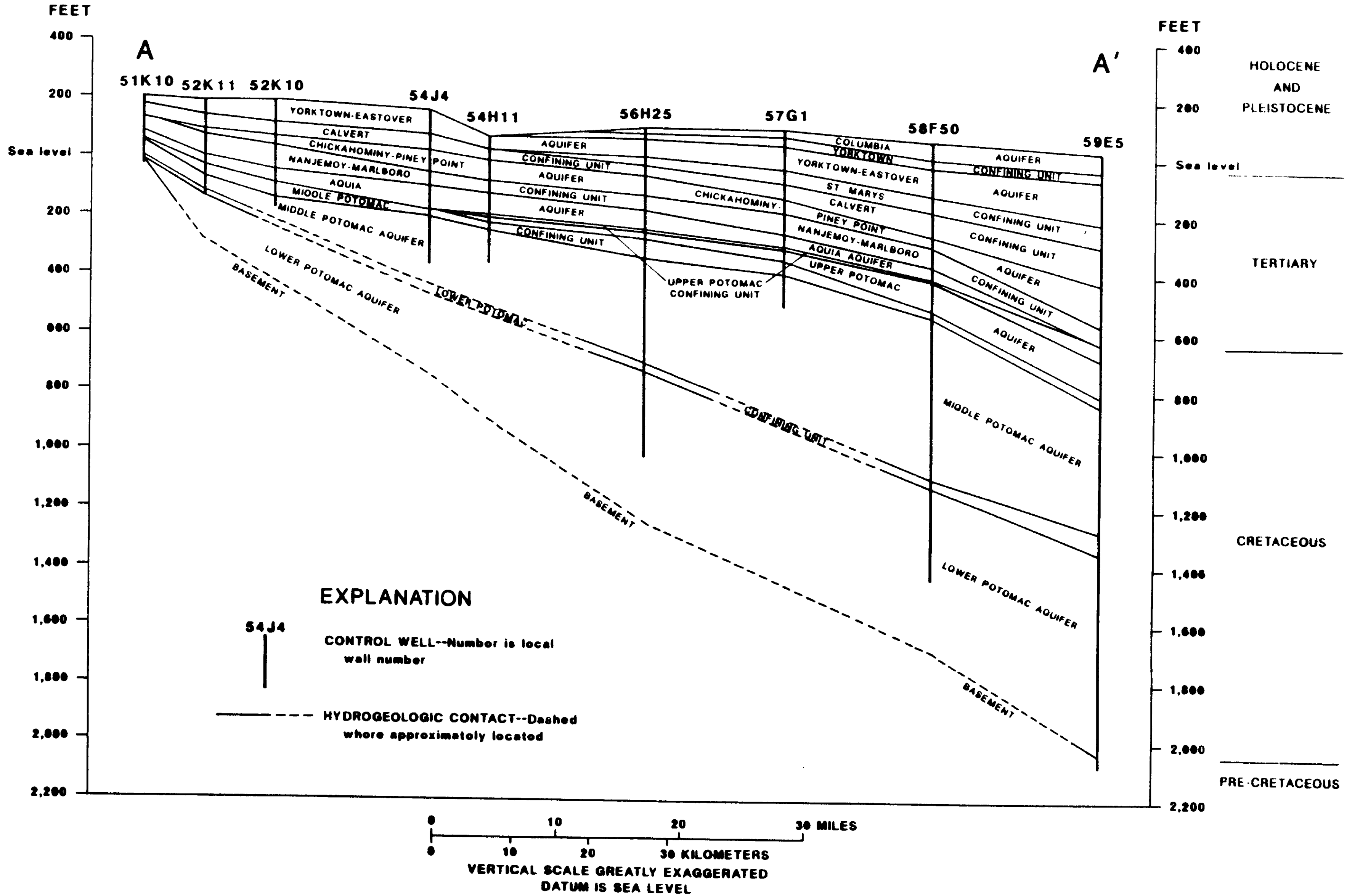


Figure 3. Hydrogeologic section A - A' from well 51K 10, Hanover County, to well 59E 5, city of Hampton, Virginia.

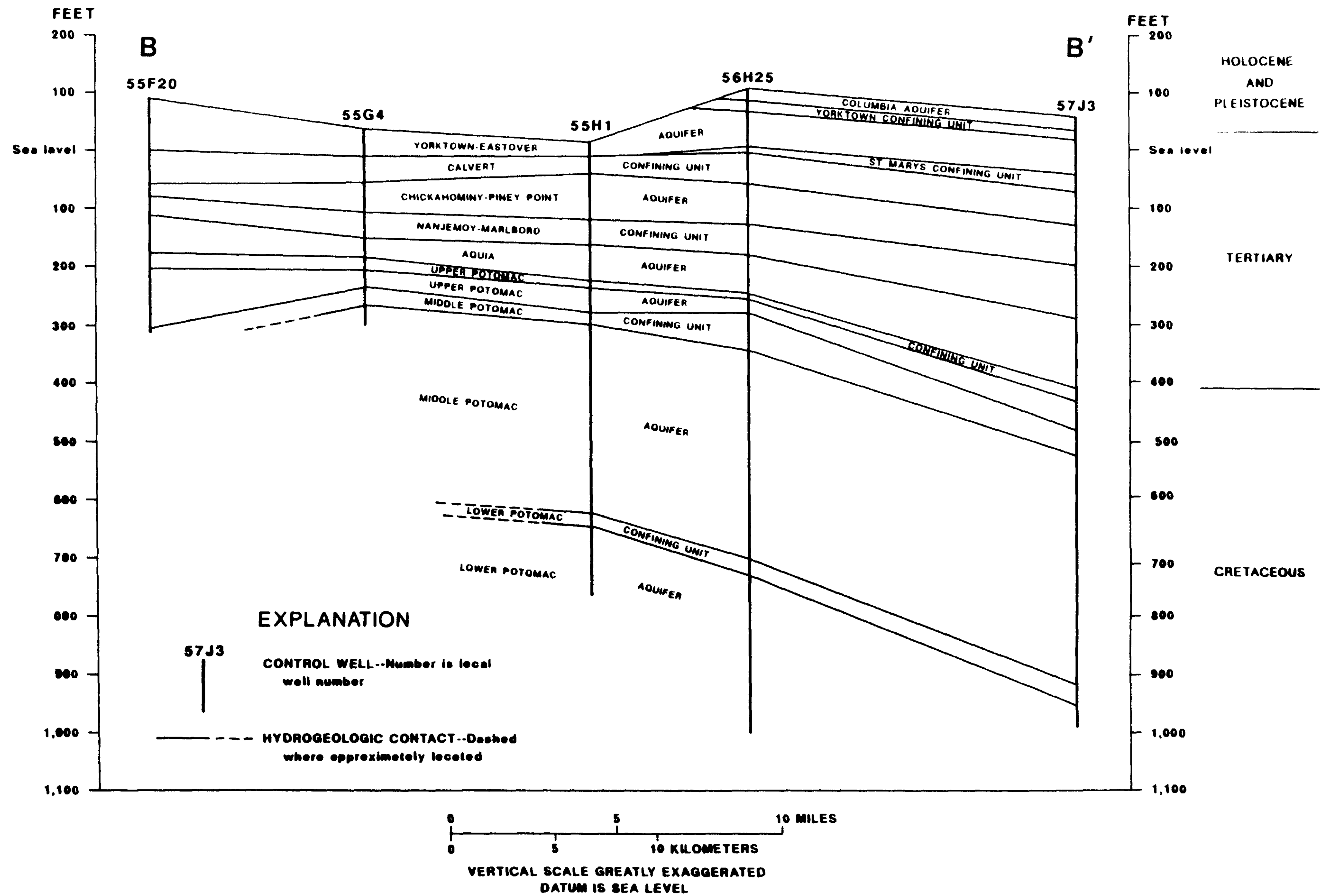


Figure 4. Hydrogeologic section B - B' from well 55F 20, Surry County, to well 57J 3, King and Queen County, Virginia.

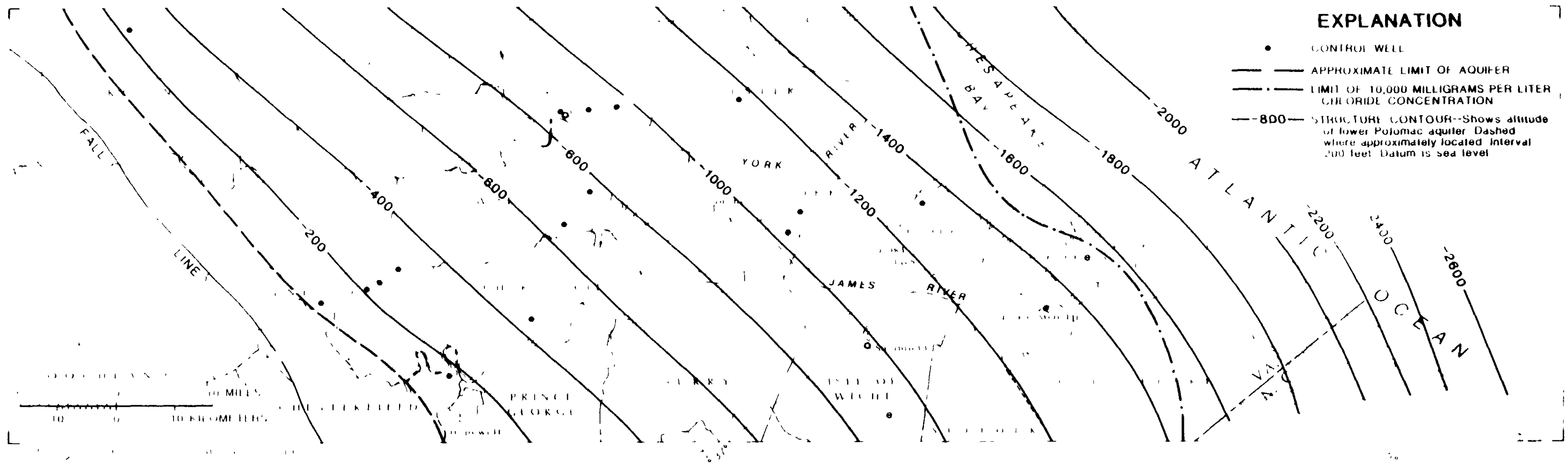


Figure 5. Altitude of top of Yorktown-Eastover aquifer.

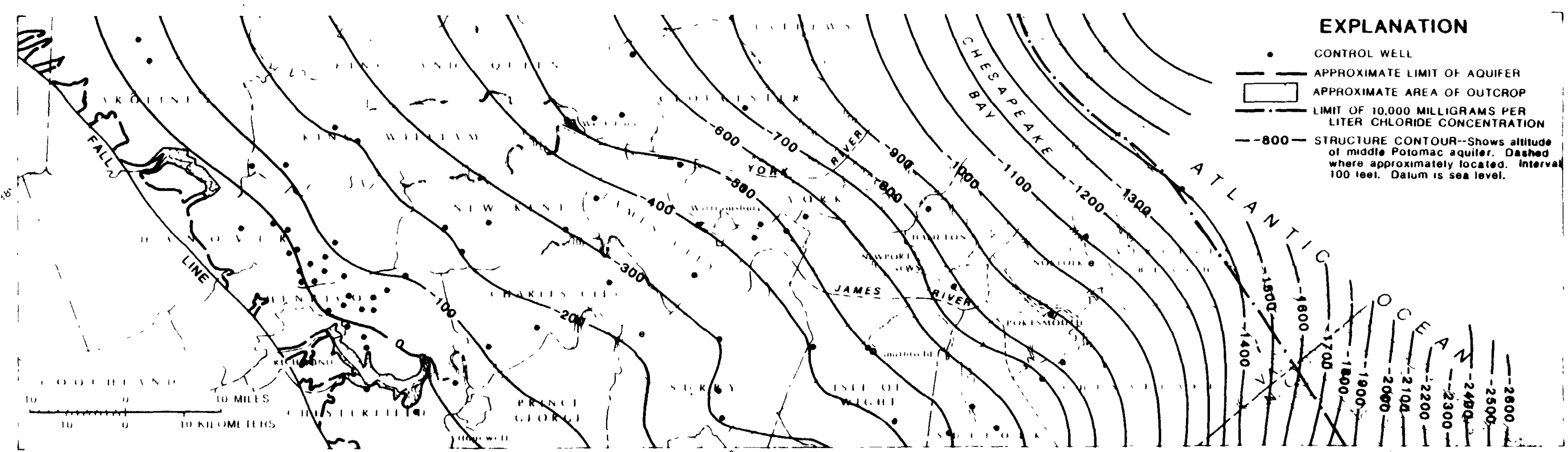


Figure 6. Altitude of top of Chickahominy-Piney Point aquifer.

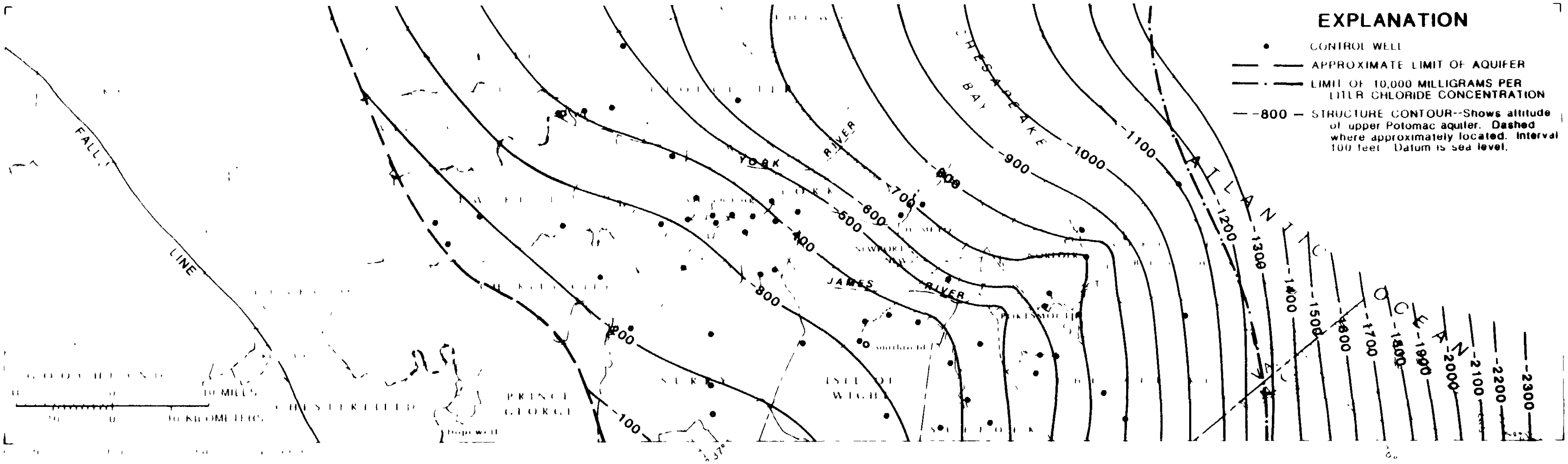


Figure 7. Altitude of top of Aquia Aquifer.

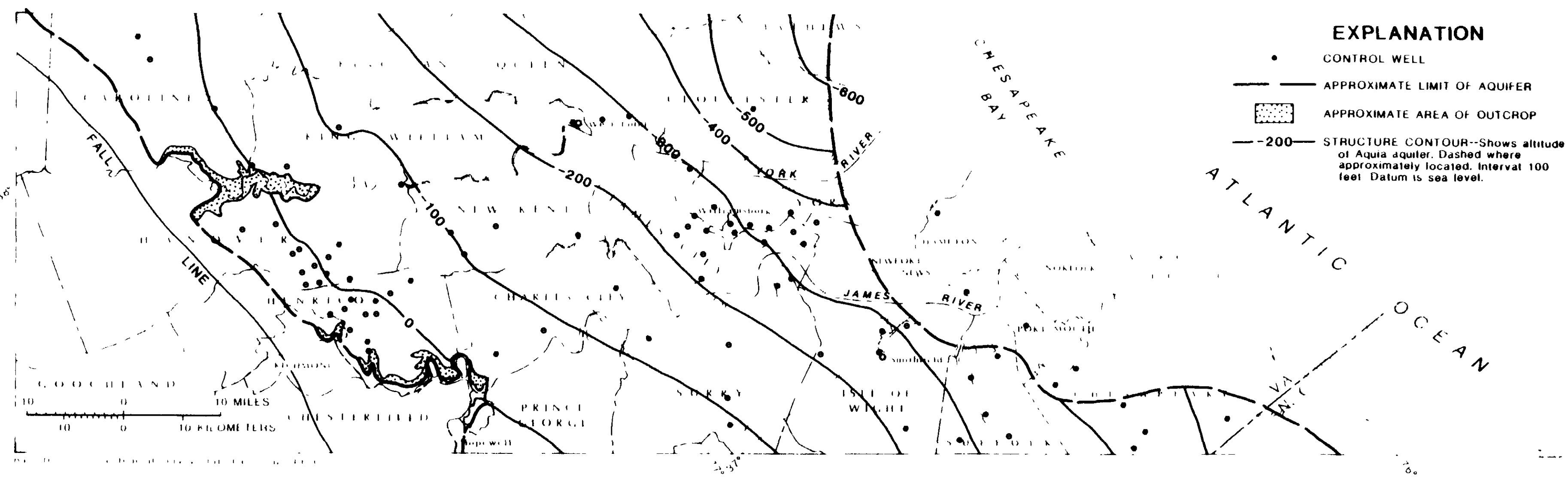


Figure 8. Altitude of top of upper Potomac aquifer.

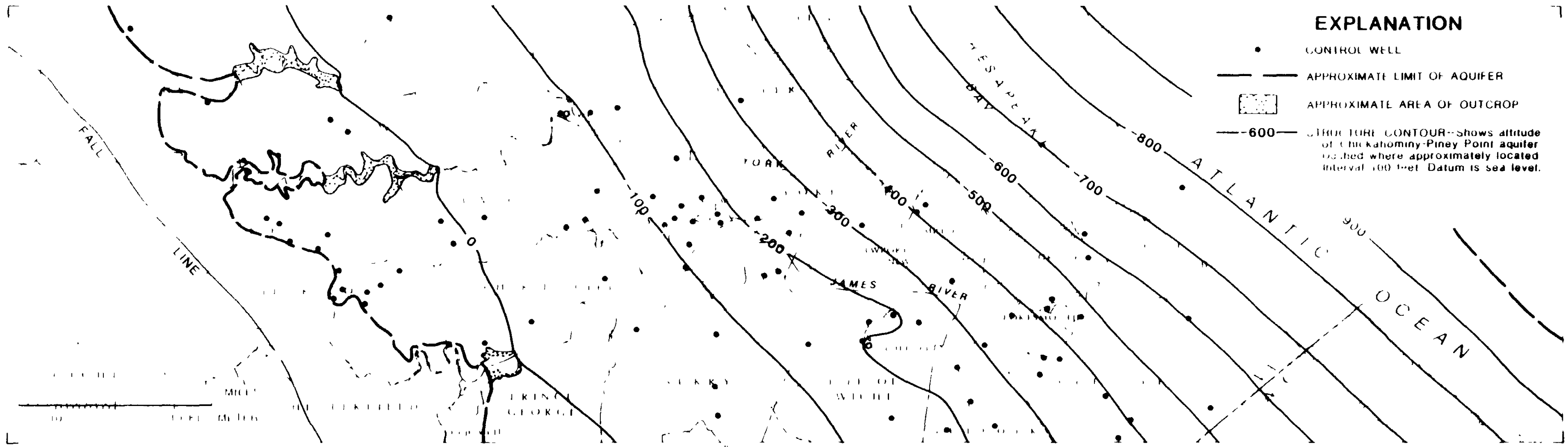


Figure 9. Altitude of top of middle Potomac aquifer

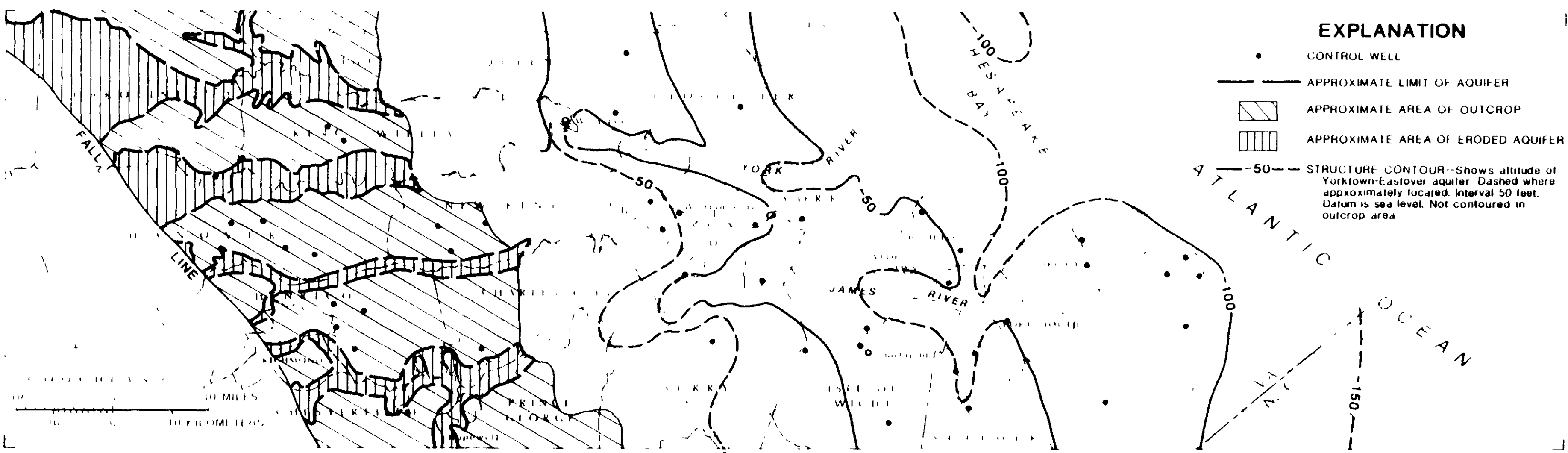


Figure 10. Altitude of top of lower Potomac aquifer.

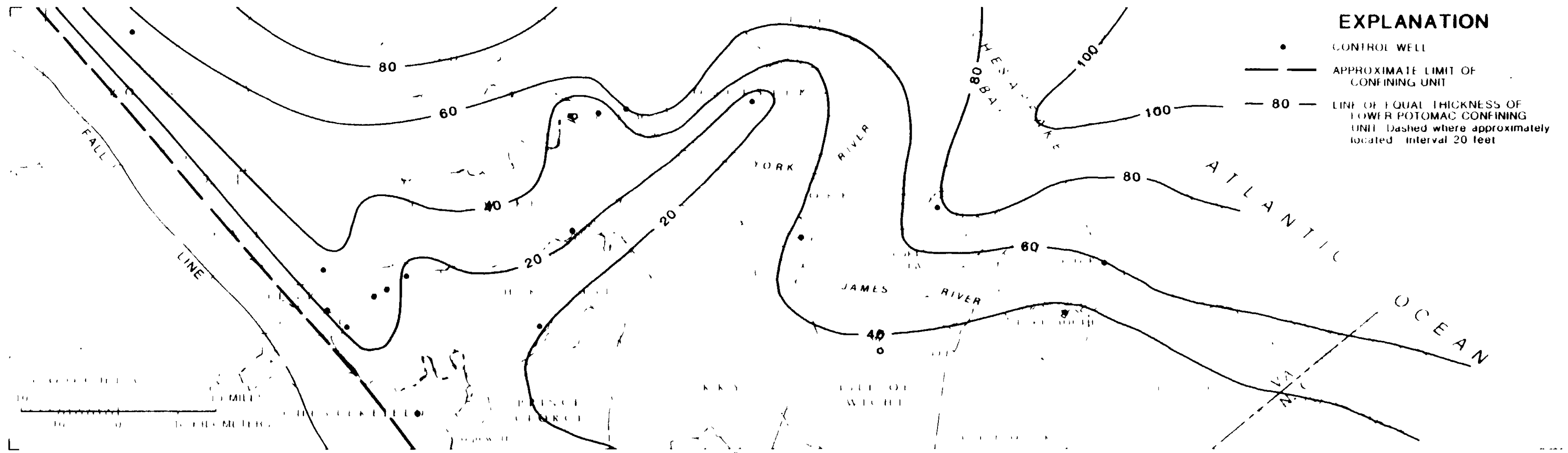


Figure 11. Thickness of Yorktown confining unit.

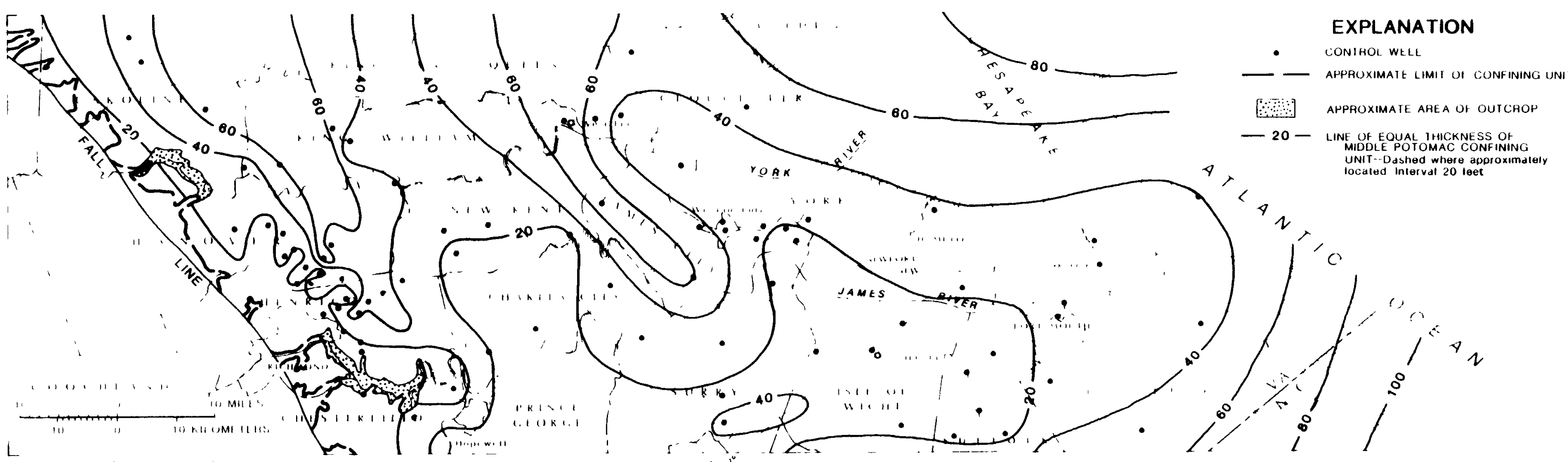


Figure 12. Thickness of St. Marys confining unit.

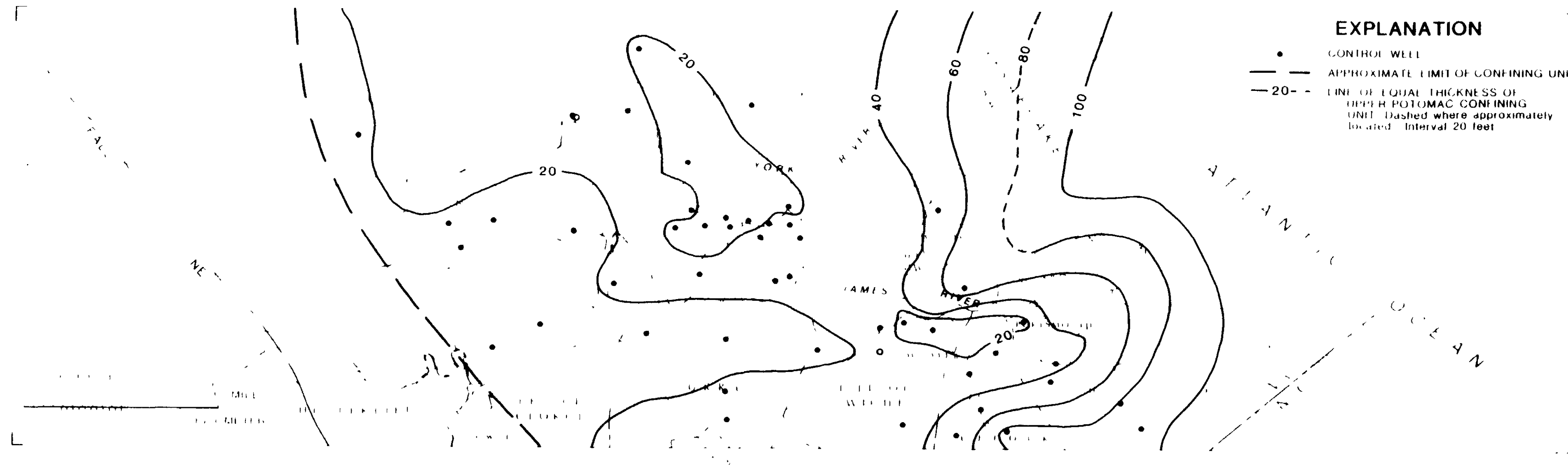


Figure 13. Thickness of Calvert confining unit.

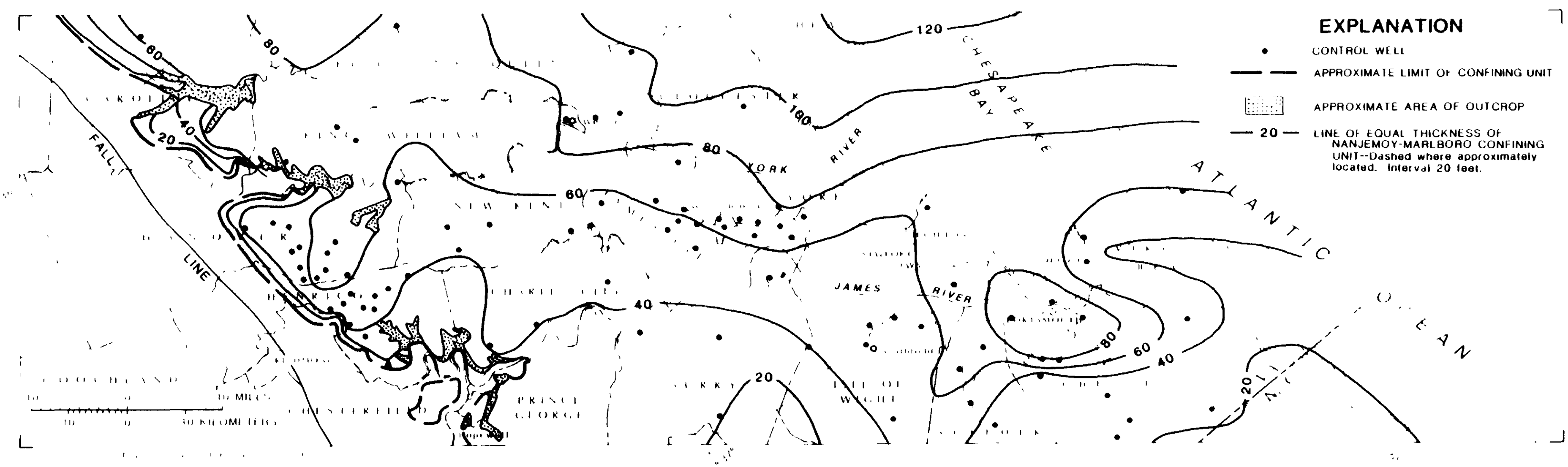


Figure 14. Thickness of Nanjemoy-Marlboro confining unit.

Figure 15. Thickness of upper Potomac confining unit.

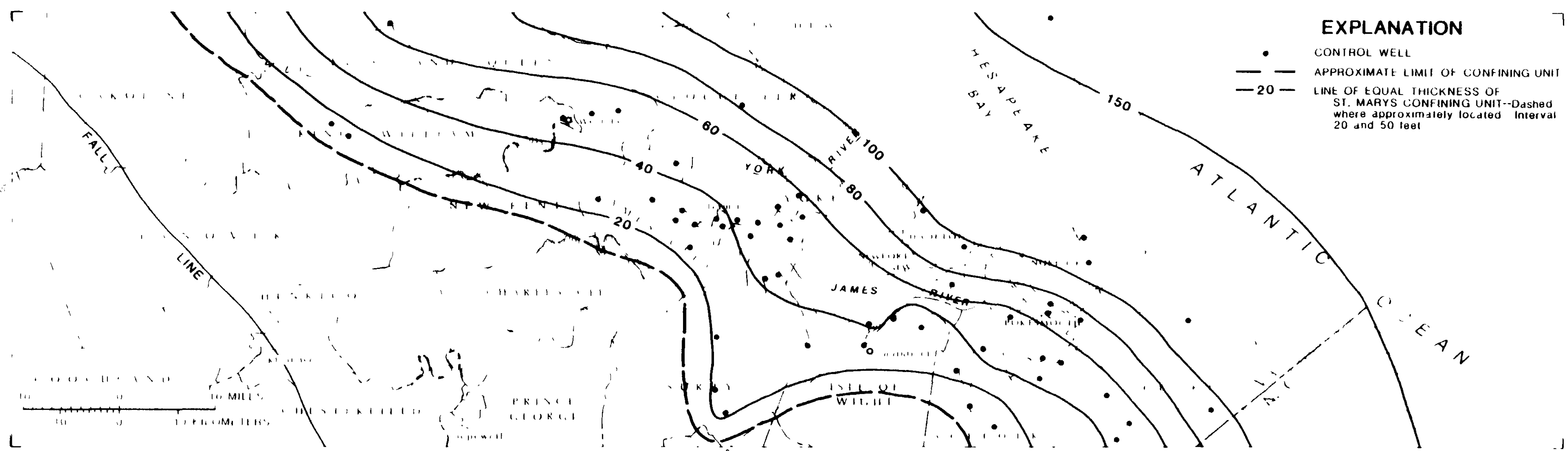


Figure 16. Thickness of middle Potomac confining unit.

Figure 17. Thickness of lower Potomac confining unit.

Yorktown confining unit ranges in thickness from a featheredge at the western limit to 40 feet at well 58F 18 in central York County (fig. 11). Along its western limit, the Yorktown confining unit is highly dissected and commonly caps the higher land elevations. In the eastern part of the study area, the Yorktown confining unit is overlain by the Columbia aquifer.

The Chickahominy-Piney Point aquifer is of middle Teritiary age and includes sediments of the Miocene and Oligocene Old Church Formation and the Eocene Chickahominy and Piney Point Formations. It is present throughout the study area, except along the Fall Line. The aquifer crops out in a small area along the James River and in a much more extensive area along the Pamunkey River (fig. 6). In cross-section, the Chickahominy-Piney Point aquifer is both lenticular and wedge-shaped. It is lenticularly shaped from the updip limit to well 58F 50 just east of the city of Williamsburg and thickens to 82 feet at well 55H 6 in southern New Kent County. The aquifer thins to a featheredge along the updip limit and to 30 feet at well 58F 18 in central York County. East of wells 58F 18 and 58F 50, the Chickahominy-Piney Point aquifer becomes wedge-shaped and thickens to 146 feet at well 59E 5 in the city of Hampton. The lenticularly-shaped section consists of medium-to-coarse glauconitic sand, interbedded with clay and indurated shellbeds. The wedge-shaped section consists of coarse-to-very coarse quartz sand. The Chickahominy-Piney Point aquifer is overlain by the Calvert confining unit which thickens from a featheredge at the updip limit to 134 feet at well 59E 6 in the city of Hampton (fig. 13). The Calvert confining unit is overlain by the St. Marys confining unit in the eastern half of the study area and by the Yorktown-Eastover aquifer in the western half. The St. Marys confining unit thickens to 70 feet at well 59E 5 in the city of Hampton (fig. 12) and is also overlain by the Yorktown-Eastover aquifer.

The Aquia aquifer is the lowermost aquifer of Teritiary age in the study area and includes sediments of the Paleocene Aquia Formation. It is present throughout the study area, except in a narrow band just east of the Fall Line and in the extreme eastern part of the study area. The aquifer crops out along both the James and Pamunkey Rivers (fig. 7). In cross-section, the Aquia aquifer is lenticularly-shaped. It attains a thickness of 62 feet at well 55H 1 in southeastern New Kent County and thins to a featheredge at both its updip and downdip limits. The updip limit is erosional, while the downdip limit is gradational--that is, the sandy aquifer sediments gradually change to clay. The aquifer consist of fine-to-medium glauconitic sand with thin interbedded silt and shell. The Aquia aquifer is overlain by the Nanjemoy-Marlboro confining unit which ranges in thickness from a featheredge along the updip limit to 80 feet at well 58F 18 in central York County (fig. 14). The Nanjemoy-Marlboro confining unit is overlain by the Chickahominy-Piney Point aquifer.

The upper Potomac aquifer includes sediments of the upper part of the Cretaceous Potomac Formation and the Paleocene Brightseat Formation. It is the thinnest of the aquifers of Cretaceous age and is present throughout the eastern two-thirds of the study area (fig. 8). The aquifer thickens from a featheredge along the updip limit to 87 feet at well 59E 5 in the city of Hampton and consists of fine-to medium, thickly-bedded sand interlayered with thin clay. The upper Potomac aquifer is overlain by the upper Potomac confining unit. The upper Potomac confining unit is highly variable in thickness, ranging from 6 feet at well 57G 21 near the city of Williamsburg to

74 feet at well 59D 20 in the city of Newport News (fig. 15). The upper Potomac confining unit is overlain by the Aquia aquifer, except in the eastern part of the study area, where the confining unit is overlain by the Nanjemoy-Marlboro confining unit.

The middle Potomac aquifer includes sediments of the middle part of the Cretaceous Potomac Formation and is the second thickest aquifer of the study area. It is present throughout the study area and crops out along the James and Pamunkey Rivers, just east of the Fall Line (fig. 9). The aquifer thickens from a featheredge along the Fall Line to 428 feet at well 59E 5 in the city of Hampton and consists of interlensing clay, silt, and medium to coarse sand with interbedded gravel. The middle Potomac aquifer is overlain by the middle Potomac confining unit. The middle Potomac confining unit is highly variable in thickness, ranging from 10 feet at well 52K 9 in Hanover County to 64 feet at well 56H 25 in James City County (fig. 16). The middle Potomac confining unit is overlain by the upper Potomac aquifer throughout the study area, except near the Fall Line, where the confining unit is overlain by the Aquia aquifer.

The lower Potomac aquifer includes sediments of the lower part of the Cretaceous Potomac Formation and is the lowermost and thickest aquifer in the study area, except where it is missing near the Fall Line. It is restricted to the subsurface (fig. 10) and thickens from a featheredge along the western limit to 689 feet at well 59E 5 in the city of Hampton. The aquifer consists of massively-bedded clayey sand, sandy clay, and coarse sand with interbedded gravel. The lower Potomac aquifer overlies the pre-Createaceous basement rock surface and is overlain by the lower Potomac confining unit. The lower Potomac confining unit is highly variable in thickness, ranging from 19 feet at well 54G 10 in Charles City County to 78 feet at well 59E 5 in the city of Hampton (fig. 17), and is overlain by the middle Potomac aquifer.

Occurrence, Movement, and Use of Ground Water

Ground water is defined as water in the subsurface that is under a pressure equal to or greater than atmospheric pressure. Ground water is present within the saturated zone in pore spaces between the sediment grains that form aquifers and confining units and is a major source of water flowing to streams, ponds, and reservoirs.

How water enters, moves through, and leaves the ground-water flow system are important to the study of ground-water resources. These three components are addressed in the "hydrologic cycle" that is illustrated in figure 18. The hydrologic cycle describes the continuous movement of water above, on, and below the surface of the earth. It has neither a beginning nor an end. Discussion of ground water commonly begins with precipitation. Rain water infiltrates the ground and percolates downward into the saturated zone. The upper part of the saturated zone forms the water-table aquifer. Water moves downward or laterally through this aquifer along flow paths toward discharge sites such as seeps, springs, streams, the Chesapeake Bay, or Atlantic Ocean. Water that moves downward in the water-table aquifer eventually encounters less permeable (conductive) sediments. These finer-grained sediments, such as silt and clay, partially impede downward movement of ground water, forcing more lateral movement of water through the aquifer. The silt and clay deposits form confining units that divide the remaining sedimentary section into a

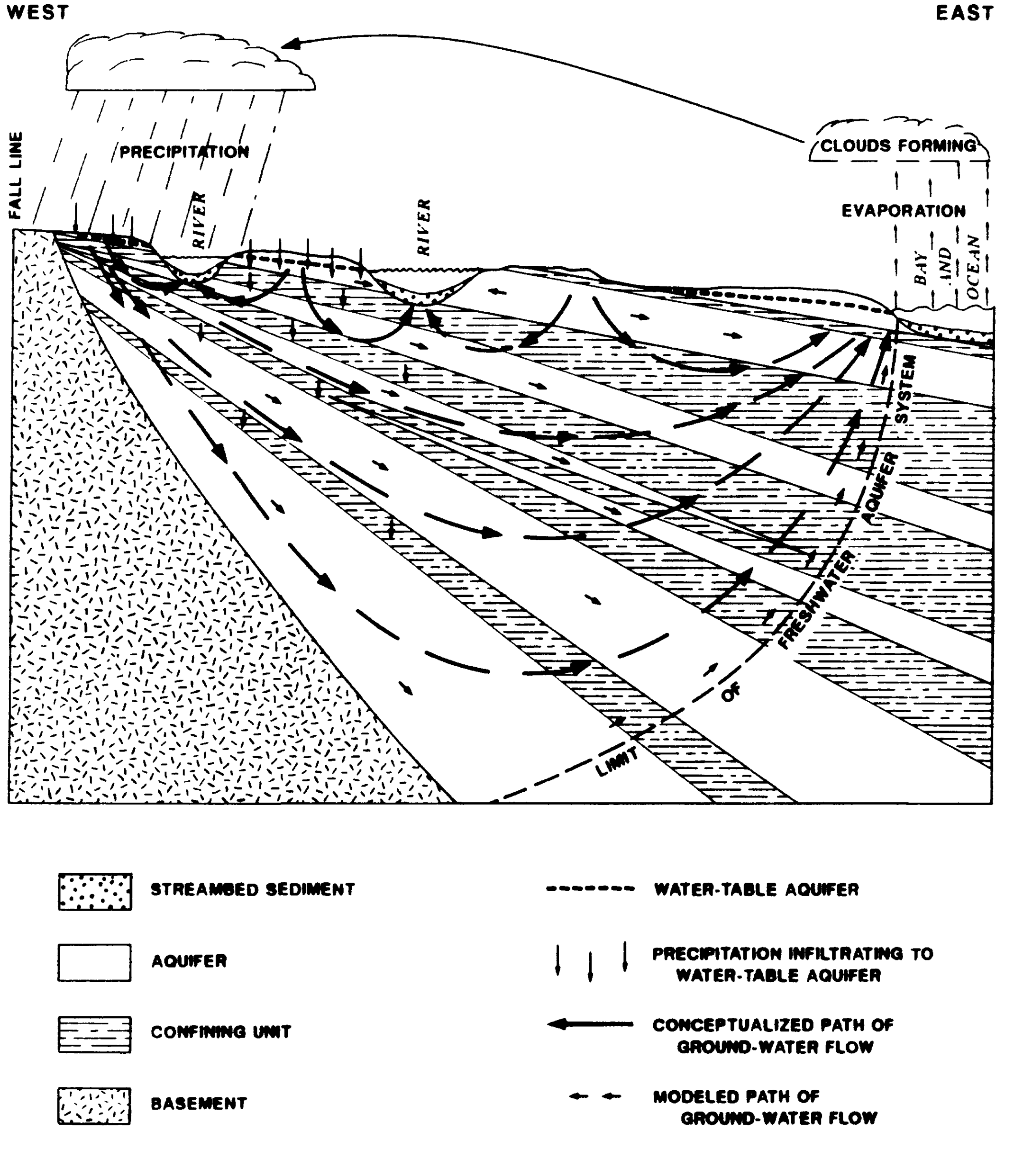


Figure 18. Generalized hydrologic cycle for York-James Peninsula.

series of separate confined aquifers. However, some water still moves through the confining unit and recharges the underlying aquifers.

Water in confined aquifers also moves both laterally and vertically along flow paths toward sites of discharge. Vertical movement of water within confined aquifers is again impeded by confining units and the process is continuously repeated as water moves throughout the entire layered sequence of sediments. Thus, the dominant direction of flow is lateral through the aquifers and vertical through the confining units. Fresh ground water eventually encounters salty ground water in the lower aquifers of the eastern parts of the study area. Density differences between these two types of water forces the fresh ground water upwards. Upward moving fresh ground water again is impeded by confining units but eventually discharges into the Chesapeake Bay or Atlantic Ocean. Water evaporates from these surface reservoirs and forms clouds which, in turn, produce rain to continue the hydrologic cycle again.

The above paragraphs describe the general flow of ground-water for the York-James Peninsula before wells were drilled to withdraw ground water. The withdrawal of ground water from the aquifers has caused a steady decline in water levels throughout the study area and has altered both local and regional flow directions. The earliest documented wells in the study area date back to about 1890. Records indicate that, from 1890 to about 1920, most wells drilled into confined aquifers flowed naturally to land surface. As more wells were drilled and water was depleted from the aquifers faster than it was recharged, the potentiometric surface in the aquifers began to decline. Wells eventually stopped flowing as the potentiometric surface declined below land surface. In order to maintain needed supplies, pumps were installed. As the need for water grew, the withdrawal of ground water was increased, further lowering water levels in aquifers. Estimated annual ground-water withdrawal from the model area is shown in figure 19. Withdrawal estimates include water from flowing wells and commercial, industrial, and water-supply usage. Domestic use was not included because it is assumed to represent only a small percentage of non-returned water. Total withdrawal for 1983 was estimated to be about 39 Mgal/d (million gallons per day). The relative significance of each aquifer throughout the history of ground-water development is shown in figure 20. Aquifer withdrawal rates were computed by adding ground-water use values for all wells screened in an individual aquifer (Kull and Laczniak, 1986). For wells screened in multiple aquifers, aquifer withdrawal rates were estimated from the ratio of the length of aquifer screened to the total length of well screened. The 1983 estimated ground-water withdrawal from the model area is given in table 3. The Potomac aquifers supplied about 87 percent of the total withdrawal in 1983. The middle and upper Potomac aquifers have provided the major portion of the ground water to the Peninsula; however, the importance of individual aquifers to local water supply varies throughout the study area. Ground water is withdrawn primarily from the lower and middle Potomac aquifers in the western part of the study area. The middle and upper Potomac aquifers and the Chickahominy-Piney Point aquifer supply most of the water in the central part of the study area. The Yorktown-Eastover and Columbia aquifers supply the majority of water to the eastern part of the study area because the deeper confined aquifers contain water with high concentrations of dissolved solids. The largest withdrawal of ground water from the model area is near the town of West Point and was estimated to be about 15.6 Mgal/d for 1983. Other major centers of ground-water withdrawal that

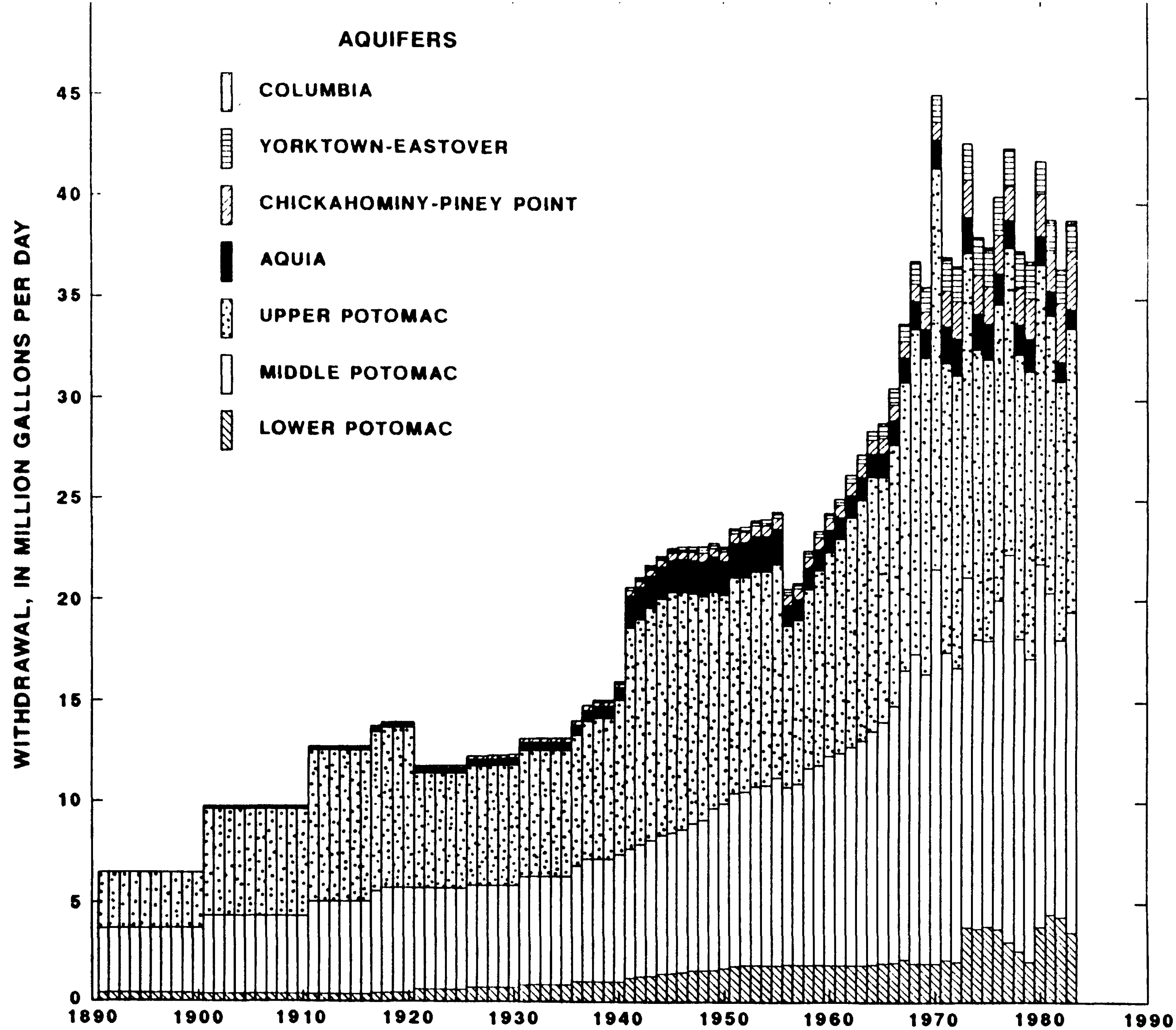


Figure 19. Annual ground-water withdrawal from model area.

affect the flow of ground water within the study area are located (1) near the cities of Suffolk and Williamsburg, (2) in the western part of the city of Newport News, (3) in the central part of James City County, (4) in the eastern parts of Hanover and Henrico counties, and (5) near the town of Smithfield. Prior to pumping, ground water flowed through the confined aquifers toward and eventually discharging to the Chesapeake Bay and Atlantic Ocean. Today, because of the withdrawal of large volumes of water, the dominant direction of flow in the confined aquifers is toward the major pumping centers.

Quality of Ground Water

Water quality is an important aspect of the ground-water resource in the York-James Peninsula. Each ground-water user has a range of tolerance for quality-related constituents based on individual need. A thorough knowledge of the concentration and distribution of dissolved-chemical constituents in ground water can further aid in identifying sources of ground water available for specific water-supply needs. This section describes (1) the general changes in the composition of ground water as it moves along a flow path through the Coastal Plain sediments, (2) the general quality of ground water in aquifers throughout the York-James Peninsula, (3) those factors affecting ground-water quality, and (4) the water-quality problems commonly associated with aquifers of the York-James Peninsula.

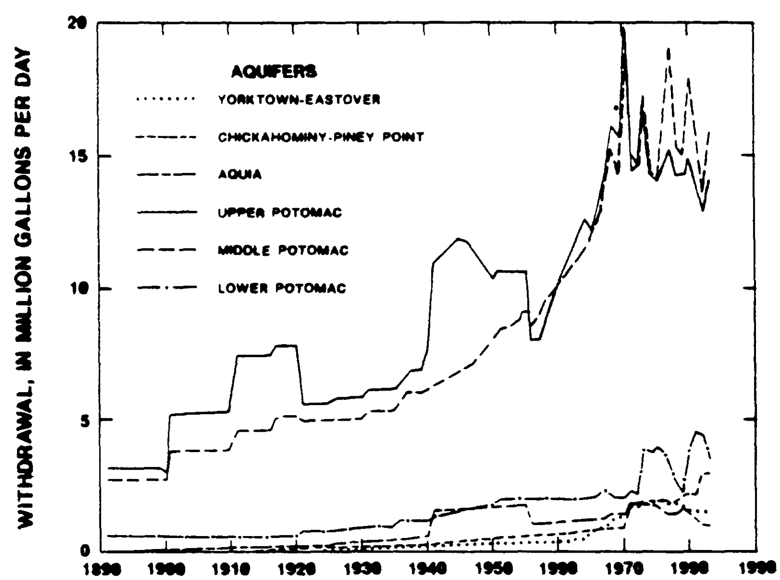


Figure 20. Annual ground-water withdrawal from aquifers in model area.

Table 3.--Estimated ground-water withdrawals from model area by aquifer, 1983

[Mgal/d is million gallons per day]

Aquifer	Withdrawal (Mgal/d)	Percentage of total
Columbia	0.100	0.26
Yorktown-Eastover	1.373	3.52
Chickahominy-Piney Point	2.939	7.55
Aquia	.903	2.32
Virginia Beach	.008	.02
Upper Potomac	14.16	36.39
Middle Potomac	15.873	40.79
Lower Potomac	3.560	9.15
Total	38.916	100.00

Available water-quality data were compiled, wells sampled, and two ground-water research stations installed and sampled in order to characterize the general water quality of aquifers in the York-James Peninsula. Additional sources of data were Federal and State agencies, local governments, and well-drilling companies. Water-quality analyses with major cation-anion imbalances greater than eight percent were considered unreliable and were not used. If water-quality analyses were unavailable for aquifers in particular areas, wells were sampled to obtain the needed data. One research station, designated RS-1 (wells 56H 25 to 56H 30, fig. 2) was installed in the western part of James City County. A second research station, designated RS-2 (wells 58F 50 to 58F 55, fig.2), was installed in the western part of the city of Newport News. Each research station consists of six wells, each screened in different aquifers in order to provide a vertical hydrologic profile of water levels and water quality. Water-quality analyses and source aquifers for wells sampled during the study are given in table 4. A statistical summary of all water-quality data compiled during this study is presented by aquifer in tables 5-11. These tables provide the likely ranges of dissolved-constituent concentrations for aquifers within the study area.

Precipitation that recharges the ground-water flow system typically contains low concentrations of dissolved constituents. As precipitation

Table 4--Water-quality analyses of wells sampled during study

[°C is degrees Celsius, mg/L is milligrams per liter, µg/L is micrograms per liter, µS/cm is microsiemens per centimeter at 25° Celsius, a dash indicates constituent analysis is unavailable]

Local Well Number	Date Sampled	Temperature (°C)	Calcium, Dissolved (mg/L)	Magnesium, Dissolved (mg/L)	Potassium, Dissolved (mg/L)	Sodium, Dissolved (mg/L)	Chloride, Dissolved (mg/L)	Sulfate, Dissolved (mg/L)	Alkalinity, Field (mg/L) as $CaCO_3$	Fluoride, Dissolved (mg/L)	Silica, Dissolved (mg/L)	pH (Standard Units)	Hardness (mg/L as $CaCO_3$)	Specific Conductance (µS/cm)	Boron, Dissolved (µg/L)	Iron, Total Recoverable (µg/L)	Iron, Dissolved (µg/L)	Manganese, Total Recoverable (µg/L)	Manganese, Dissolved (µg/L)	Zinc, Dissolved (µg/L)	Aluminum, Dissolved (µg/L)	Solids Residue at 180°C, Dissolved (mg/L)	Carbon, Organic, Total (mg/L)	Nitrogen, Ammonia, Dissolved (mg/L)	Nitrogen, NO2+NO3, Dissolved (mg/L)	Phosphorus, Total (mg/L)	Source Aquifer
52J10	08-30-84	20.0	17	5.1	15	12	1.8	7.3	102	0.1	13	7.4	63	230	80	2100	1600	40	37	200	200	167	—	0.16	0.17	<0.01	Middle Potomac
52K3	08-30-84	18.5	.95	.51	22	40	1.9	19	104	.3	29	7.6	5	258	120	300	190	<10	5	13	200	206	5.5	.30	<.10	.03	Middle Potomac
52K14	08-30-84	19.0	18	7.8	18	17	1.8	20	125	.2	18	7.5	77	290	90	290	190	40	39	50	500	196	4.0	.17	<.10	.15	Middle Potomac
53J8	07-30-85	17.5	9.3	4.2	13	41	2.1	11	181	.4	11	8.4	41	308	190	440	86	10	17	8	<100	172	—	.18	<.10	<.01	Lower Potomac
55G5	07-05-84	18.0	26	3.3	7.6	27	6.4	6.9	134	.4	45	7.8	79	350	100	340	91	10	4	17	<100	222	.6	.11	<.10	.02	Chickahominy-Piney Point
55H19	06-22-84	16.5	22	6.8	5.8	22	15	7.0	133	.3	27	8.5	83	450	50	180	11	10	2	280	200	179	—	—	—	<.01	Chickahominy-Piney Point
55J6	08-23-84	19.0	15	5.6	8.3	32	4.9	4.6	136	.4	28	8.0	61	260	90	260	38	<10	2	21	<100	180	1.0	.14	<.10	.02	Aquia
56H25	04-09-85	19.0	5.1	1.2	5.7	450	340	61	484	.3	15	7.8	18	2200	1200	1000	500	30	40	20	100	1190	1.5	.09	<.10	.03	Lower Potomac
56H26	04-10-85	18.5	18.0	2.3	8.6	100	6.0	11.0	262	1.1	20	7.9	54	540	400	780	170	60	68	<3	100	310	1.5	.04	<.10	.06	Middle Potomac
56H27	04-10-85	17.0	3.5	.97	8.4	160	15	16	350	2.2	30	7.8	13	725	790	250	32	<10	12	<3	100	432	1.8	.15	<.10	.39	Upper Potomac
56H28	04-11-85	18.0	11	3.1	11	120	13	19	305	1.8	20	8.2	40	640	20	2200	27	20	14	<3	<100	357	1.8	.19	<.10	.12	Aquia
56H29	04-11-85	16.0	48	3.7	5.2	10	3.9	4.8	147	.2	56	7.6	140	315	40	380	270	30	23	<3	<100	204	1.3	.10	<.10	.02	Chickahominy-Piney Point
56H30	04-11-85	16.0	78	1.1	.8	4.7	9.0	6.5	182	<.1	12	7.3	200	390	20	8700	38	210	170	6	<100	218	2.7	.02	<.10	.09	Yorktown-Eastover
58F50	06-19-84	22.0	45	20	19	1400	2000	120	244	.7	17	7.7	190	6000	1600	4000	1200	150	140	<10	<100	3860	0.6	.60	<.10	<.01	Lower Potomac
58F51	06-20-84	20.5	20	11	16	940	1300	90	328	1.2	32	7.4	95	5000	1600	3900	2400	100	70	150	<100	2660	0.3	.49	<.10	<.03	Middle Potomac
58F52	06-20-84	19.5	6.1	2.4	13	520	540	64	422	2.0	15	8.0	25	2400	1700	690	480	30	20	30	<100	1390	0.3	.42	<.10	.10	Upper Potomac
58F53	07-05-84	19.5	4.7	2.5	13	380	160	18	653	2.2	36	8.2	22	1700	2600	700	360	20	15	26	<100	1090	8.5	.49	<.10	.06	Chickahominy-Piney Point
58F54	06-22-84	20.0	29	3.4	6.2	71	17	13	254	.5	12	8.1	86	460	400	1500	15	120	110	96	<100	300	7.3	.10	.19	.01	Yorktown-Eastover
58F55	06-22-84	23.5	84	1.9	1.5	13	26	5.0	244	.1	10	7.3	220	470	<20	550	260	630	610	280	<100	291	2.5	<.01	<.10	<.02	Columbia
59E6	08-09-84	24.0	82	59	62	3000	4400	350	407	.2	24	7.0	450	>8000	1500	8700	8200	220	200	1000	—	7960	0.9	2.70	<.10	<.01	Upper Potomac
59E6	08-31-84	23.0	99	100	83	3100	4700	470	706	.7	25	7.3	660	>8000	5100	3600	3600	110	100	100	—	9120	4.8	4.10	<.10	<.01	Chickahominy-Piney Point
59E6	09-06-84	22.0	100	110	79	2900	4800	350	525	.6	41	7.4	700	>8000	5100	11000	3200	100	70	180	600	8590	4.4	4.30	<.10	.22	Chickahominy-Piney Point

Table 5.--Summary of water-quality analyses from Columbia aquifer in the York-James Peninsula

[N is number of samples, C_a CO_3 is calcium carbonate, mg/L is milligrams per liter, μg/L is micrograms per liter, μs/cm is microsiemens per centimeter, °C is degrees Celsius, -- indicates insufficient number of constituent analyses, < indicates less than value shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	17	86.00	2.90	42.21	43.00	25.51
Magnesium, dissolved, mg/L ..	17	14	.09	5.02	4.3	3.77
Potassium, dissolved, mg/L ..	12	4.3	.6	2.22	1.85	1.14
Sodium, dissolved, mg/L	13	55	5.2	25.2	20	16.55
Alkalinity as $CaCO_3$, mg/L ...	5	406	15	169.6	126	154.94
Chloride, dissolved, mg/L ...	19	93	9.7	34.28	27	22.48
Sulfate, dissolved, mg/L	17	29	1.32	9.81	6	9.13
Specific conductance, μs/cm	7	628	114	345.43	339	177.38
pH, standard units	15	8.05	6.5	7.56	7.8	.5
Nitrogen, nitrite plus nitrate dissolved, mg/L ...	1	--	--	--	<.01	--
Phosphate, ortho., dissolved, mg/L......................	0	--	--	--	--	--
Organic carbon, total, mg/L .	0	--	--	--	--	--
Hardness, total as $CaCO_3$, mg/L......................	18	220	16	102.17	107.5	62.54
Fluoride, dissolved, mg/L ...	18	0.5			.21	--
Silica, dissolved, mg/L	13	40	6.6	21.31	20	11.14
Iron, total,μg/L	7	710	80	408.57	350	248.29
Iron, dissolved, μg/L	4	5200	90	1477.5	310	2484.17
Manganese, total, μg/L	5	5900	30	1250	70	2600
Manganese, dissolved, μg/L ..	2	610	200	405	405	---
Dissolved solids, residue at 180°C, mg/L............	15	762	63	262	227	168

infiltrates into and moves downgradient through the ground-water flow system toward discharge areas, its chemical composition is modified by contact with minerals in the sediment. The water-quality diagram in figure 21 generalizes the chemical changes in ground water moving downgradient along a regional pre-pumping flow path (Back, 1966). Water in recharge areas (A in fig. 21) is dominated by a mixture of sodium, calcium, and magnesium cations and bicarbonate anions. The chemical character of ground water changes to a calcium-bicarbonate water downgradient from the recharge areas (B in fig. 21). This change in chemical character occurs from the dissolution of calcite in shell material found within the sediments. If ground water becomes saturated with

Table 6.--Summary of water-quality analyses from Yorktown-Eastover aquifer in the York-James Peninsula

[N is number of samples, $CaCO_3$ is calcium carbonate, mg/L is milligrams per liter, µg/L is micrograms per liter, µs/cm is microsiemens per centimeter, °C is degrees Celsius, -- indicates insufficient number of constituent analyses, < indicates less than value shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	34	261.00	1.80	59.93	56.50	45.18
Magnesium, dissolved, mg/L ..	34	39	.1	5.82	3.45	8.02
Potassium, dissolved, mg/L ..	25	16	.8	4.4	2.6	4.11
Sodium, dissolved, mg/L	26	804	3.5	86.84	20.5	182.84
Alkalinity as $CaCO_3$, mg/L ...	11	294	12	154.18	167	82.79
Chloride, dissolved, mg/L ...	35	1190	3.1	96.47	21.5	248.53
Sulfate, dissolved, mg/L	35	119	1.13	16.24	9.9	21.32
Specific conductance, µs/cm	18	4380	285	720.89	427	938.04
pH, standard units	21	8.9	7.1	7.63	7.55	.42
Nitrogen as $NO_2 + NO_3$, dissolved, mg/L	4	.25	<.01	--	.1	--
Phosphate, ortho., dissolved, mg/L.......................	5	.52	<.01	--	.09	--
Organic carbon, total, mg/L .	1	--	--	--	4.6	--
Hardness, total as $CaCO_3$, mg/L.......................	30	812	5.	170.71	165	139.14
Fluoride, dissolved, mg/L ...	29	.9	<.01	--	.1	--
Silica, dissolved, mg/L	26	40	9.7	18.04	15.5	8.48
Iron, total, µg/L	11	8700	30	2909.09	710	3677.08
Iron, dissolved, µg/L	13	120	<.01	--	20	--
Manganese, total, µg/L	3	210	40	123.33	120	85.05
Manganese, dissolved, µg/L ..	2	170	110	140	140	--
Dissolved solids, residue at 180°C, mg/L	29	2280	108	328	248	390

Table 7.--Summary of water-quality analyses from Chickahominy-Piney Point aquifer in the York-James Peninsula

[N is number of samples, C_a CO_3 is calcium carbonate, mg/L is milligrams per liter, µg/L is micrograms per liter, µs/cm is microsiemens per centimeter, °C is degrees Celsius, -- indicates insufficient number of constituent analyses, < indicates less than value shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	64	99.00	1.10	19.96	19.00	16.67
Magnesium, dissolved, mg/L ..	64	100	.7	4.82	3	12.30
Potassium, dissolved, mg/L ..	59	83	1.4	10.38	8.5	10.49
Sodium, dissolved, mg/L	59	3100	2.4	136.53	33	419.37
Alkalinity as $CaCO_3$, mg/L ...	50	770	5	184.02	139	144.45
Chloride, dissolved, mg/L ...	69	4800	.5	118.51	4.2	589.92
Sulfate, dissolved, mg/L	67	470	1.6	16.34	7	56.91
Specific conductance, µs/cm	47	3799	205	477.87	300	586.03
pH, standard units	50	9.4	5.6	7.63	7.8	.73
Nitrogen as $NO_2 + NO_3$, dissolved, mg/L	22	.35	<.01	--	.03	--
Phosphate, ortho., dissolved, mg/L......................	42	.64	<.01	--	.03	--
Organic carbon, total, mg/L .	8	7.1	1.4	4.74	5.55	2.06
Hardness, total as $CaCO_3$ mg/L......................	66	140	6	59.72	56.5	37.53
Fluoride, dissolved, mg/L ...	67	3.2	.1	.73	.5	.65
Silica, dissolved, mg/L	62	71	2	38.45	39.02	16.2
Iron, total, µg/L	12	2900	10	395.83	60	815.99
Iron, dissolved, µg/L	32	1300	10	103.72	25	235.8
Manganese, total, µg/L	7	110	10	28.57	10	36.71
Manganese, dissolved, µg/L ..	6	100	2	29	19	36.41
Dissolved solids, residue at 180°C, mg/L	64	9120	20	460	224	1151

Table 8--Summary of water-quality analyses from Aquia aquifer in the York-James Peninsula

[N is number of samples, Ca CO3 is calcium carbonate, mg/L is milligrams per liter, µg/L is micrograms per liter, µs/cm is microsiemens per centimeter, °C is degrees Celsuis, -- indicates insufficient number of constituent analyses, < indicates less than value shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	124	82.00	<0.01	--	3.20	--
Magnesium, dissolved, mg/L ..	124	59	<.01	--	1.35	--
Potassium, dissolved, mg/L ..	113	62	1.3	10.81	10	7.41
Sodium, dissolved, mg/L	120	3000	4.6	289.78	216.5	332.27
Alkalinity as $CaCO_3$, mg/L ...	65	521	49	314.23	331	85.27
Chloride, dissolved, mg/L ...	132	4400	.3	199.37	54.5	440.99
Sulfate, dissolved, mg/L	126	350	1.6	28.94	15	41
Specific conductance, µs/cm	61	5700	265	1278.18	1010	987.74
pH, standard units	60	9.1	6.4	7.84	7.95	.52
Nitrogen as NO_2 + NO_3, dissolved, mg/L	23	.52	<.01	--	.1	--
Phosphate, ortho., dissolved, mg/L......................	52	2.1	<.01	--	.45	--
Organic carbon, total, mg/L .	4	6.4	2.4	5.15	5.9	1.85
Hardness, total as $CaCO_3$, mg/L	129	450	1.9	26.57	13	49.52
Fluoride, dissolved, mg/L ...	121	5.4	.1	2.28	2.4	1.27
Silica, dissolved, mg/L	117	52	2.5	20.21	19	8.19
Iron, total, µg/L............	21	8700	.02	724.3	100	2018.41
Iron, dissolved, µg/L	52	8200	3	449.9	45	1573.43
Manganese, total, µg/L	3	220	10	86.67	30	115.9
Manganese, dissolved, µg/L ..	4	200	12	65	25	89.97
Dissolved solids, residue at 180°C, mg/L	118	7960	162	761	484	865

Table 9.--Summary of water-quality analyses from upper Potomac aquifer in the York-James Peninsula

[N is number of samples, C_a CO_3 mg/L is milligrams per liter, µg/L is micrograms per liter, µs/cm is microsiemens per centimeter, °C is degrees Celsius, -- indicates insufficient number of constituent analyses, < indicates less than value shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	23	38.00	0.50	11.15	8.00	10.27
Magnesium, dissolved, mg/L ..	23	16	.2	3.5	2.7	3.39
Potassium, dissolved, mg/L ..	20	20	1.5	10.42	11	4.72
Sodium, dissolved, mg/L	20	600	7.9	188.29	110	187.44
Alkalinity as $CaCO_3$, mg/L ...	16	385	85	235.81	219	87.68
Chloride, dissolved, mg/L ...	28	2200	2.4	258.74	30	460.66
Sulfate, dissolved, mg/L	28	300	.6	37.71	17	57.97
Specific conductance, µs/cm	15	2450	192	816.8	480	721.93
pH, standard units	13	8.4	6.9	7.91	8	.41
Nitrogen as NO_2 + NO_3, dissolved, mg/L	6	.45	<.01	--	.07	--
Phosphate, ortho., dissolved, mg/L......................	42	2.6	<.01	--	.37	--
Organic carbon, total, mg/L .	0	--	--	--	--	--
Hardness, total as $CaCO_3$, mg/L	28	240	2.	44.58	27.15	51.1
Fluoride, dissolved, mg/L ...	27	5.5	.2	2.01	1.8	1.49
Silica, dissolved, mg/L	23	48	5.4	27.44	28	12.28
Iron, total, µg/L............	5	18000	70	4122	260	7809.68
Iron, dissolved, µg/L	9	140	10	50.56	38	42.53
Manganese, total, µg/L	3	20	8	16	20	6.93
Manganese, dissolved, µg/L ..	2	14	2	8	--	--
Dissolved solids, residue at 180°C, mg/L	23	2500	260	920	520	884

Table 10.--Summary of water-quality analyses from middle Potomac aquifer in the York-James Peninsula

[N is number of samples, C_a CO_3 mg/L is milligrams per liter, µg/L is micrograms per liter, µs/cm is microsiemens per centimeter, °C is degrees Celsius, -- indicates insufficient number of constituent analyses, < indicates less than value shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	107	45.00	<0.01	--	4.00	--
Magnesium, dissolved, mg/L ..	106	14	<.01	--	1.15	--
Potassium, dissolved, mg/L ..	99	24	.4	9.72	8.6	5.28
Sodium, dissolved, mg/L	105	940	2.4	99.14	68	127.71
Alkalinity as $CaCO_3$, mg/L ...	87	605	8	177.6	160	87.33
Chloride, dissolved, mg/L ...	115	1300	.01	--	4	--
Sulfate, dissolved, mg/L	110	80.2	2	14.36	12	12.25
Specific conductance, µs/cm	69	5000	110	485.46	345	618.43
pH, standard units	75	8.6	5.8	7.8	7.85	.46
Nitrogen as NO_2 + NO_3, dissolved, mg/L	12	0.66	<.01	--	.05	--
Phosphate, ortho., dissolved, mg/L.......................	46	2.2	<.01	--	.26	--
Organic carbon, total, mg/L .	4	4	.3	1.72	1.3	1.6
Hardness, total as $CaCO_3$, mg/L	107	150	1	33.21	12	40.19
Fluoride, dissolved, mg/L ...	109	6.1	.1	1.13	.5	1.31
Silica, dissolved, mg/L	86	45	2.9	25.69	26.5	8.82
Iron, total, µg/L............	11	3900	20	768.18	300	1190.91
Iron, dissolved, µg/L	36	2400	<.01	--	35	196.34
Manganese, total, µg/L	6	100	10	48.33	40	29.94
Manganese, dissolved, µg/L ..	6	70	5	38.17	38	27.56
Dissolved solids, residue at 180°C, mg/L	92	2660	115	361	231	383

Table 11.--Summary of water-quality analyses from lower Potomac aquifer in the York-James Peninsula

[N is number of samples, $C_a CO_3$ is calcium carbonate, mg/L is milligrams per liter, µg/L is micrograms per liter, µs/cm is microsiemens per centimeter, °C is degrees Celsius, -- indicates insufficient number of constituent analyses, < indicates less than values shown]

Water-quality constituent	N	Maximum	Minimum	Mean	Median	Standard deviation
Calcium, dissolved, mg/L	14	45.00	1.00	9.31	5.00	13.11
Magnesium, dissolved, mg/L ..	14	20	<.01	--	1	--
Potassium, dissolved, mg/L ..	12	19	3.9	7.56	5.2	4.77
Sodium, dissolved, mg/L	12	1400	41	325	126	398.3
Alkalinity as $CaCO_3$, mg/L ...	12	528	130	293	237	157.01
Chloride, dissolved, mg/L ...	14	2000	.1	340	106	559.25
Sulfate, dissolved, mg/L	14	120	8	42.11	31.75	34.09
Specific conductance, µs/cm	8	6000	308	1809.75	1135	1938.56
pH, standard units	12	8.4	7.4	7.95	7.95	0.31
Nitrogen as $NO_2 + NO_3$, dissolved, mg/L	3	<0.01	<.01	--	<.01	--
Phosphate, ortho., dissolved, mg/L	3	1.1	.09	.56	.5	.51
Organic carbon, total, mg/L .	2	1.5	.6	1.05	1.05	--
Hardness, total as $CaCO_3$, mg/L	14	190	4	34.72	20.5	47.46
Fluoride, dissolved, mg/L ...	13	3	.3	1.45	1.2	1.2
Silica, dissolved, mg/L	10	32	11	20.59	18.06	7.66
Iron, total, µg/L	4	5000	440	2610	2500	2231.98
Iron, dissolved, µg/L	10	2700	<.01	--	40	196.34
Manganese, total, µg/L	4	150	10	57.5	35	62.92
Manganese, dissolved, µg/L ..	5	810	17	209.4	40	339.1
Dissolved solids, residue at 180 °C, mg/L............	10	3860	172	1227	1026	1146

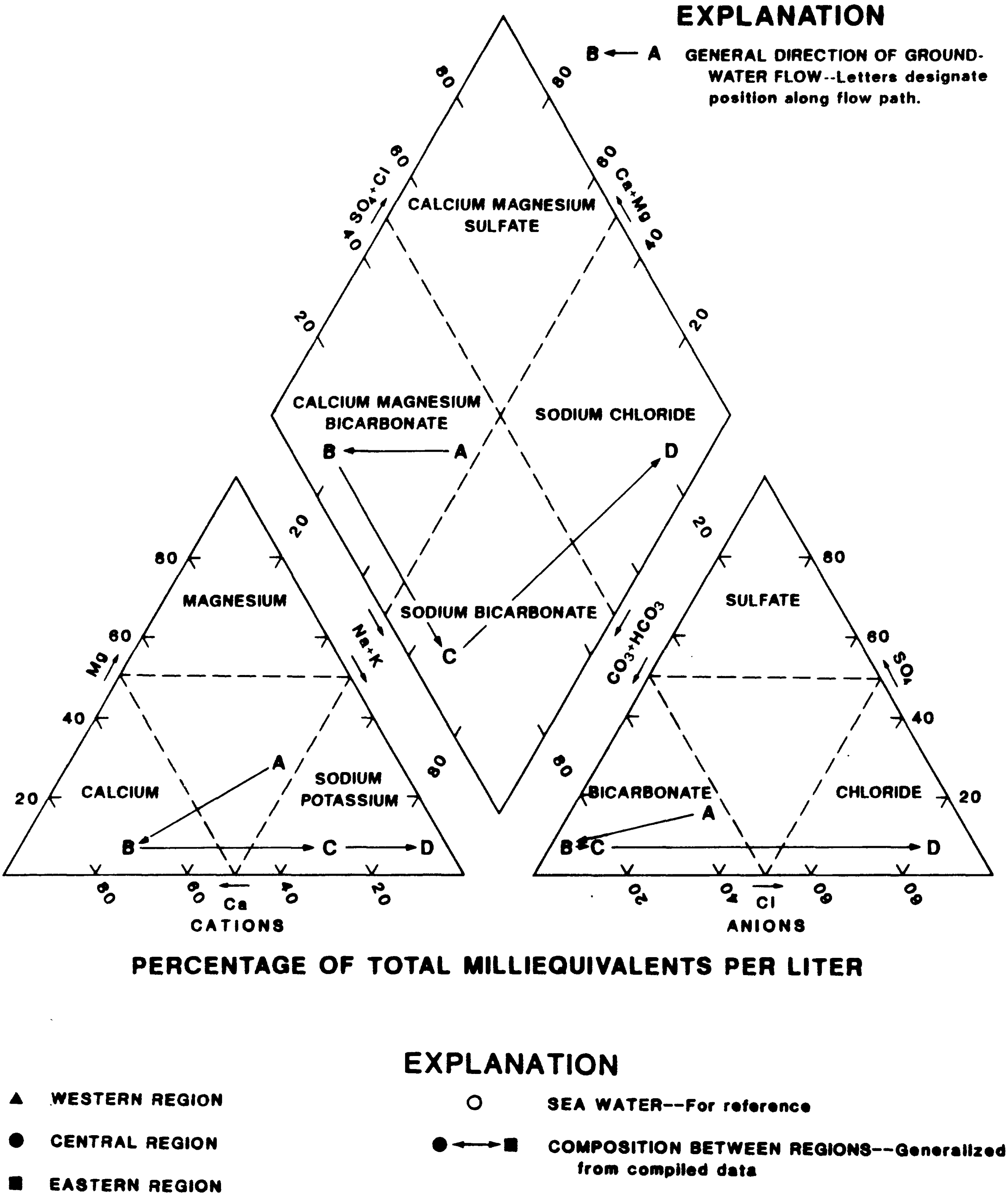


Figure 21. Change in relative chemical composition of ground water along typical prepumping flow path in York-James Peninsula.

calcium carbonate, the mineral calcite precipitates, forming hard, indurated layers, such as are present in the Chickahominy-Piney Point aquifer. As ground water continues to move along the flow path, it interacts with cation-exchanging sediments. These sediments remove calcium dissolved in the ground water and replace it with sodium. The result of this exchange process is a sodium-bicarbonate water (C in fig. 21). This is the dominant water type in the fresh ground-water flow system of the York-James Peninsula. Near the end of the flow path, ground water becomes altered again as it intermixes with salty ground water, yielding a sodium-chloride water (D in fig. 21). As salty water begins to dominate, the ground water becomes unsuitable for potable use.

Water-quality analyses were selected from the western, central, and eastern regions of the study area to document changes in the chemical composition of water quality for each aquifer. Characteristic changes in the water quality within each aquifer are illustrated by water-quality diagrams in figures 22-27. Throughout the western region of the study area aquifer-outcrop areas abound in all aquifers except the lower Potomac aquifer. These aquifers are characterized by a mixed sodium-calcium-magnesium-bicarbonate type water. The lower Potomac aquifer, which does not crop out, receives no direct recharge from precipitation and a sodium-bicarbonate type water predominates. In the central region of the of the study area, the Yorktown-Eastover and Chickahominy-Piney Point aquifers contain abundant shell material and are characterized by a calcium-bicarbonate type water; the Aquia, upper Potomac, and middle Potomac aquifers by a sodium-bicarbonate type water; and the lower Potomac aquifer by an intermediate sodium-bicarbonate type and a sodium-chloride type water. In the eastern region of the study area, the Columbia aquifer is characterized by a mixed sodium-calcium-magnesium-bicarbonate type water; the Yorktown-Eastover and Chickahominy-Piney Point aquifers by a sodium-bicarbonate type water; and the Aquia, upper Potomac, middle Potomac, and lower Potomac aquifers by a sodium-chloride type water.

Vertical differences in the quality of ground water among aquifers, at research stations RS-1 and RS-2, are illustrated in figures 28 and 29, respectively. Interestingly, these differences follow the general pattern of chemical evolution expected along lateral flow paths of individual aquifers. At RS-1 (fig. 28), water in the Yorktown-Eastover and Chickahominy-Piney Point aquifers contain a calcium-bicarbonate type water; the Aquia, upper Potomac, and middle Potomac aquifers a sodium-bicarbonate type water; and the lower Potomac aquifer an intermediate between a sodium-bicarbonate type water and a sodium-chloride type water (fig. 28). At RS-2 (fig. 29), the Columbia aquifer contains a calcium-bicarbonate type water; the Yorktown-Eastover and Chickahominy-Piney Point aquifers a sodium-bicarbonate type water; and the upper Potomac, middle Potomac, and lower Potomac aquifers a sodium-chloride type water. At greater depths water is more evolved chemically because the distance travelled along a flow path is proportionally greater. Thus, at any geographical location in the peninsula, the water quality of an aquifer generally depends on the distance from the Fall Line and the depth of the aquifer. The difference in water quality downward through the sediment at RS-1 (fig. 28) is slightly different than the generalized chemical changes in ground water (fig. 21). This deviation may be a result of natural conditions or of the alteration of regional flow patterns within aquifers by recent ground-water withdrawals.

The U.S. Environmental Protection Agency (1976) and the U.S. Public Health Service (1962) recommends limits for constituent concentrations in

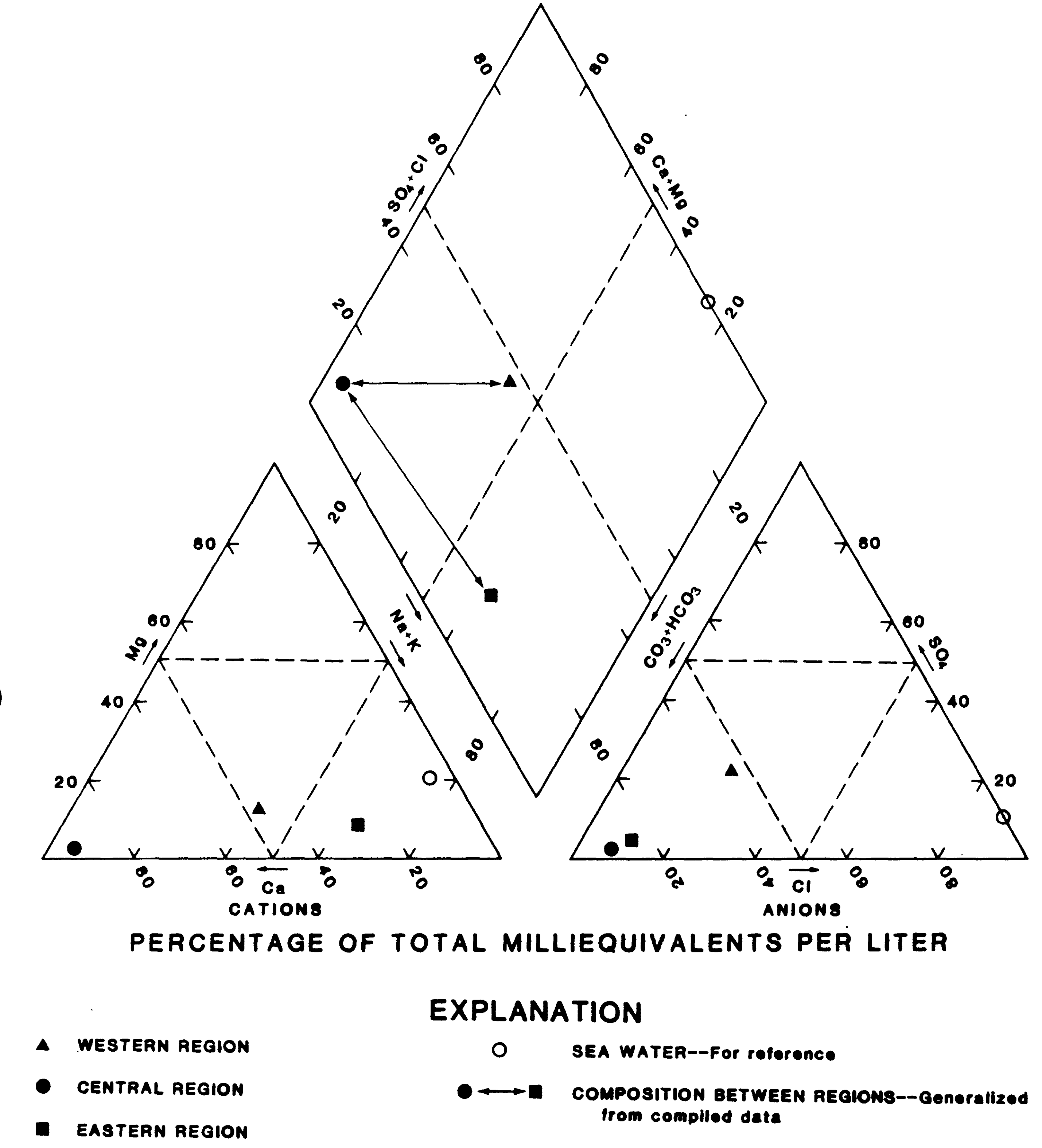
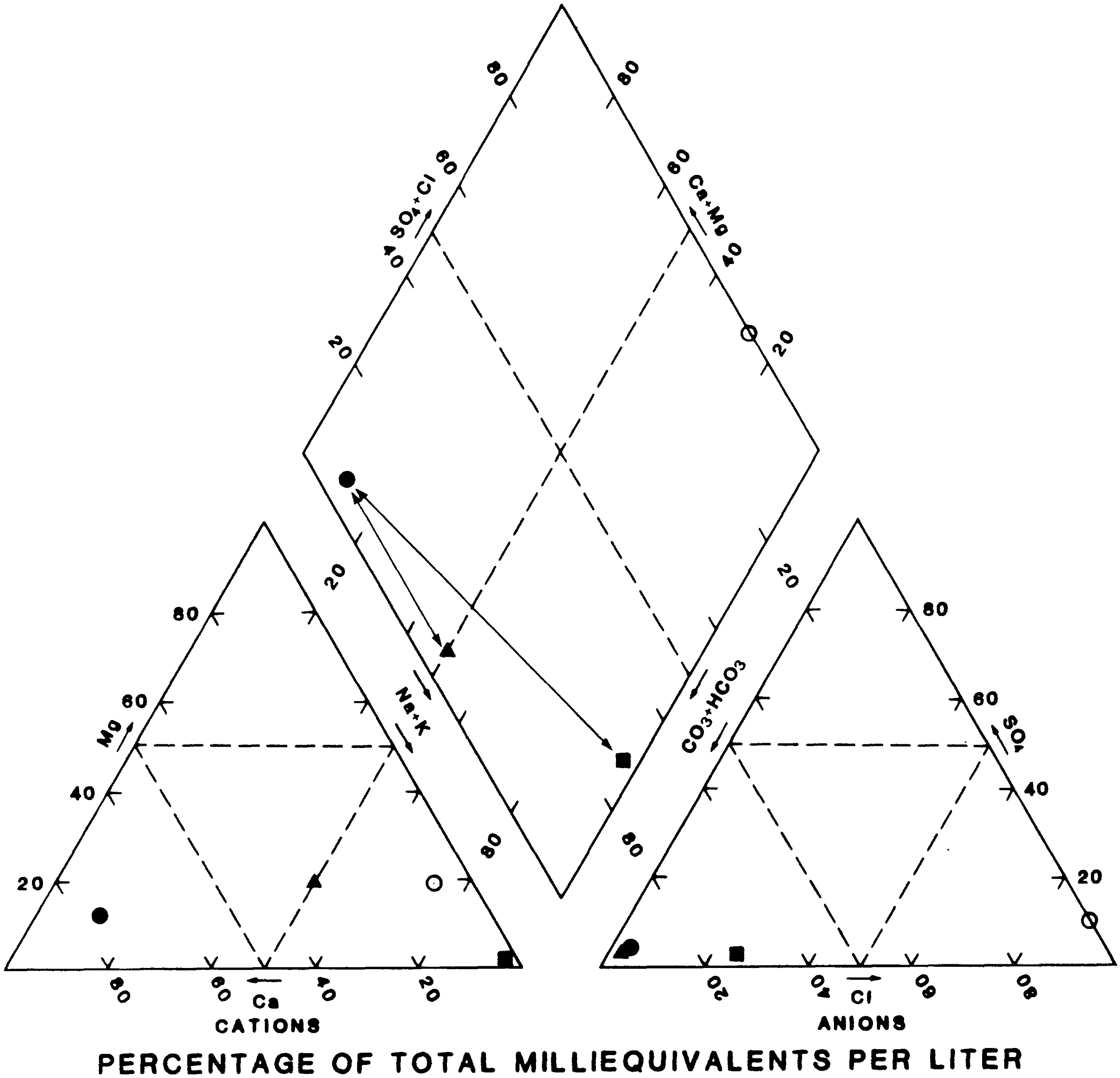


Figure 22. Relative chemical composition of ground water in Yorktown-Eastover aquifer.



EXPLANATION

▲ WESTERN REGION

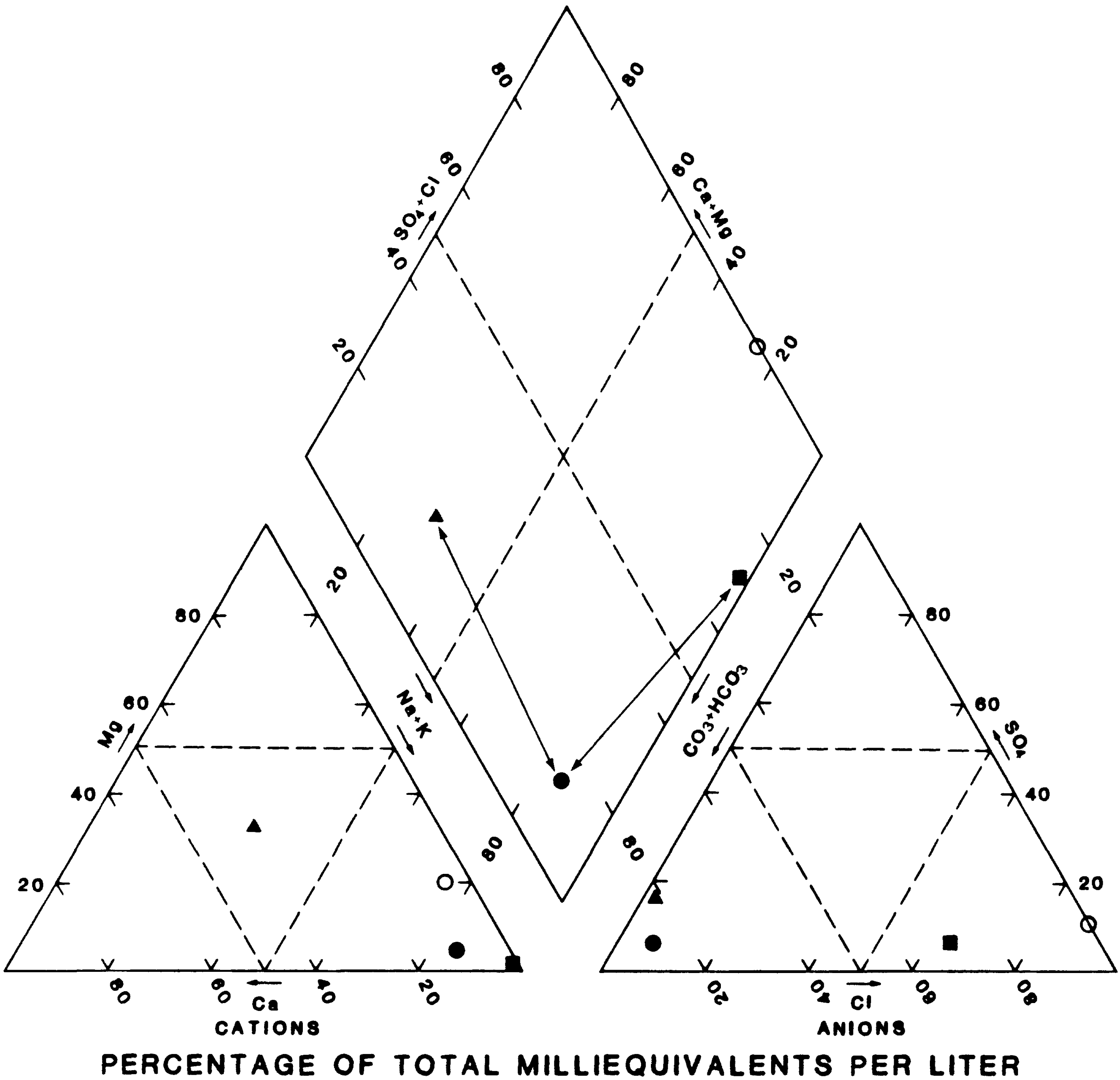
● CENTRAL REGION

■ EASTERN REGION

○ SEA WATER--For reference

●←→■ COMPOSITION BETWEEN REGIONS--Generalized from compiled data

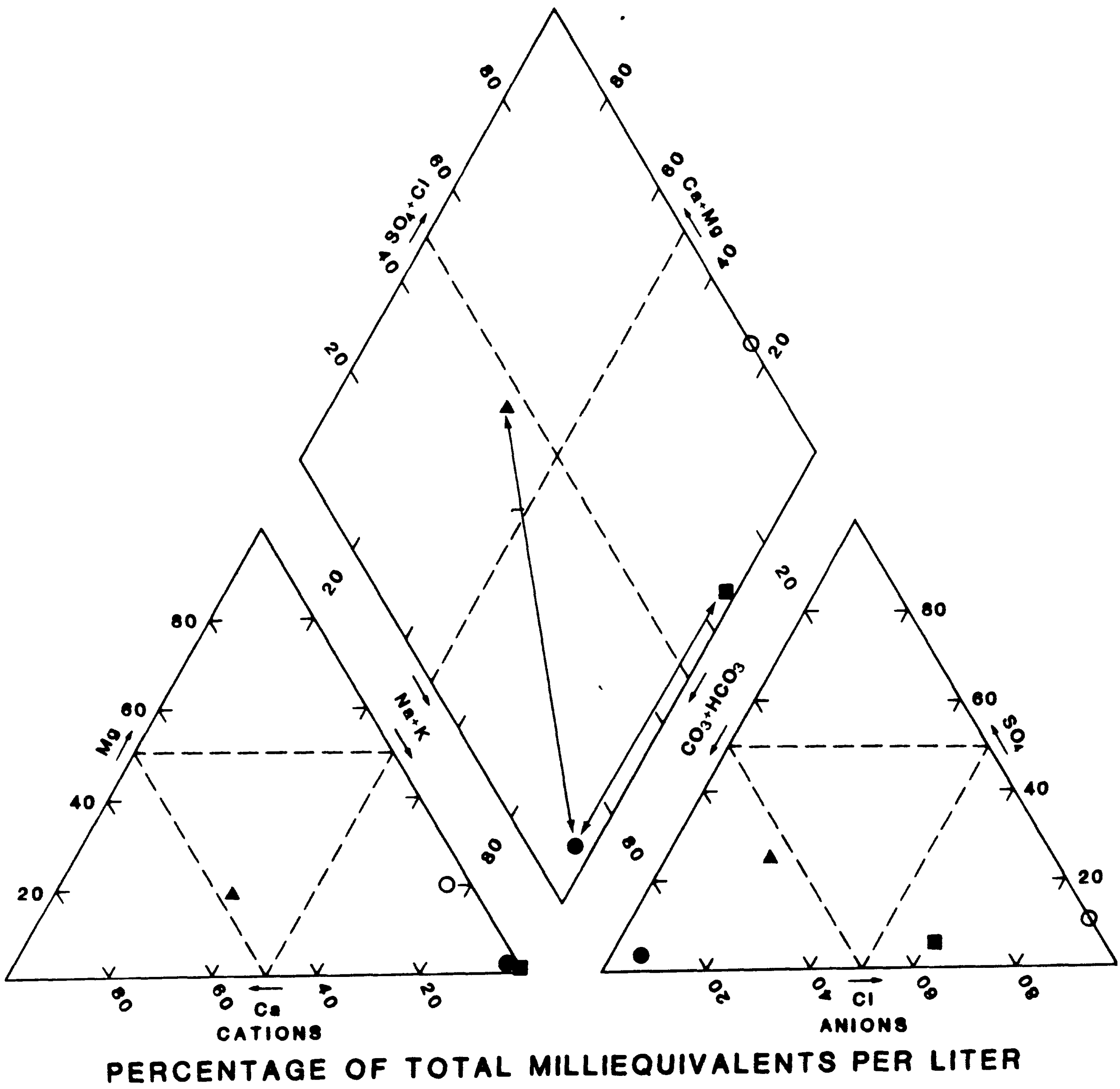
Figure 23. Relative chemical composition of ground water in Chickahominy-Piney Point aquifer.



EXPLANATION

- ▲ WESTERN REGION
- ● CENTRAL REGION
- ■ EASTERN REGION
- ○ SEA WATER--For reference
- ●←→■ COMPOSITION BETWEEN REGIONS--Generalized from compiled data

Figure 24. Relative chemical composition of ground water in Aquia aquifer.



EXPLANATION

▲ WESTERN REGION

● CENTRAL REGION

■ EASTERN REGION

○ SEA WATER--For reference

●←→■ COMPOSITION BETWEEN REGIONS--Generalized from compiled data

Figure 25. Relative chemical composition of ground water in upper Potomac aquifer.

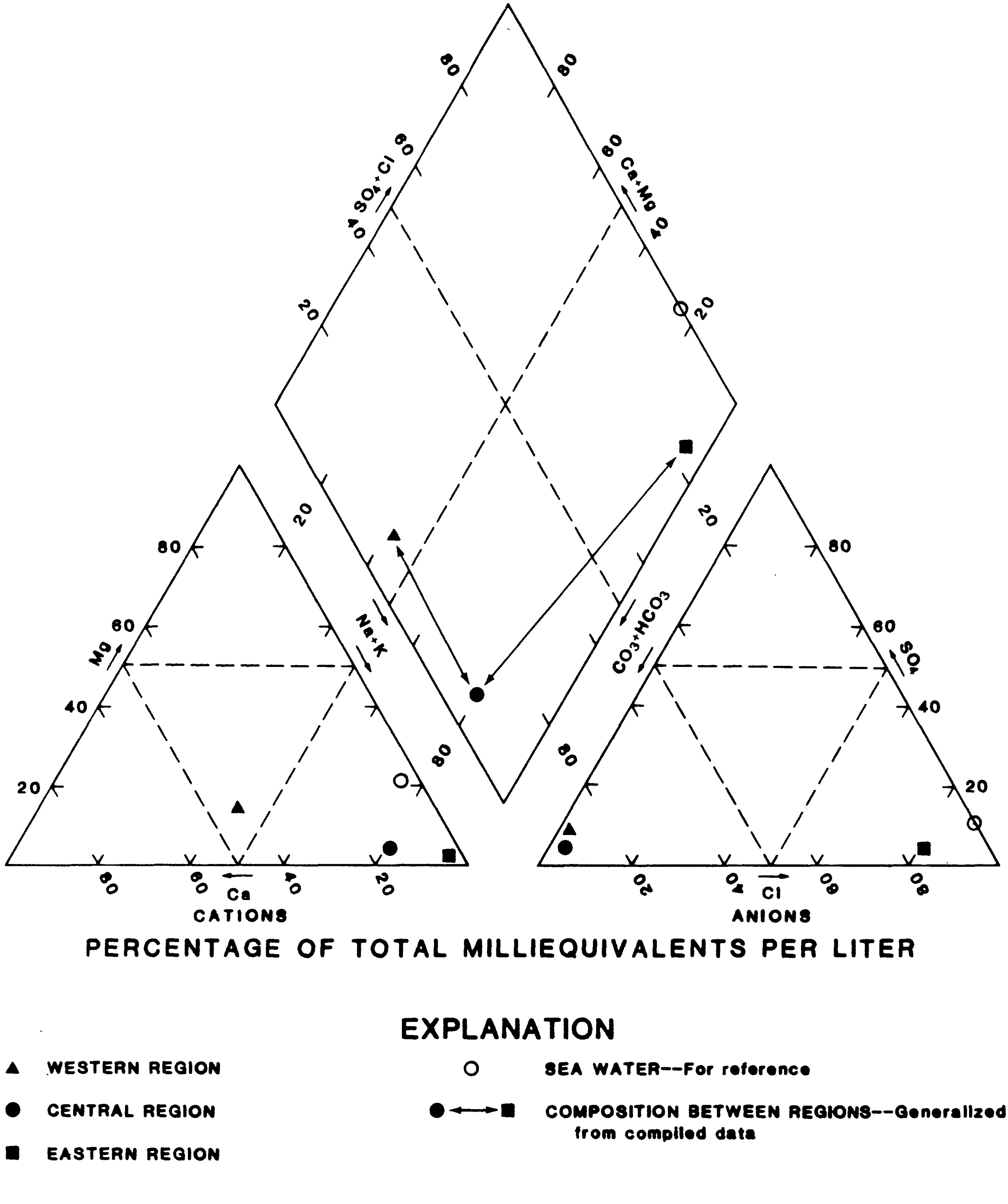


Figure 26. Relative chemical composition of ground water in middle Potomac aquifer.

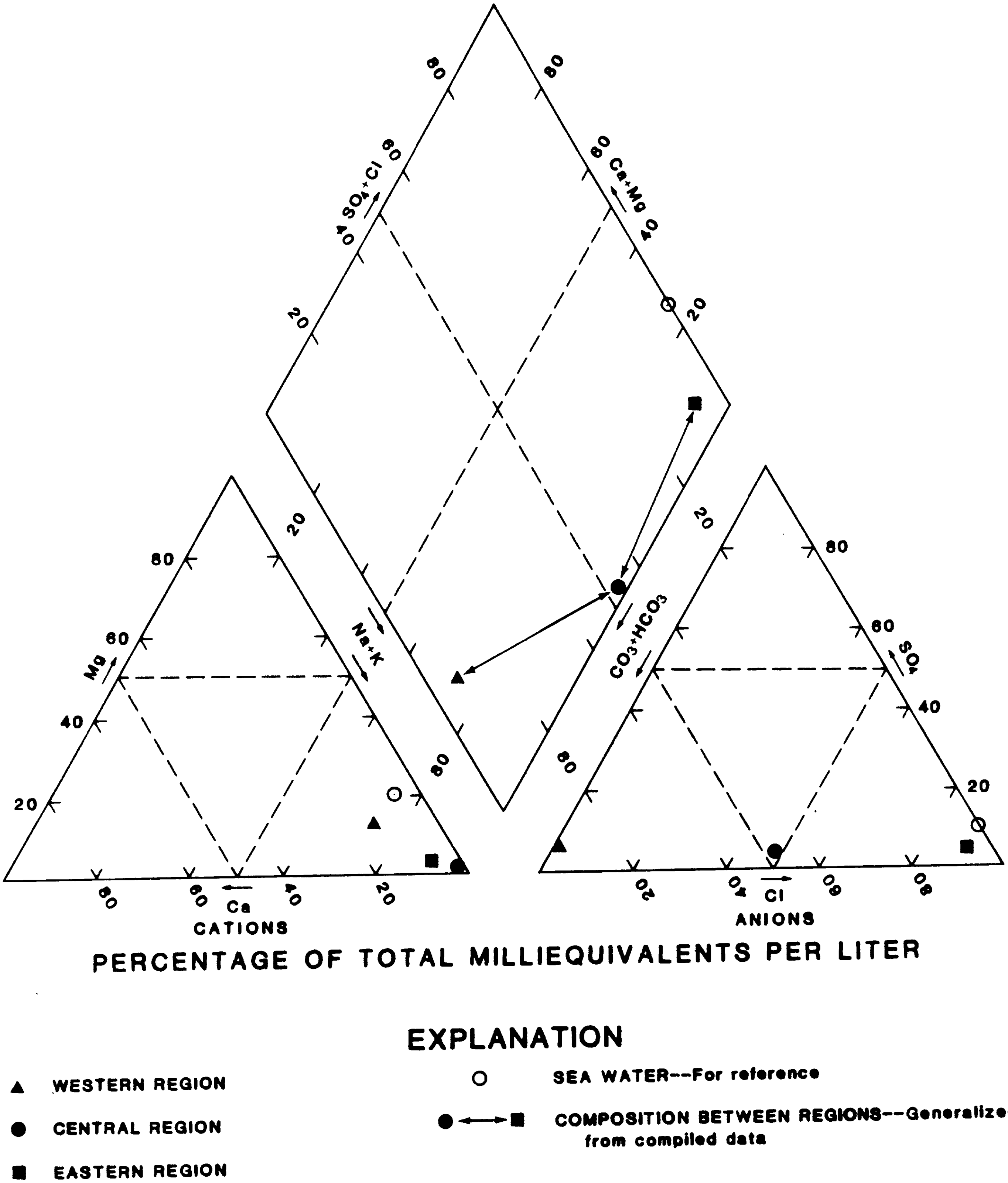
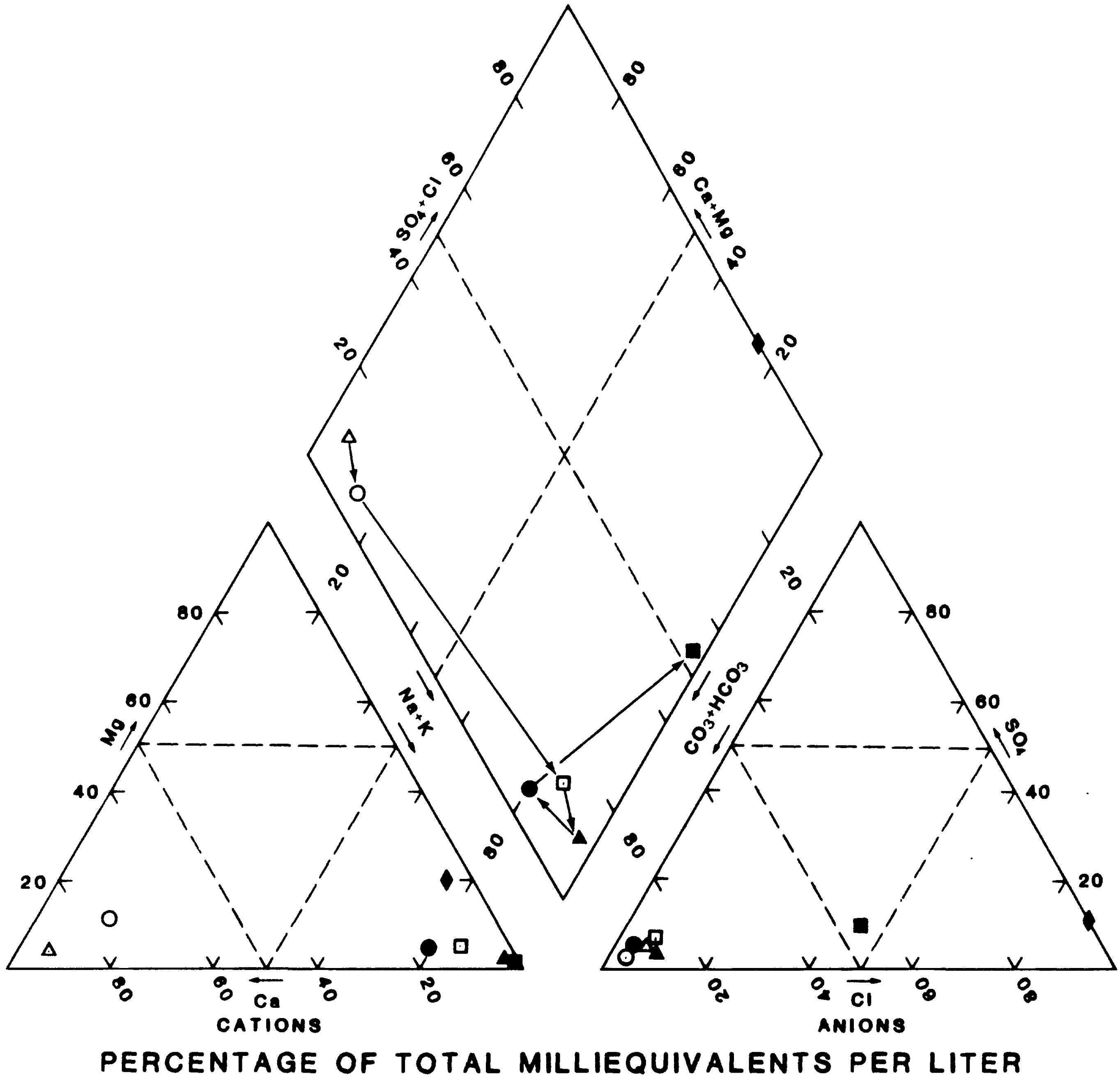


Figure 27. Relative chemical composition of ground water in lower Potomac aquifer.



EXPLANATION

- △ YORKTOWN-EASTOVER AQUIFER
- ○ CHICKAHOMINY-PINEY POINT AQUIFER
- □ AQUIA AQUIFER
- ▲ UPPER POTOMAC AQUIFER
- ● MIDDLE POTOMAC AQUIFER
- ■ LOWER POTOMAC AQUIFER
- ♦ SEA WATER--For reference
- ○→□ DIRECTION OF INCREASING DEPTH

Figure 28. Relative chemical composition of ground water in aquifers at James City County Research Station RS-1.

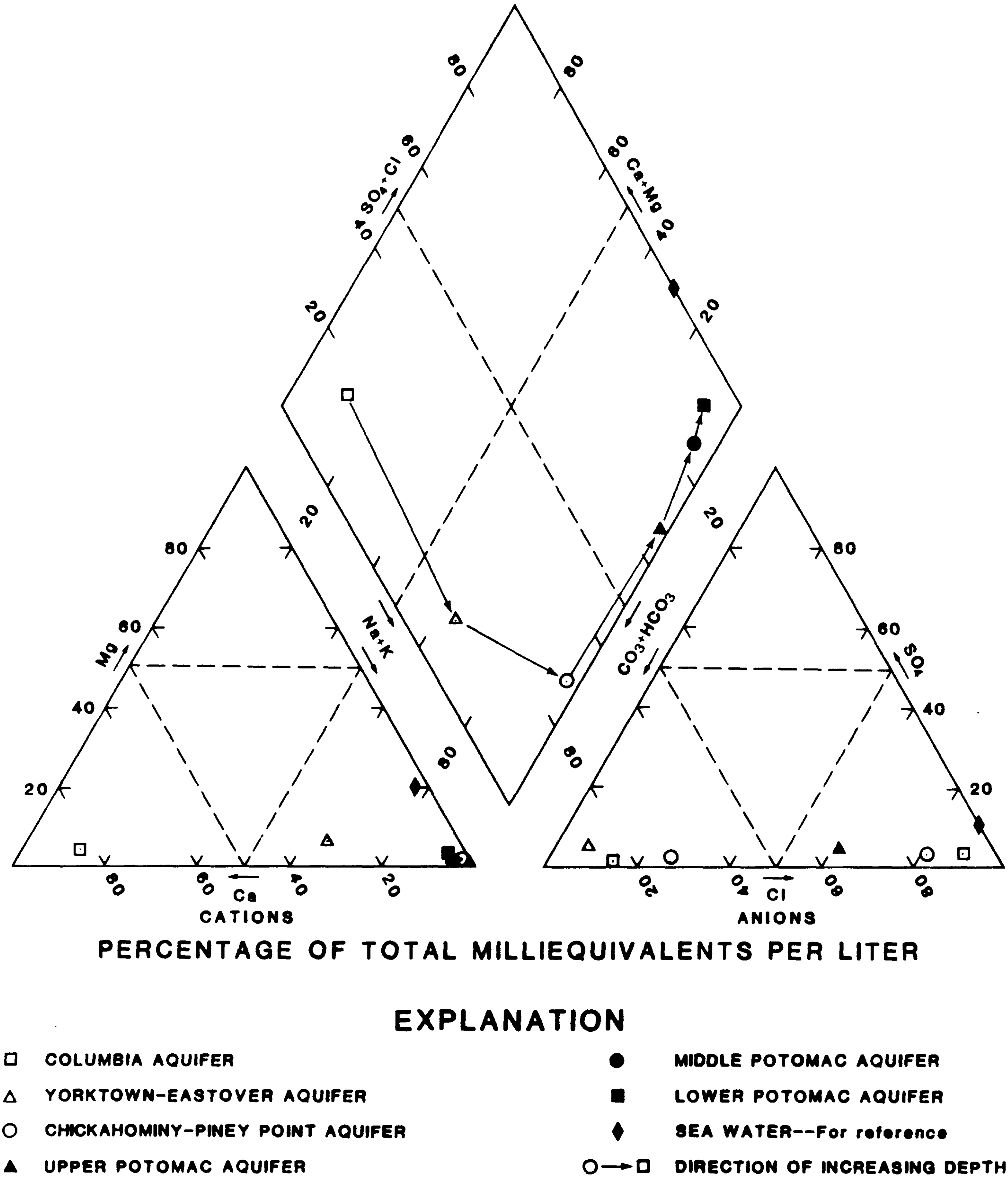


Figure 29. Relative chemical composition of groundwater in aquifers at city of Newport News Research Station RS-2.

drinking water to safeguard public health and welfare. The recommended limits for dissolved-constituent concentrations of concern in the York-James Peninsula are listed in table 12. A chloride concentration greater than 250 mg/L (milligrams per liter) imparts a salty taste to water and is undesirable for potable use. A source of chloride is decomposition of minerals in the sediment, but concentrations are greatly increased by the presence of salty ground-water.

Dissolved iron concentrations greater than 0.3 mg/L results in stains on plumbing fixtures, cooking utensils, and laundry. Dissolved iron often occurs in the reduced state (ferrous iron) and, when exposed to oxygen, oxidizes to a rust-colored particulate form. A major source of dissolved iron is the decomposition of minerals in the sediment.

A dissolved solids concentration greater than 500 mg/L imparts a mineralized taste to water and is undesirable for potable use. Dissolved solids include all constituents dissolved in the water and, depending on the dissolved constituents, can result in deposits in pipes and pumps or can cause corrosion of plumbing parts. A source of dissolved solids is the decomposition of minerals in the sediment, but concentrations are greatly increased by the presence of salty water. Fluoride concentrations greater than 1.8 mg/L result in objectionable mottling of teeth. The source of fluoride is unknown, but is assumed to be either the results of decomposition of or anion exchange with fluoride-containing minerals in the sediment.

Excessive hardness and elevated sodium concentrations also are potential ground-water quality problems but are not yet included in governmental regulations. Hardness, defined as the concentration of divalent metallic ions in water and commonly calculated as the sum of the concentrations of calcium and magnesium, usually is expressed as the concentration of calcium carbonate that would produce an equivalent hardness. Hardness bonds organic molecules in soap to form curds, thus reducing the effectiveness of soap as a cleanser. Durfor and Becker (1964) developed the classification listed in table 13 to describe hardness. Hardness becomes objectionable for ordinary domestic use at concentrations greater than 120 mg/L. A sodium concentration greater than 270 mg/L can cause health problems for people on restricted sodium diets. A source of sodium is the decomposition of and cation exchange with minerals containing sodium. Concentrations of sodium are greatly increased by the presence of salty ground water. The origin of sodium in ground water is illustrated in figure 30. The ratio of sodium-to-chloride concentrations in aquifers at RS-1 are plotted in reference to a line representing the sodium-to-chloride ratio equivalent to that of sea water. The initial displacement of the aquifer-water line to the right of the sea-water line is attributed to sodium present as a product of mineral decomposition and cation exchange. After contact with salty water, the line plots parallel to the sodium-chloride equivalent of sea water.

Wells selected from the western, central, and eastern regions of the study area identify the water-quality problems in each aquifer. A statistical summary of the water-quality constituents of concern are listed for each aquifer by region in table 14. Water-quality problems for each aquifer, identified by median values in table 14, are summarized by region in table 15. The table shows that in the eastern region, only the Yorktown-Eastover and Columbia aquifers contain water that is usable as a potable supply; however,

Table 12.--Pertinent dissolved constituent limits for drinking water

[Recommended limit for fluoride at average annual air temperature of 17.7 - 21.9° Celcius; mg/L is milligrams per liter]

Substance	Recommended[1] limit (mg/L)
Chloride	250
Dissolved iron	.3
Dissolved solids	500
Fluoride	1.8

[1] U.S. Environmental Protection Agency (1976) and U.S. Public Health Service (1962)

Table 13.--Classification of hardness

[Adapted from Durfor and Becker (1964), mg/L is milligrams per liter; > indicates greater than]

Hardness range (mg/L as calcium carbonate)	Description
0 - 60	Soft
>60 - 120	Moderately hard
>120 - 180	Hard
>180	Very hard

Table 14.--Statistical summary of selected ground-water quality constituents in York-James Peninsula by region and aquifer
[Constituent concentrations are milligrams per liter, except for dissolved iron which is in micrograms per liter, and pH which is in standard units, a dash indicates insufficient number of constituent analysis]

Aquifer		Western Region				Central Region				Eastern Region			
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Columbia	Sodium									2	23	13	32
	Chloride									2	39	26	52
	pH		Aquifer not				Aquifer used			1	7.3	--	--
	Hardness		present				only for			2	203	185	220
	Fluoride						domestic supply			2	0.15	0.1	0.2
	Dissolved iron									1	260	--	--
	Dissolved solids									2	306	291	321
	Calcium									2	76	67	84
	Bicarbonate									2	237	176	298
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Yorktown-Eastover	Sodium					2	7.9	4.7	11	2	438	71	804
	Chloride					5	9.0	3.1	20	4	103	17	950
	pH		Aquifer used			5	7.3	5.6	7.5	1	8.1	--	--
	Hardness		only for			5	110	83	223	4	203	185	220
	Fluoride		domestic supply			5	0.1	0.0	0.1	3	0.55	0.4	0.6
	Dissolved iron					4	54	10	120	1	15	--	--
	Dissolved solids					5	144	108	264	3	566	300	2280
	Calcium					5	44	32	83	3	35	29	58
	Bicarbonate					5	140	93	240	4	376	242	625
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Chickahominy-Piney Point	Sodium	1	36	--	--	31	289	2.4	350	3	890	370	3,100
	Chloride	1	3.9	--	--	37	4.2	0.5	290	3	1,000	160	4,800
	pH	1	7.8	--	--	30	7.6	5.6	8.4	3	8.2	7.3	9.4
	Hardness	1	96	--	--	37	64	12	140	2	18	14	22
	Fluoride	1	0.3	--	--	37	0.5	0.1	3.0	3	1.2	0.7	2.2
	Dissolved iron	0	--	--	--	20	18.5	10	270	2	195	30	360
	Dissolved solids	1	219	--	--	34	204	20	940	3	2,300	1,080	9,120
	Calcium	1	24	--	--	35	20.7	2.0	48	3	4.7	1.1	99
	Bicarbonate	1	--	--	37	37	160	6	426	3	796	640	961
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Aquia	Sodium	1	24	--	--	6	130	19	191	2	340	80	600
	Chloride	1	2.9	--	--	11	38	3.4	375	4	848	7	2,200
	pH	1	7.6	--	--	5	8.2	7.4	8.3	0	--	--	--
	Hardness	1	150	--	--	11	32	16	110	4	49	7.9	240
	Fluoride	1	0.5	--	--	10	1.3	0.4	2.2	4	1.3	0.5	2.4
	Dissolved iron	0	--	--	--	4	28.5	10	70	2	50	10	90
	Dissolved solids	0	270	--	--	8	338	162	553	3	1,530	295	2,372
	Calcium	1	32	--	--	8	9.1	4.2	38	3	18	4.6	20
	Bicarbonate	1	210	--	--	11	330	122	440	4	503	290	724
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Upper Potomac	Sodium	1	7.8	--	--	12	285	19	380	9	420	150	3,000
	Chloride	1	13	--	--	14	180	15	330	11	390	6.9	4,400
	pH	1	6.4	--	--	10	7.8	7.3	8.3	6	7.9	7.0	9.1
	Hardness	1	82	--	--	14	21	13	100	11	22	6.0	450
	Fluoride	1	0.2	--	--	12	1.6	1.0	2.4	10	2.7	0.2	3.7
	Dissolved iron	0	--	--	--	7	50	20	300	5	60	3.0	8,200
	Dissolved solids	1	166	--	--	13	718	162	957	9	1,241	380	7,960
	Calcium	1	24	--	--	13	4.6	3.2	38	11	3.9	1.6	82
	Bicarbonate	1	60	--	--	14	384	122	427	11	414	270	638
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Middle Potomac	Sodium	38	52	11	160	3	220	100	250	2	714	489	940
	Chloride	40	3.0	0.8	127	3	79	6	84	2	895	491	1,300
	pH	34	7.7	6.6	8.6	2	7.7	7.5	7.9	1	7.4	--	--
	Hardness	37	26	1.0	135	3	8	8	54	2	59	22	95
	Fluoride	39	0.3	.01	2.2	3	1.9	1.1	2.1	2	1.7	1.2	2.2
	Dissolved iron	12	21	5.0	1,600	3	200	170	320	1	2,400	--	--
	Dissolved solids	29	199	126	262	3	566	310	664	2	1,982	1,305	2,660
	Calcium	37	8.4	0.0	38	3	3.0	2.5	18	21	12.6	5.2	20
	Bicarbonata	39	175	36	240	3	446	320	450	2	420	400	440
	Constituent	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value	Number of wells	Median value	Minimum value	Maximum value
Lower Potomac	Sodium	2	54	41	66	1	450	--	--	1	1,400	--	--
	Chloride	2	1.6	1.0	2.1	1	340	--	--	1	2,000	--	--
	pH	2	8.0	7.6	8.4	1	7.8	--	--	1	7.7	--	--
	Hardness	2	23	4.0	41	1	18	--	--	1	190	--	--
	Fluoride	2	0.4	0.4	0.4	1	0.3	--	--	1	0.7	--	--
	Dissolved iron	2	175	0.0	350	1	500	--	--	1	1,200	--	--
	Dissolved solids	1	172	--	--	1	1,190	--	--	1	3,860	--	--
	Calcium	2	5.2	1.0	9.3	1	5.1	--	--	1	45.0	--	--
	Bicarbonate	2	190	159	221	1	590	--	--	1	297	--	--

Table 15.--Summary of ground-water quality problems in aquifers of the York-James Peninsula by region

Aquifer	Western region	Central region	Eastern region
Columbia	Aquifer not present	Aquifer used only for domestic supply	Very hard water
Yorktown-Eastover	Aquifer used only for domestic supply	Moderately hard water	Hard water Calcite precipitation
Chickahominy-Piney Point	Moderately hard water Calcite precipitation	Moderately hard water	Elevated sodium Elevated chloride Elevated dissolved solids Calcite precipitation
Aquia	Hard water	Calcite precipitation	Elevated sodium Elevated chloride Elevated dissolved solids Calcite precipitation
Upper Potomac	Aquifer not present	Elevated dissolved solids Elevated fluoride	Elevated sodium Elevated chloride Elevated dissolved solids Elevated fluoride
Middle Potomac	No apparent problems	Elevated fluoride Elevated dissolved solids	Elevated sodium Elevated chloride Elevated dissolved solids Elevated fluoride Elevated dissolved iron
Lower Potomac	No apparent problems	Elevated sodium Elevated chloride Elevated dissolved solids Elevated dissolved iron	Elevated sodium Very hard water Elevated chloride Elevated dissolved solids Elevated dissolved iron

water in these aquifers commonly is hard to very hard. In the central region, all aquifers, except the lower Potomac, contain water that is generally usable as a potable supply; however, local quality problems do exist. Common local problems are high fluoride and dissolved solids in the middle Potomac and upper Potomac aquifers, and hard water in the Chickahominy-Piney Point and Yorktown-Eastover aquifers. In the western region, the lower Potomac and middle Potomac aquifers contain what is considered the best-quality water in the study area. Water in the Chickahominy-Piney Point and Aquia aquifers is moderately hard to hard.

Limit lines in figures 31-36 identify regions within each aquifer where recommended limits of selected water-quality constituents are exceeded. Limit lines were constructed from the data statistically summarized in tables 5-11. Dissolved iron is a problem in many local areas but cannot be regionalized within the aquifers. In some figures, point data exceeding recommended limits are identified where limit lines could not be determined because of insufficient data. The Yorktown-Eastover aquifer (fig. 31) contains high concentrations of chloride and sodium in eastern areas fringing the Chesapeake Bay, and high concentrations of hardness in the eastern half of the peninsula. The Chickahominy-Piney Point aquifer (fig. 32) contains elevated concentrations of chloride, sodium, dissolved solids, and fluoride in the eastern region, and hardness is a problem in parts of the western and central regions. The Aquia aquifer (fig. 33) contains high concentrations of chloride, sodium, dissolved solids, and fluoride in the eastern region, and hardness is a problem in the western region. The upper Potomac aquifer (fig. 34) contains high concentrations of chloride, sodium, and dissolved solids in the eastern region. Fluoride is present in elevated concentrations in the central and eastern regions, and hardness is a problem only in the extreme eastern region

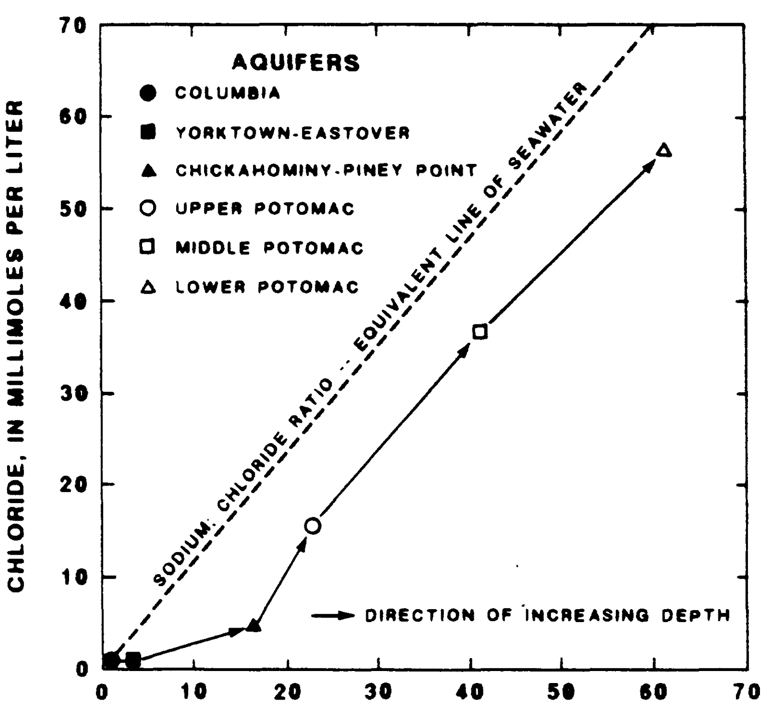


Figure 30. Relative chloride ion as a function of sodium ions for aquifers at city of Newport News Research Station RS-2.

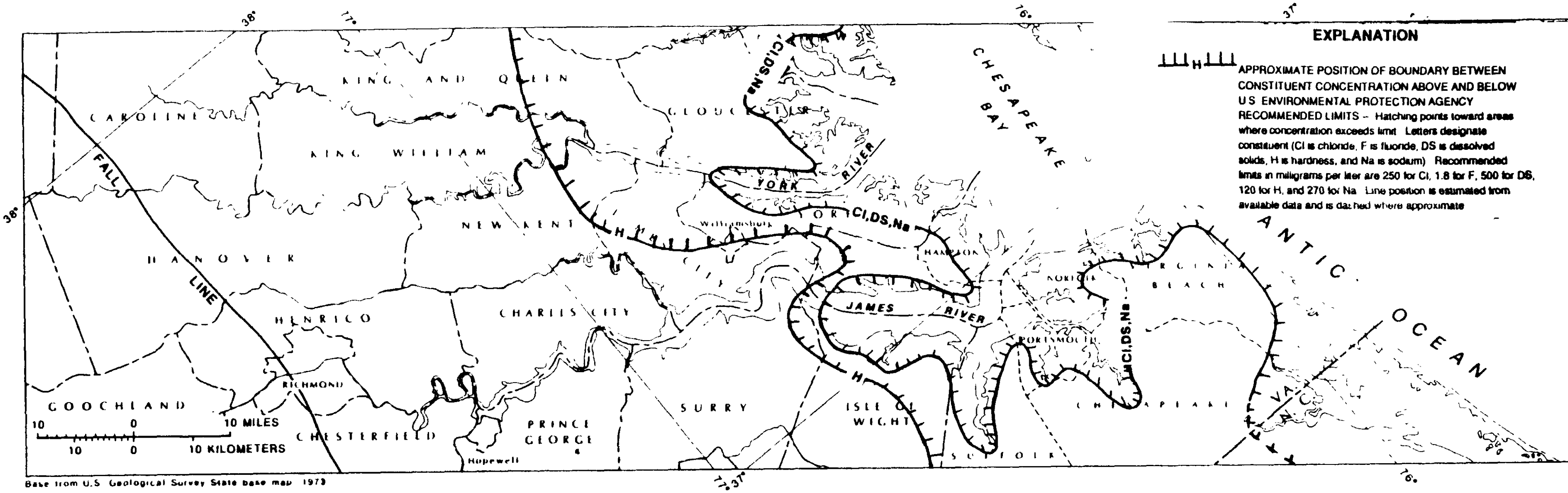


Figure 31. Areas exceeding recommended limits of selected dissolved constituents in Yorktown-Eastover aquifer.

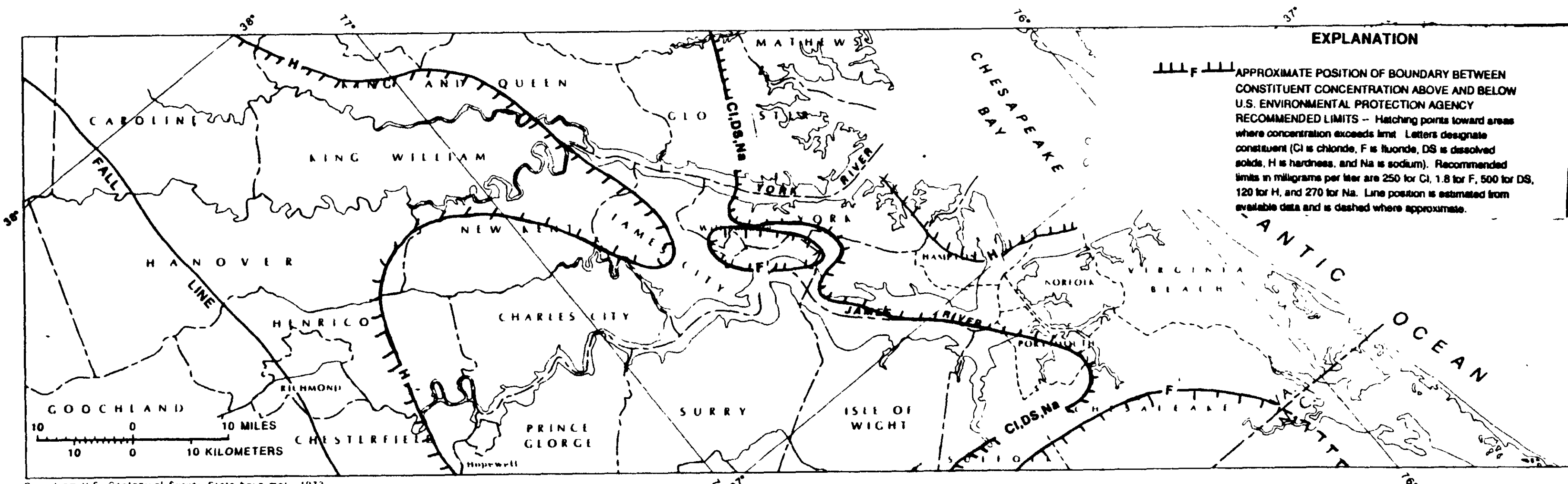


Figure 32. Areas exceeding recommended limits of selected dissolved constituents in Chickahominy-Piney Point aquifer.

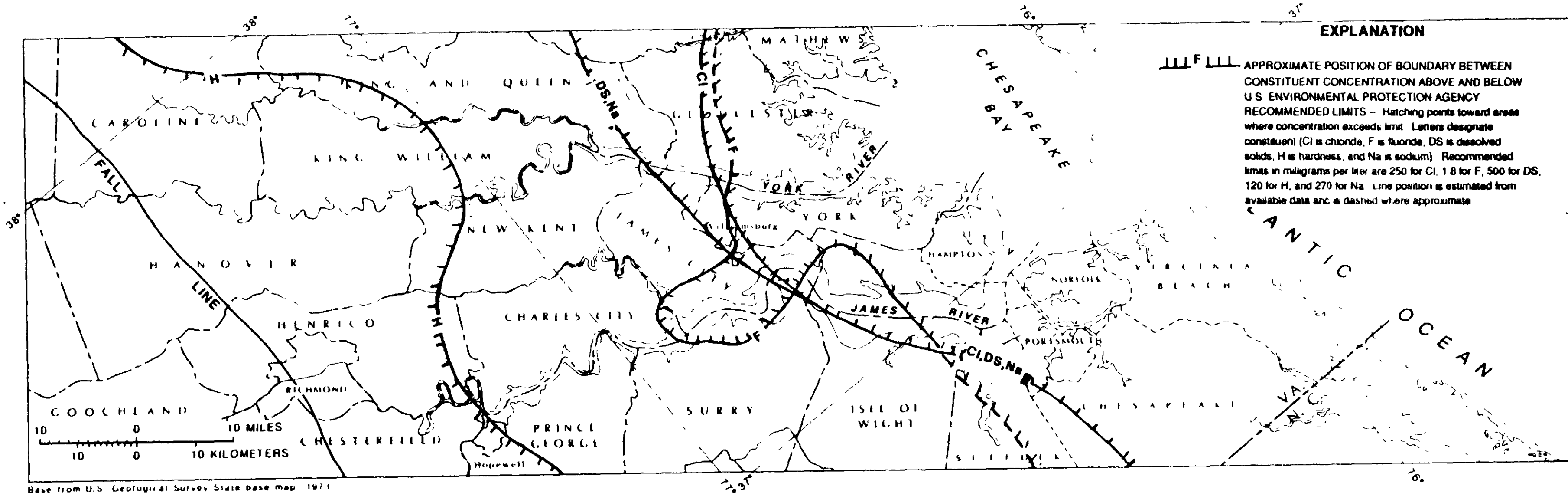


Figure 33. Areas exceeding recommended limits of selected dissolved constituents in Aquia aquifer.

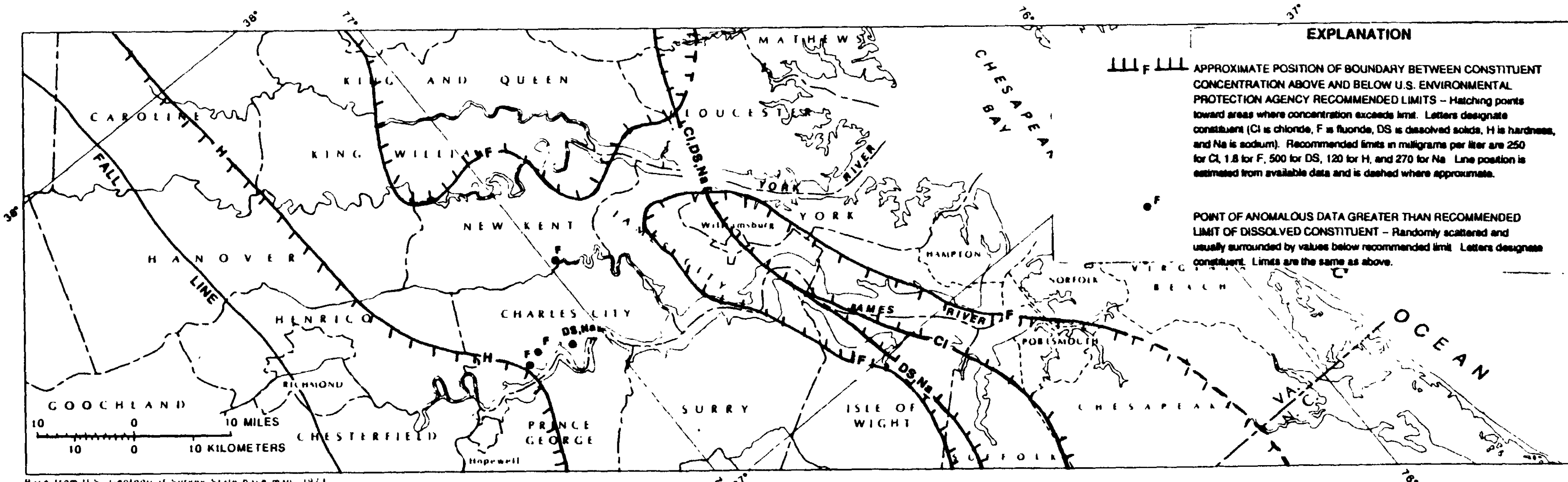


Figure 34. Areas exceeding recommended limits of selected dissolved constituents in upper Potomac aquifer.

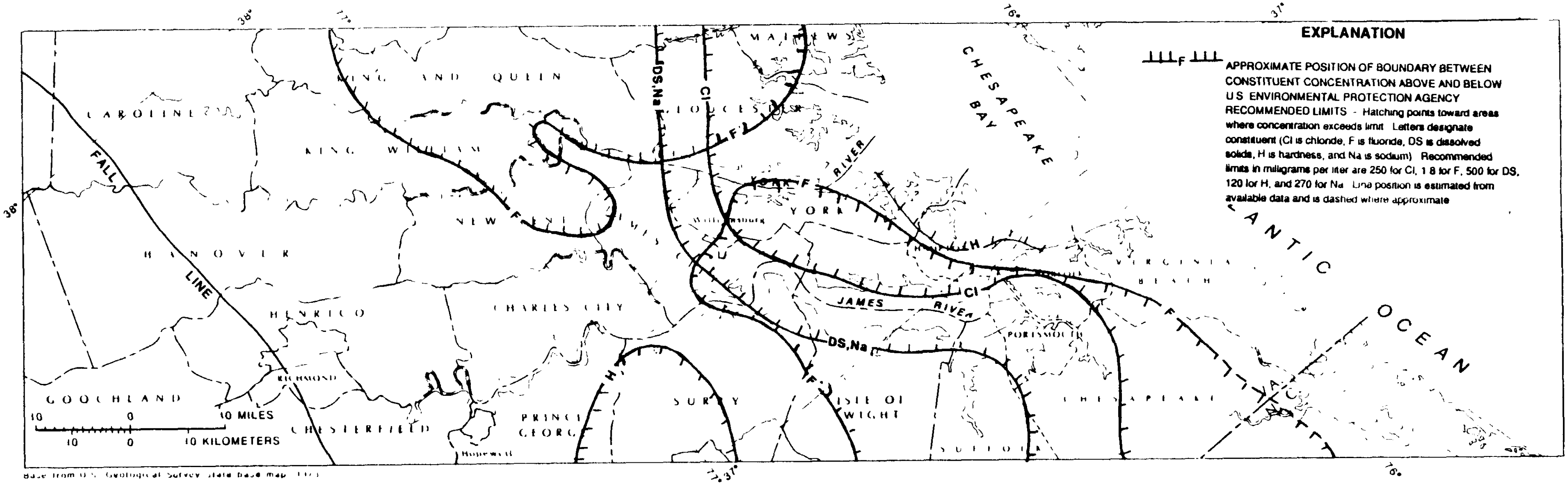


Figure 35. Areas exceeding recommended limits of selected dissolved constituents in middle Potomac aquifer.

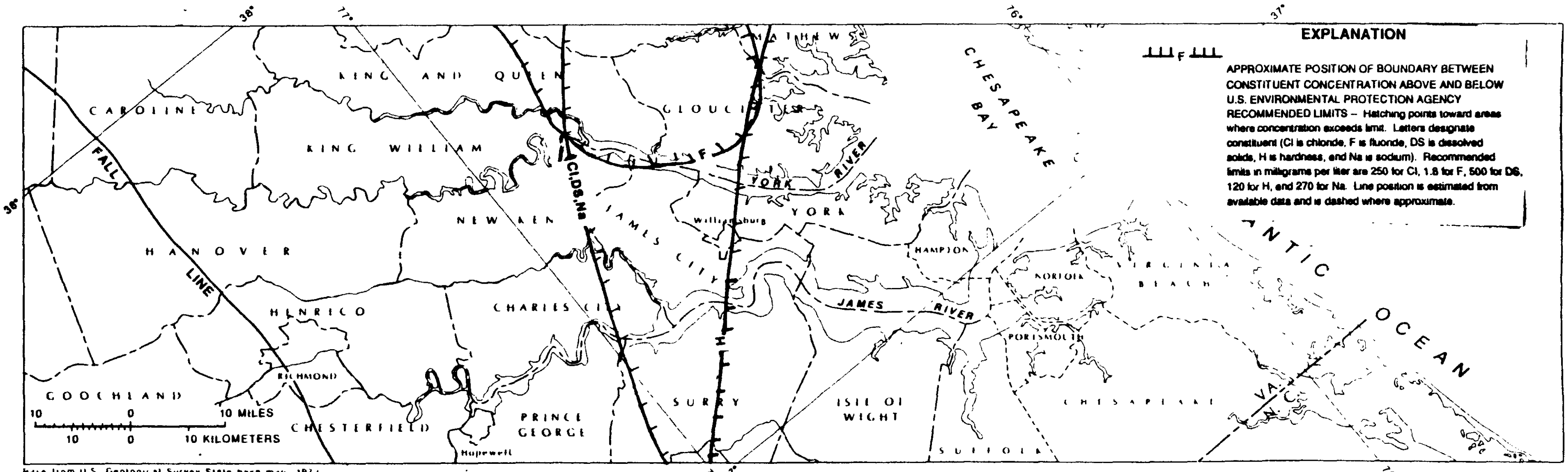


Figure 36. Areas exceeding recommended limits of selected dissolved constituents in lower Potomac aquifer.

where the water is highly mineralized. The middle Potomac aquifer (fig. 35) contains elevated concentrations of chloride, sodium, and dissolved solids in the eastern region, and hardness is a problem in the western region. Numerous local areas within this aquifer contain water with elevated concentrations of fluoride and dissolved solids. The lower Potomac aquifer (fig. 36) contains water with high concentrations of chloride, sodium, and dissolved solids in the eastern and central regions, and hardness is a problem in the eastern region. Overall, the ground-water quality throughout the study area is best in the western and central regions. For the most part, water in the eastern region is salty and only the upper two aquifers, the Columbia and the Yorktown-Eastover, contain potable water.

Hydraulic Characteristics

The ability of a ground-water flow system to store and transmit water is determined by the hydraulic characteristics of the aquifers and confining units. Hydraulic characteristics affect the water-yielding capacity of wells, the magnitude of water-level decline associated with pumpage, and the volume and velocity of water flowing through an aquifer. Transmissivity is the principal hydraulic characteristic that measures the ability of water to flow through an aquifer. Vertical leakance is the principal hydraulic characteristic that measures the ability of water to flow through a confining unit. Transmissivity and vertical leakance depend on the physical properties of the sediment through which water moves. Transmissivity is the product of the horizontal (bed-parallel) hydraulic conductivity and the saturated thickness of the aquifer. Vertical leakance is the quotient of the vertical (bed-normal) hydraulic conductivity and the thickness of the confining unit. Hydraulic conductivity is the volume of water that will flow, in a unit time, under a unit hydraulic gradient, through a unit area of sediment. Hydraulic gradient is the change in static water level (hydraulic head) per unit distance in a given direction.

Storage coefficient is the principal hydraulic characteristic that measures the ability of an aquifer to store or release water. Storage coefficient is the product of the specific storage and the saturated thickness of the aquifer. Specific storage is the volume of water released from or taken into storage per unit volume of aquifer per unit change in hydraulic head. The following sections describe the methods used to determine the hydraulic characteristics of aquifers and confining units for the development of a digital flow model used in the assessment of ground-water flow. It should be noted that much of the data analyzed to estimate hydraulic characteristics were obtained from drillers' records. Because the method of data collection and data analysis and the completeness of record varied from one driller to another, the quality of the data is considered to vary as well.

Aquifer Tests

Analysis of aquifer-test data gives quantitative values for aquifer transmissivity and storage. An aquifer test involves analyzing the change in water level with time caused by imposing a stress upon an aquifer. A common method of imposing stress is to pump water from a well and measure the decline in water level that results in the pumping well and (or) other nearby observation wells. After pumping water from the aquifer for a specified time, preferably more than 24 hours, the pump is turned off, and the rise in water level is measured as hydraulic head in the aquifer returns to its prepumped level.

Two general types of methods for analyzing aquifer-test data from confined aquifers are used. One type assumes that all water pumped from a confined aquifer is obtained from within the aquifer and is known as "non-leaky methods." The second type assumes that water recharges the confined aquifer through an overlying and (or) underlying confining unit(s) and is known as "leaky methods." A transmissivity computed by a leaky method is lower than one computed by a non-leaky method.

Few aquifer tests are available that actually reflect the change in water level within an individual aquifer because most of the wells which have been tested are open to more than one aquifer. Aquifer transmissivity and storage coefficients computed with aquifer-test data from an individual aquifer are summarized by method in table 16. Leaky-method transmissivities are believed to more closely approximate actual values. From these data, the ability to describe spatial differences in the distribution of hydraulic characteristics within an aquifer is limited; therefore, the following method supplements aquifer-test results.

Specific-Capacity Tests

Specific capacity is most commonly used to determine the ability of a well to yield water, but also can be used to estimate transmissivity if the value of specific capacity becomes constant over time. The specific capacity of a well is the quotient of the rate of discharge of water from a well and the change in water level within the well that results from the pumpage. Transmissivities were calculated from specific capacities compiled for the model area by an iterative procedure which uses the following equation given by Walton (1970):

$$[Q/s = T/(264 \log ((Tt)/2{,}693\ r^2S)) - 65.5)] \qquad (1)$$

where

Q is well discharge in gallons per minute;
s is the change in water level within the well in feet;
T is transmissivity of the aquifer in gallons per day per foot;
t is length of pumping in days;
r is the radius of the pumping well in feet;

and

S is specific yield if the aquifer is unconfined and storage coefficient if the aquifer is confined.

The procedure required an initial estimate of T which is calculated with the following equation given by Theis (1963) and Brown (1963):

$$T = Q/s\ [K-264 \log (5S) + 264 \log (t)] \qquad (2)$$

where

K is a factor equal to:

$-66 - 264 \log (3.74r^2 \times 10^{-6})$ if the aquifer is unconfined

Table 16.--Summary of aquifer-test results in model area

[ft^2/d is feet squared per day, Number is number of wells, -- indicates no values reported]

Aquifer		Leaky aquifers		Non-leaky aquifers			
		Type curve[1]		Type curve[2]		Straight line[3]	
		Transmissivity (ft^2/d)	Storage coefficient (dimensionless)	Transmissivity (ft^2/d)	Storage coefficient (dimensionless)	Transmissivity (ft^2/d)	Storage coefficient (dimensionless)
Yorktown-Eastover	Maximum	5,750	6.3×10^{-3}	8,820	--	8,820	1.3×10^{-2}
	Minimum	330	1.4×10^{-4}	210	--	30	1.0×10^{-4}
	Median	3,070	1.1×10^{-3}	2,470	--	950	2.5×10^{-4}
	Mean	3,020	1.7×10^{-3}	2,750	1.1×10^{-4}	1,900	2.6×10^{-3}
	Number	6	6	4	1	32	10
Chicka-hominy-Piney Point	Maximum	--	--	11,300	--	16,100	3.1×10^{-2}
	Minimum	--	--	3,710	--	130	1.0×10^{-4}
	Median	--	--	5,530	--	4,790	--
	Mean	--	--	6,960	--	6,740	--
	Number			7		3	2
Aquia	Maximum	--	--	--	--	8,010	--
	Minimum	--	--	--	--	2,780	--
	Median	--	--	--	--	--	--
	Mean	--	--	8,680	--	--	--
	Number			1		2	
Upper Potomac	Maximum	--	--	10,200	2.6×10^{-4}	15,000	--
	Minimum	--	--	4,410	1.0×10^{-7}	2,360	--
	Median	--	--	8,500	--	6,230	--
	Mean	--	--	7,870	--	8,070	--
	Number			5	2	8	
Middle Potomac	Maximum	8,750	2.4×10^{-4}	17,700	--	17,700	4.6×10^{-5}
	Minimum	1,850	4.1×10^{-5}	1,360	--	660	3.9×10^{-5}
	Median	--	--	4,920	--	2,240	--
	Mean	--	--	7,240	--	4,930	--
	Number	2	2	4		6	2
Lower Potomac	Maximum	--	--	--	--	3,540	2.2×10^{-4}
	Minimum	--	--	--	--	1,370	2.0×10^{-4}
	Median	--	--	--	--	3,100	--
	Mean	2,630	3.5×10^{-4}	3,260	1.5×10^{-4}	2,670	--
	Number	1	1	1	1	3	2

Hauntush, 1960[1]
Theis, 1935[2]
Cooper-Jacob, 1946[3]

and

$-66 - 264 \log (3.74r^2 \times 10^{-9})$ if the aquifer in confined.

The value of S is assumed equal to 0.20 for unconfined aquifers and $1x10^{-4}$ for confined aquifers. Before substitution into equation 2, S is multiplied by 1,000 for confined aquifers. Specific capacity, Q/s, is calculated by substituting the initial estimate of transmissivity into equation 1. The calculated specific capacity is then compared to the measured value. If the difference is less than $1X10^{-5}$ percent, the calculated transmissivity is assumed reasonable and the procedure is halted. If the difference is greater than $1 X 10^{-5}$ percent, the transmissivity is adjusted by the equation:

$$T = T + (T \times P) \tag{3}$$

where

P is percent difference between calculated and measured values of Q/s.

The adjusted transmissivity is substituted into equation 1 and specific capacity is recalculated. The difference between the calculated and measured specific capacity again is compared and the procedure is either repeated or halted accordingly. The horizontal hydraulic conductivity was computed from the transmissivity by the equation:

$$K_h = T/m \tag{4}$$

where

K_h is the horizontal hydraulic conductivity of the aquifer in feet per day;

and

m is the saturated thickness of the aquifer in feet.

A summary of well yields, specific capacities, transmissivities, and hydraulic conductivities derived from specific-capacity tests is given by aquifer in table 17. The table also lists specific capacities that are adjusted for partial penetration by the following equation (Turcan, 1963):

$$Q_a/s = Q/s[K_p(1+7 \ /r/(2K_pm)\cos((K_p\pi)/2))] \tag{5}$$

where

Qa/s is the adjusted specific capacity in gallons per minute per foot of water-level decline;

and

K_p is the ratio of screen length to saturated aquifer thickness.

Table 17.--Summary statistics of well yield, specific capacity, transmissivity, and hydraulic conductivity derived from specific capacity tests in the model area

[gal/min is gallons per minute, gal/min/ft is gallons per minute per foot, ft^2/d is feet squared per day, ft/d is feet per day, Number is number of wells]

Aquifer		Well yield (gal/min)	Specific capacity (gal/min/ft)		Transmissivity (ft^2/d)		Hydraulic conductivity (ft/d)	
			Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
Columbia	Maximum	50	16.7	35.5	3,790	8,500	92.7	170
	Minimum	3	.2	1.7	104	328	1.7	6.4
	Median	30	1.2	5.0	223	872	6.2	24.0
	Mean	29.6	3.5	8.5	844	1,810	28.1	50.8
	Number	10	10	8	8	8	8	8
Yorktown-Eastover	Maximum	450	31.6	123	10,100	44,200	156	353
	Minimum	4	.1	.2	23	40	.3	.7
	Median	50	1.9	11.9	567	3,840	4.7	25.1
	Mean	82.3	4.4	20.5	1,470	6,900	13.0	54.8
	Number	63	65	59	60	59	59	59
Chickahominy-Piney Point	Maximum	316	48	63.2	16,600	22,100	331	442
	Minimum	5	.2	.2	54	67	1.2	1.5
	Median	82.5	2.7	8.9	990	2,740	24.3	52.7
	Mean	109.4	7.7	12.6	2,700	4,230	60.4	87.3
	Number	38	40	35	37	35	35	35
Aquia	Maximum	550	21.6	23.4	6,980	8,100	189	219
	Minimum	12	.2	.2	46	40	1.2	1.8
	Median	186	3.8	5.5	1,130	1,670	36.2	55.2
	Mean	210	5.5	7.3	1,670	2,270	51.3	66.8
	Number	18	18	18	18	18	18	18
Upper Potomac	Maximum	1,450	83.3	68	24,300	24,700	385.5	344
	Minimum	20	.6	.7	170	194	2.8	4.0
	Median	245	6.9	12.0	2,300	3,740	36.0	59.2
	Mean	391	11.2	16.9	3,650	5,490	58.8	82.5
	Number	102	102	99	100	99	99	99
Middle Potomac	Maximum	1,083	19.4	111	6,660	41,900	34.7	262
	Minimum	3.0	.1	.2	20	60	.2	.7
	Median	62.0	1.6	3.4	450	1,010	4.7	10.9
	Mean	160	3.0	10.9	870	3,750	7.2	23.4
	Number	64	74	73	71	70	70	70
Lower Potomac	Maximum	2,000	11.5	11.6	3,550	3,560	50.7	50.7
	Minimum	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	6	7	6	6	6	6	6

The table indicates that the highest yielding wells are in the Potomac aquifers. Transmissivities computed from specific-capacity tests compare reasonably well with values computed from aquifer tests in areas where both types of data are available, suggesting that specific capacities may be appropriate for estimating regional transmissivities in areas lacking aquifer-test data.

Laboratory Analysis of Core Samples

While the previous methods discussed provide measurements of hydraulic characteristics averaged over large areas of aquifers or confining units, core analyses provide values specific to a site and sediment sample. Sediment cores were analyzed to provide estimates of the vertical hydraulic conductivity and mineralogy of confining units and clay layers within aquifers. Core samples were collected during the drilling of the two research stations and were analyzed by the U.S. Army Corps of Engineers Hydraulic Laboratory in Cincinnati, Ohio. The samples analyzed consisted of undisturbed sediment cores that averaged two-and-one-half inches in diameter by one foot in length. Cores were collected in order to compare vertical hydraulic conductivity in confining-unit sediments of fluvial origin to sediments of marine origin and to identify clay types. Core analyses also provided data to substantiate vertical hydraulic conductivity values for confining units used in the model developed by Harsh and Laczniak (1986). Sample depth, hydrogeologic unit, laboratory vertical hydraulic conductivity, and basic mineralogy of the core sediment are shown in table 18 for each research station. Results of laboratory hydraulic conductivity compare favorably with values used for model simulation by Harsh and Laczniak (1986). Confining unit sediments of fluvial origin appear to be tighter (less permeable) than those of marine origin, however, the lower fluvial confining units also might be tighter because of greater over-burden pressures.

Table 18.--Core analyses from ground-water research stations located in the York-James Peninsula

[ft/d is feet per day]

James City County Research Station -- RS-1

Hydrogeologic units	Sample depth (in feet, datum is sea level) top	Sample depth (in feet, datum is sea level) bottom	Laboratory vertical hydraulic conductivity (ft/d)	Percent sand	Percent clay	Clay-type groups (in decreasing order)
Calvert confining unit	-141.1	-142.9	5.39×10^{-4}	40	60	Smectite, illite/glauconite, kaolinite (trace)
Middle Potomac confining unit	-336.5	-338.0	2.01×10^{-5}	25	75	Smectite, iron-rich chlorite, illite/glauconite

Newport News Research Station -- RS-2

Hydrogeologic units	Sample depth (in feet, datum is sea level) top	Sample depth (in feet, datum is sea level) bottom	Laboratory vertical hydraulic conductivity (ft/d)	Percent sand	Percent clay	Clay-type groups (in decreasing order)
Calvert confining unit	-260.5	-262.7	5.88×10^{-4}	1	99	Smectite, iron-rich illite, kaolinite
Nanjemoy-Marlboro confining unit	-306.1	-307.4	2.56×10^{-5}	6	94	Smectite, iron-rich illite, kaolinite
Nanjemoy-Marlboro confining unit	314.0	315.0	1.26×10^{-5}	16	84	Smectite, iron-rich illite, kaolinite
Clay in middle Potomac aquifer	-637.0	638.7	7.6×10^{-5}	16	84	Smectite, iron-rich illite, iron-rich chlorite
Clay in lower Potomac aqufier	-705.3	-706.5	8.1×10^{-5}	11	89	Smectite, iron-rich illite, kaolinite

SIMULATION OF GROUND-WATER FLOW

The ground-water resources of the York-James Peninsula were assessed with the aid of a digital, ground-water flow model. The model was calibrated to water levels measured prior to and throughout the history of ground-water pumpage. Once calibrated, the model simulated changes in ground-water flow conditions that resulted from projected scenarios of increased withdrawal. Model results were used to assess the availability of ground water as a continued source of supply for meeting the future water needs of the peninsula.

Description of Conceptual and Digital Flow Models

The digital flow model developed for this study applies the computer program written by McDonald and Harbaugh (1984) to simulate ground-water flow. This program uses the finite-difference method to solve the three-dimensional, second-order, partial-differential equation that describes the flow of ground water through a porous media. The conceptualization of the Coastal Plain multiaquifer system discussed in detail by Harsh and Laczniak (1986) is idealized as a layered sequence of aquifers separated by confining units (fig. 37). This conceptualization allows for the quasi-three-dimensional solution of the ground-water-flow equation if (1) it can be assumed that most lateral flow occurs within the aquifers, (2) vertical flow is controlled by confining units, and (3) water released from confining-unit storage is negligible. These assumptions are considered valid because the lateral hydraulic conductivities of aquifers are much greater than those of confining units, the vertical hydraulic conductivities of confining units are sufficiently lower than those of aquifers, and simulation times are long enough to minimize effects of water released by confining unit storage. In the quasi-three-dimensional approach, aquifers are connected by a resistance-to-flow term (vertical leakance) that simulates the impeding nature of intervening confining units.

Grid and Boundaries

Aquifers and confining units were divided into rectangular grids of 105 by 39 blocks (fig. 38). Grid blocks were assigned values that represent the average hydraulic characteristics and hydrologic stresses of respective aquifers and confining units. Thus, each grid describes the lateral variations of hydraulic characteristics within each hydrogeologic unit and also defines the limits of each aquifer and confining unit. Block dimensions vary from a minimum of 1.36 to a maximum of 4.08 square miles. The finer-grid spacing in the western two-thirds of the study area simulates more detail. Grid orientation and model conceptualization are consistent with the regional digital flow model of the Virginia Coastal Plain (Harsh and Laczniak, 1986).

Boundaries of the digital flow model were chosen to best approximate ground-water flow conditions in the study area. The northeastern and southwestern model limits extend beyond the York-James Peninsula to include nearby ground-water users that strongly influence the flow of ground water within the study area. These model boundaries are approximated by fluxes that simulate lateral flow into and out of the model area where aquifers continue beyond the model limits. This type of boundary reduces the overall grid size by eliminating the need to simulate parts of aquifers outside the area of interest.

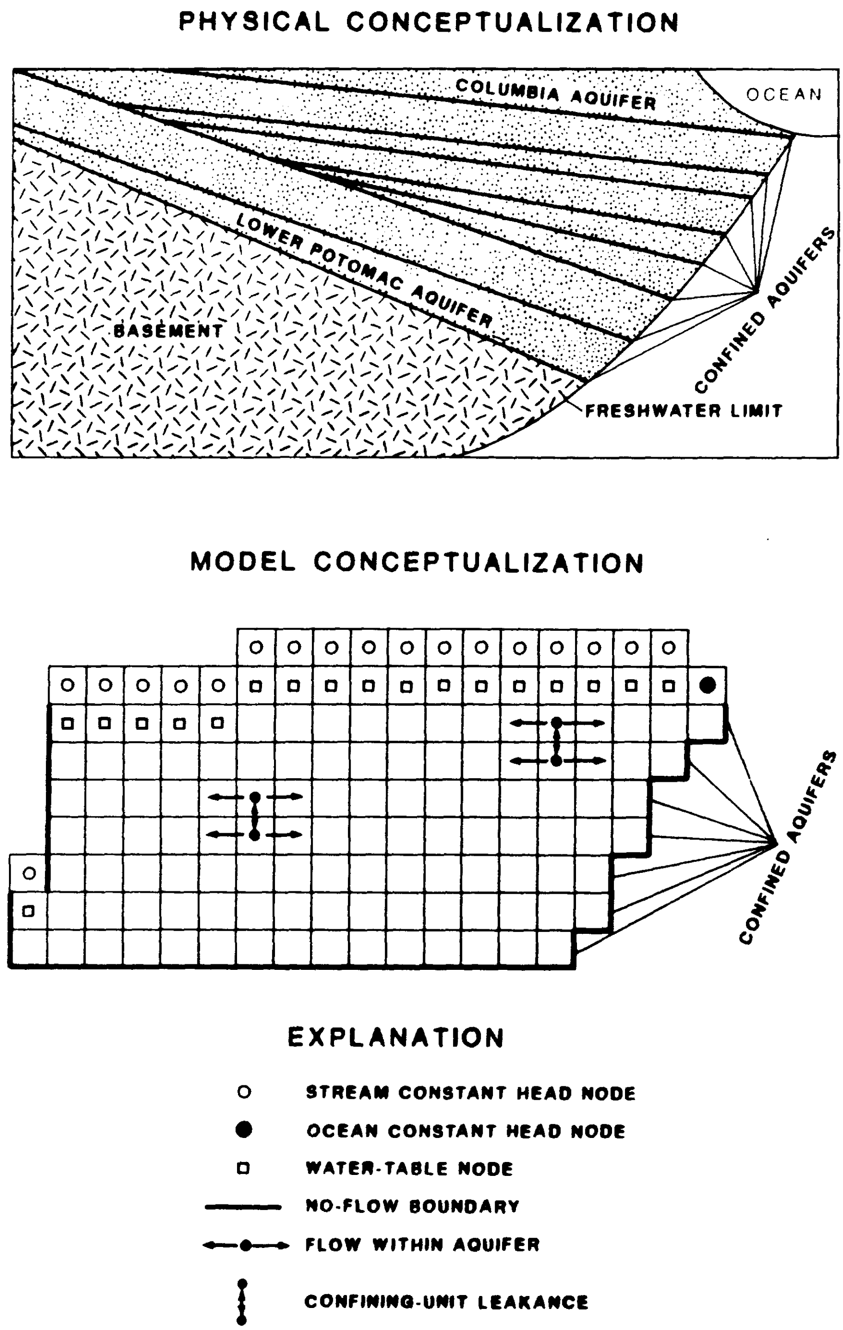


Figure 37. Physical and model conceptualization of ground-water flow system.

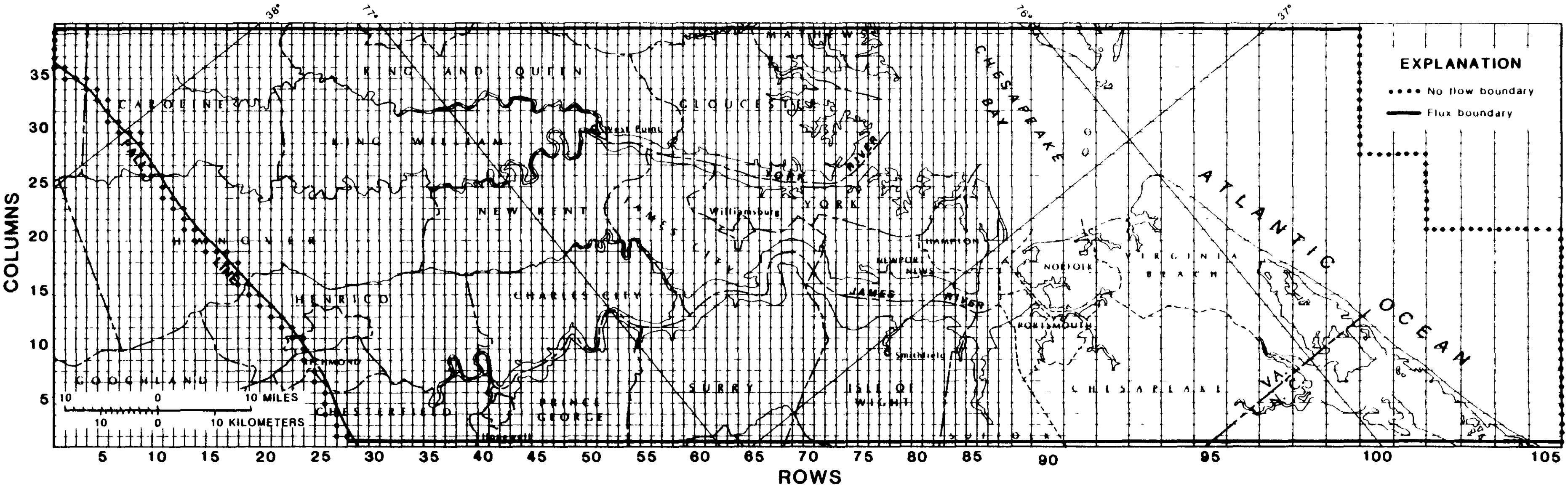


Figure 38. Two-dimensional grid and model boundaries.

The western and lower limits of the model are simulated as no-flow boundaries. The western limit approximates the contact between the metamorphic and igneous rocks of the Piedmont physiographic province and the unconsolidated sediment of the Coastal Plain physiographic province. The lower limit approximates the contact between aquifer sediment and the underlying basement rock. A no-flow condition along this boundary is supported by the large permeability contrast between these respective rock types.

The seaward limit of freshwater in each aquifer is the eastern limit of the model. This limit is defined as the 10,000-mg/L chloride concentration (Meisler, 1986). Flow across this boundary is assumed negligible because of the density differences between fresh and salty water. Thus, this limit is simulated by a no-flow boundary. The stable position of this boundary throughout the history of ground-water development has been documented by Larson (1981).

The upper limit is simulated as a constant-head (water-level) boundary and approximates the recharge-discharge relation between surface water and the water-table (unconfined) aquifer. Grid-block values were estimated from U.S. Geological Survey topographic maps (quadrangles covering 7 1/2-minutes of latitude and longitude, published at a scale of 1:24,000 or 1 inch = 2,000 feet) and approximate the average stage of surface water within a grid block. This boundary is assumed constant in time because of the relative consistency in the stage of surface water over the period of simulation.

Aquifer and Confining-Unit Characteristics

Hydraulic characteristics were determined for each grid block. Transmissivities and storage coefficients were estimated for aquifers and vertical leakances were estimated for confining units. Data quantifying these characteristics in each block were not always available; therefore, grid-block values were calculated from the physical and hydrologic properties that define these hydraulic characteristics. Calculated values were refined and verified from values determined by field and laboratory methods. Values are stored on computer files at the Virginia Office of the U.S. Geological Survey in Richmond, Virginia.

Transmissivity

Transmissivity for each grid block was calculated by multiplying the average hydraulic conductivity by the average thickness of the aquifer within the grid block. Average aquifer thickness values were determined from top of aquifer maps (fig. 5-10), confining unit thickness maps (fig. 11-17), and a map delineating the structure top of the underlying basement surface (Meng and Harsh, 1984). Average hydraulic conductivities were estimated from specific-capacity and aquifer-test data, laboratory analyses of core samples, and grain-size analyses of aquifer sediment.

Maps of aquifer transmissivity are shown in figures 39-46. Transmissivity generally increases eastward from the western (updip) limit of the aquifer and then decreases near the eastern (freshwater) limit. Increases reflect a thickening of aquifer sediment. Decreases reflect a thinning of aquifer sediment because of increased clay content, a decrease in freshwater-saturated thickness of the aquifer, and (or) a decrease in the hydraulic conductivity of

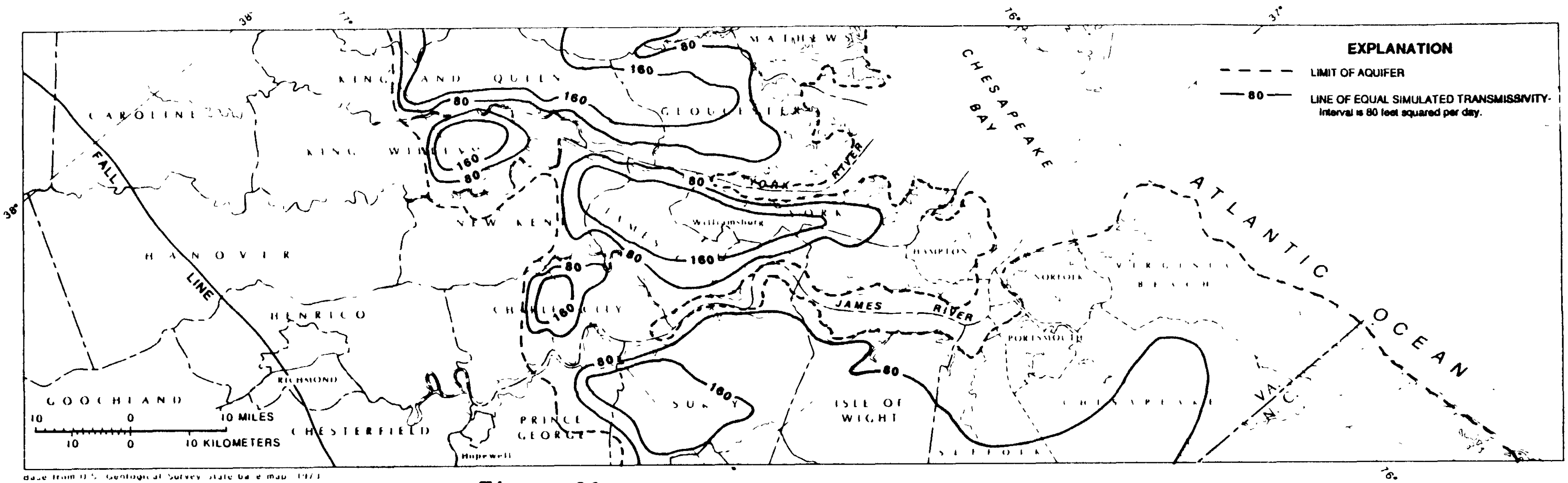


Figure 39. Transmissivity of Columbia aquifer.

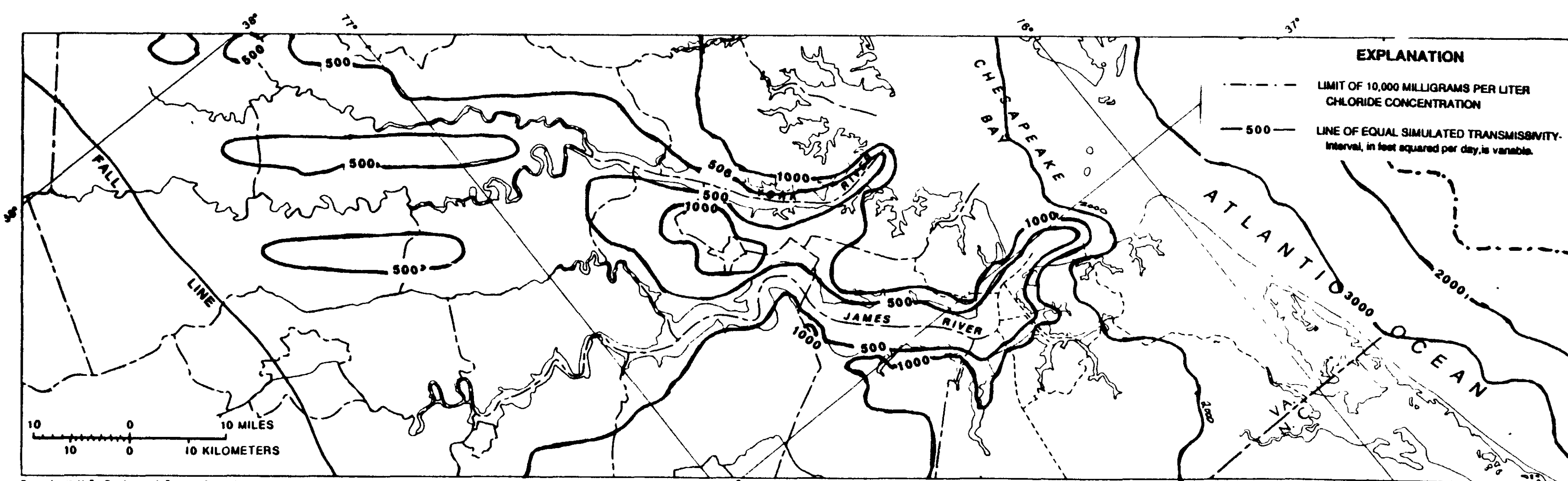


Figure 40. Transmissivity of Yorktown-Eastover aquifer.

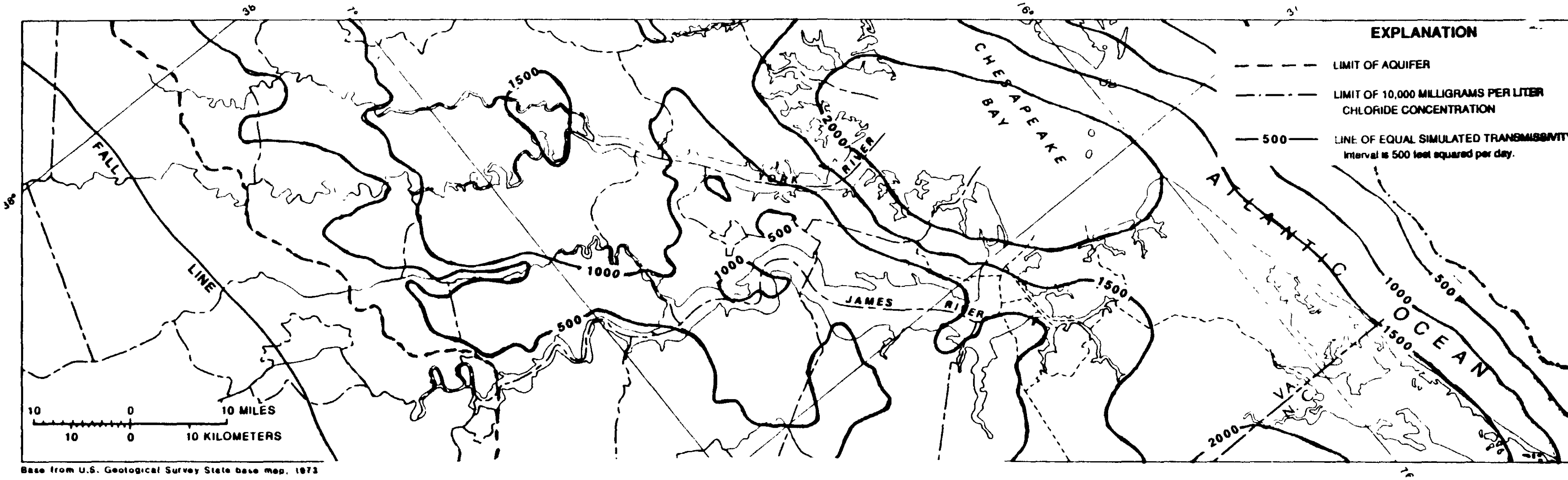


Figure 41. Transmissivity of Chickahominy-Piney Point aquifer.

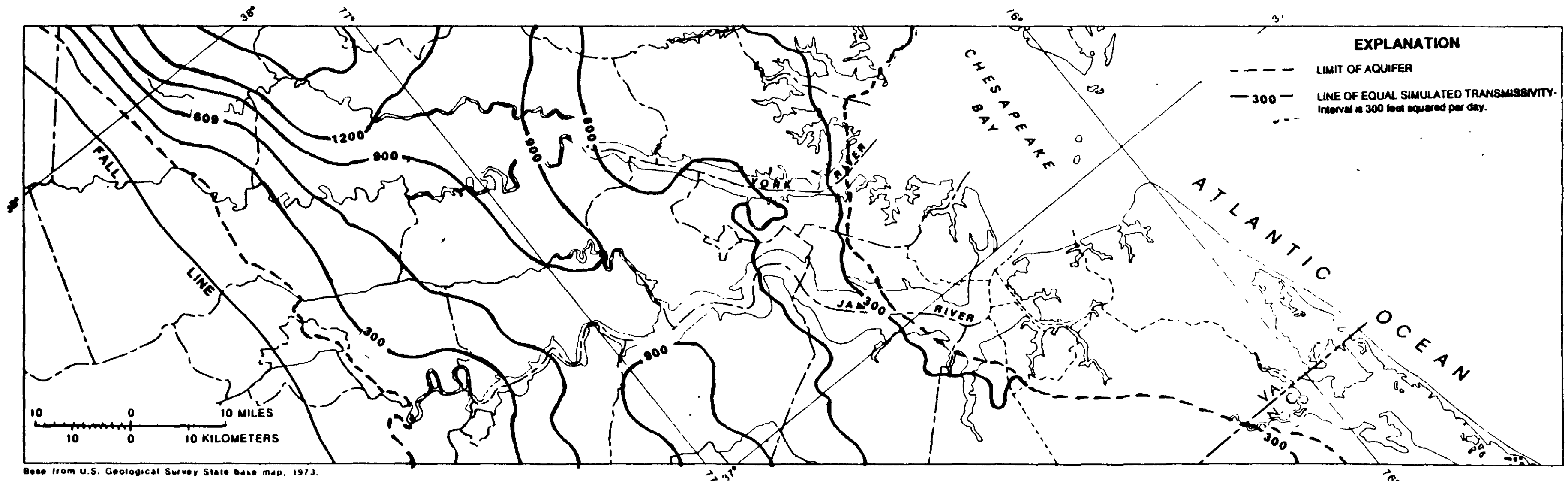


Figure 42. Transmissivity of Aquia aquifer.

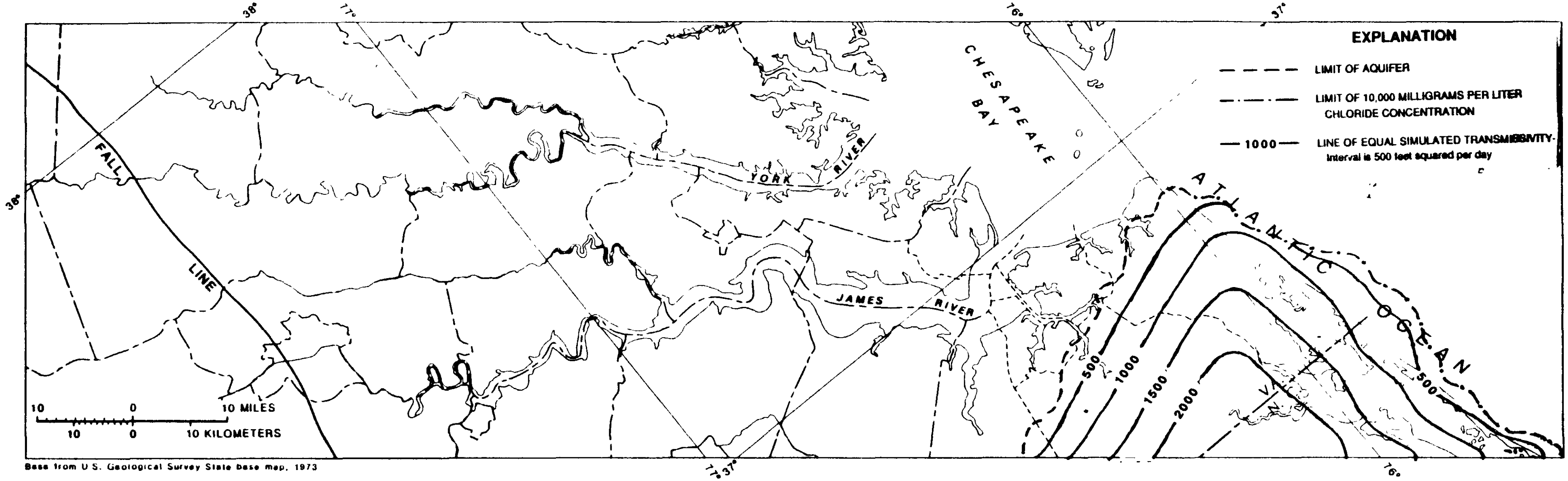


Figure 43. Transmissivity of Virginia Beach aquifer.

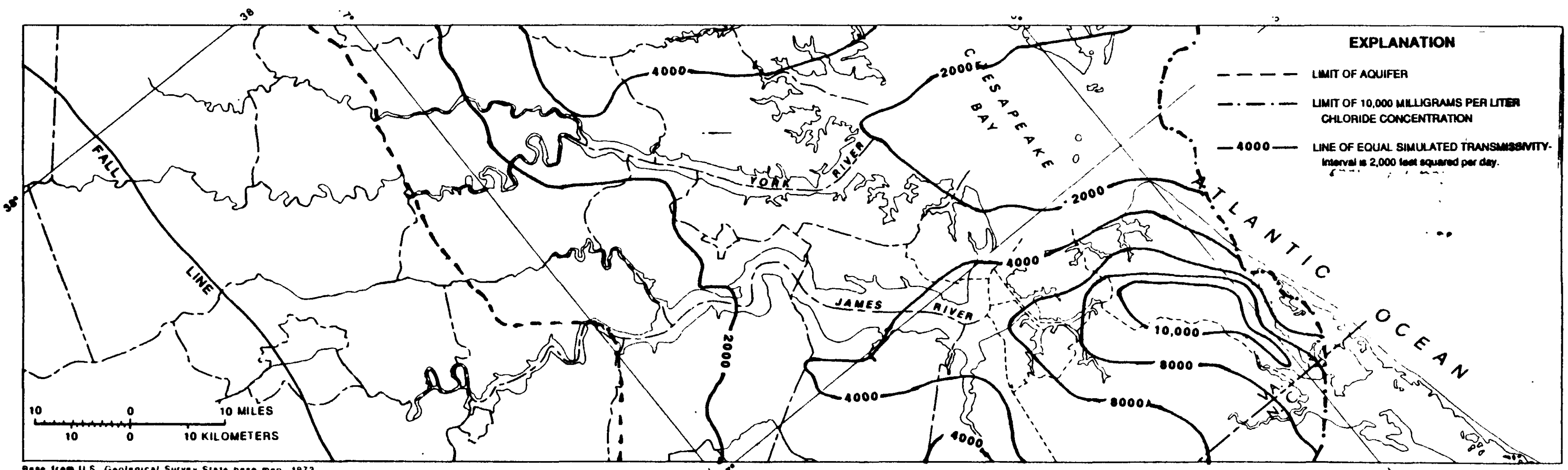


Figure 44. Transmissivity of upper Potomac aquifer.

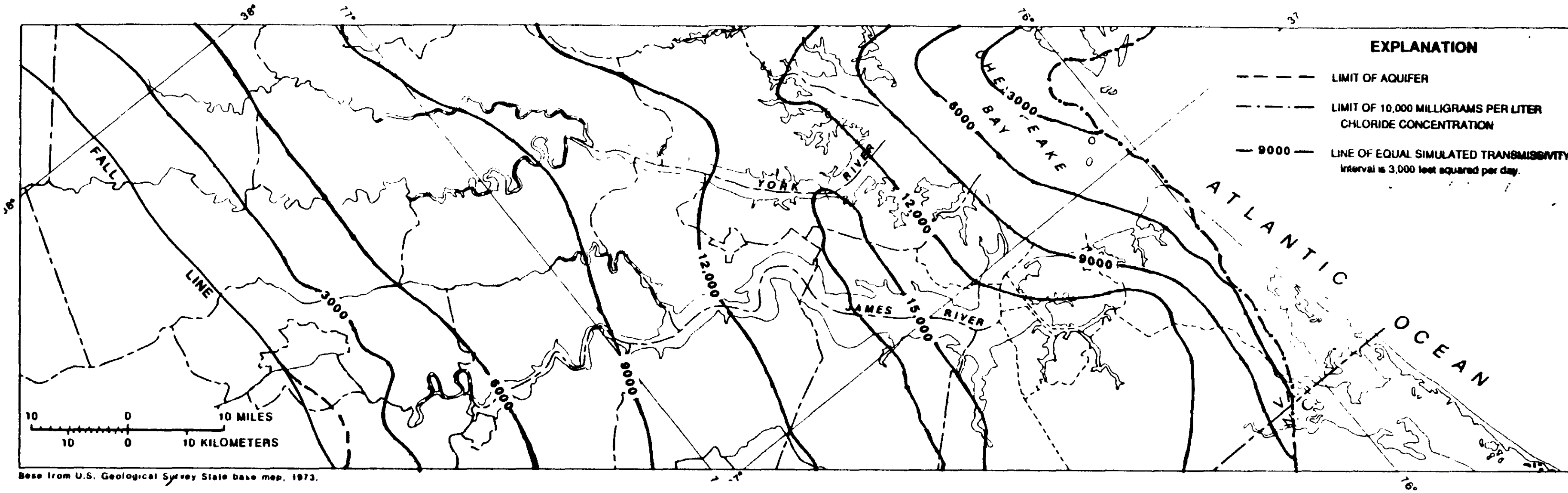


Figure 45. Transmissivity of middle Potomac aquifer.

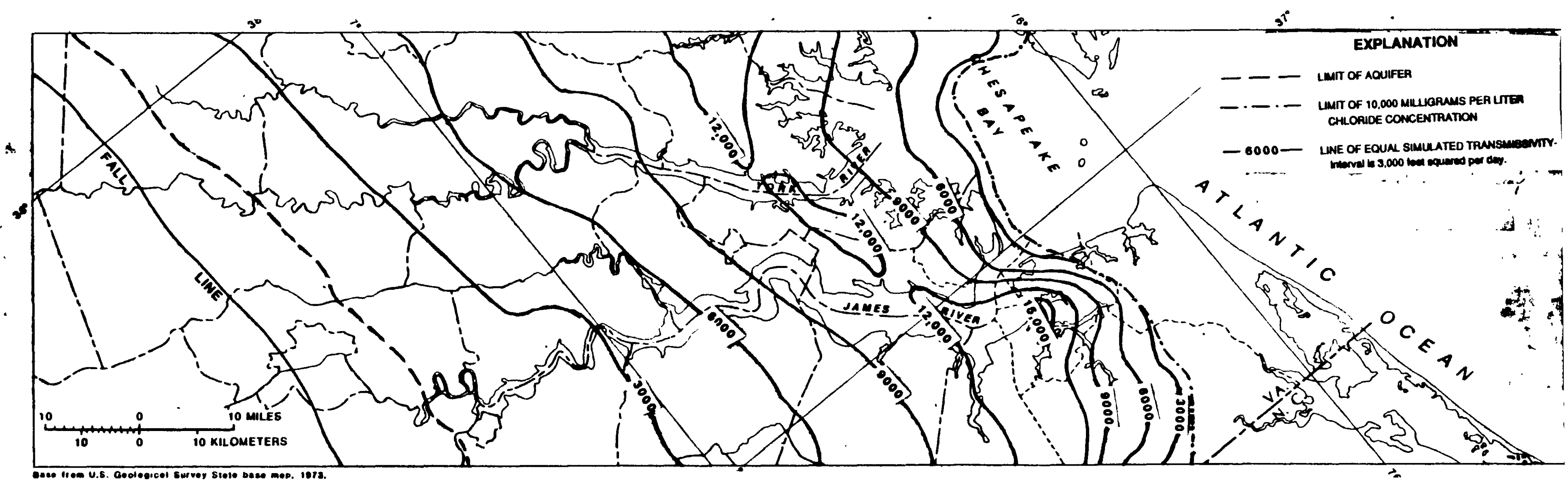


Figure 46. Transmissivity of lower Potomac aquifer.

the sediment. Lower transmissivities also are present along major river channels where ancient and present-day rivers have eroded the original aquifer material and replaced it with less permeable (conductive) sediment. The highest transmissivities are in the upper, middle, and lower Potomac aquifers and are a function of higher hydraulic conductivity and a greater thickness of aquifer sediment. The ranges of transmissivity are listed by aquifer in table 19.

Storage coefficient

Storage coefficient for each grid block was calculated by multiplying the average thickness of the aquifer by the estimated specific storage of the aquifer. A specific storage of $1x10^{-6}$ was assumed for the confined aquifers. This value is considered reasonable if all water released from aquifer storage results from the compressibility of water (Lohman, 1979). A storage coefficient of 0.15 was assumed for water-table (unconfined) grid blocks. This value represents the specific yield of an unconfined aquifer. The areal distribution of aquifer storage coefficient closely parallels the trends of transmissivity. The range of storage coefficient are listed by aquifer. in table 20.

Vertical leakance

Vertical leakance is a measure of the ability of a confining unit to transmit water between aquifers and is defined as the quotient of vertical hydraulic conductivity and the thickness of the confining unit. Vertical leakance for each grid block was calculated by dividing the average vertical hydraulic conductivity by the adjusted thickness of the confining unit for each grid block. The average vertical hydraulic conductivity for each confining unit was determined from laboratory analyses of core samples and are listed in table 21. Confining-unit thicknesses shown in figures 11-17 were adjusted to account for changes in vertical leakance that result from areal variations in vertical hydraulic conductivity. Thus, adjusted confining-unit thicknesses, shown in figures 47-54, inversely reflect areal changes in vertical leakance. Vertical leakance generally decreases downdip (west to east) because confining units thicken and the vertical hydraulic conductivity of the sediment decreases. Greater vertical leakances are present in areas underlying major river systems and Chesapeake Bay. In these areas, ancient and present-day rivers have eroded the original confining unit sediments and have replaced them with more permeable deposits (greater vertical hydraulic conductivity). Hack (1957) describes the ancient Pleistocene river system of Chesapeake Bay. The ranges of vertical leakance are listed by confining unit in table 22.

Time Discretization and Ground-Water Withdrawals

The quantity of ground water withdrawn has varied throughout the history of its development (1891-1983). In order to account for transient changes in withdrawal, time was divided into eleven pumping periods. Model-simulated pumping periods are the years: 1891-1920, 1921-39, 1940-45, 1946-52, 1953-57, 1958-64, 1965-67, 1968-72, 1973-77, 1978-80, and 1981-83. Each pumping period starts on January 1st of its beginning year and ends on December 31st of its ending year. Withdrawal in each grid block was calculated for each pumping period from annual withdrawal data. Total estimated annual withdrawal is compared to simulated withdrawal in figure 55. Simulated withdrawal for each pumping period are listed by aquifer in table 23.

Table 19--Minimum and maximum values of model transmissivity

[Values in feet squared per day]

Aquifer	Transmissivity	
	Minimum	Maximum
Columbia	18	544
Yorktown-Eastover	146	3,818
Chickahominy-Piney Point	21	2,479
Aquia	21	1,702
Virginia Beach	86	2,868
Upper Potomac	105	11,491
Middle Potomac	259	15,724
Lower Potomac	165	15,552

Table 20--Minimum and maximum values of model storage coefficient

[Values are dimensionless]

Aquifer	Storage coefficient	
	Minimum	Maximum
Columbia	1.50×10^{-1}	1.50×10^{-1}
Yorktown-Eastover	1.20×10^{-5}	1.50×10^{-1}
Chickahominy-Piney Point	1.19×10^{-6}	1.38×10^{-4}
Aquia	1.19×10^{-6}	9.48×10^{-5}
Virginia Beach	2.40×10^{-6}	7.80×10^{-5}
Upper Potomac	2.40×10^{-6}	2.62×10^{-5}
Middle Potomac	6.00×10^{-6}	1.50×10^{-1}
Lower Potomac	4.80×10^{-6}	4.50×10^{-4}

Table 21--Estimated vertical hydraulic conductivity of confining units

[Values in feet per day]

Confining unit	Vertical hydraulic conductivity
Yorktown	8.64×10^{-4}
St. Marys	4.15×10^{-4}
Calvert	4.49×10^{-5}
Nanjemoy-Marlboro	3.63×10^{-5}
Virginia Beach	5.18×10^{-5}
Upper Potomac	3.63×10^{-5}
Middle Potomac	3.28×10^{-5}
Lower Potomac	2.42×10^{-5}

Table 22--Minimum and maximum values of model vertical leakance

[Values in $days^{-1}$]

Confining unit	Vertical Leakance	
	Minimum	Maximum
Yorktown	1.35×10^{-5}	1.73×10^{-2}
St. Marys	6.38×10^{-7}	6.92×10^{-3}
Calvert	6.83×10^{-8}	4.49×10^{-3}
Nanjemoy-Marlboro	5.72×10^{-8}	3.63×10^{-3}
Virginia Beach	6.39×10^{-7}	1.13×10^{-5}
Upper Potomac	6.05×10^{-8}	1.21×10^{-5}
Middle Potomac	2.36×10^{-7}	3.28×10^{-4}
Lower Potomac	2.10×10^{-7}	2.42×10^{-5}

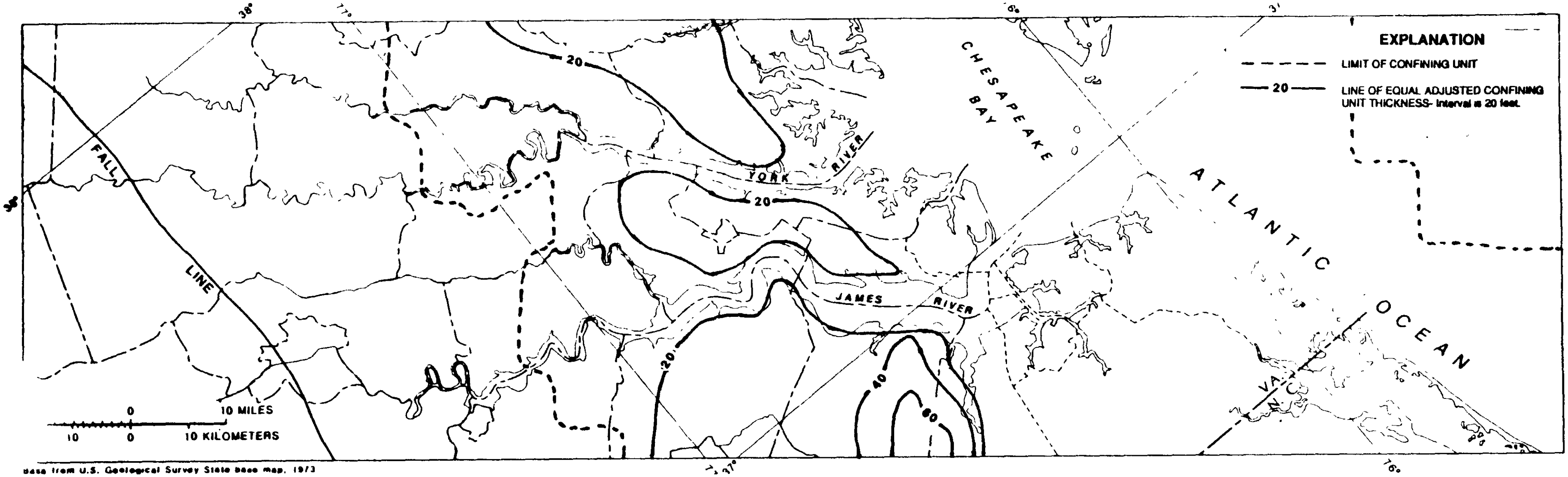


Figure 47. Adjusted thickness of Yorktown confining unit.

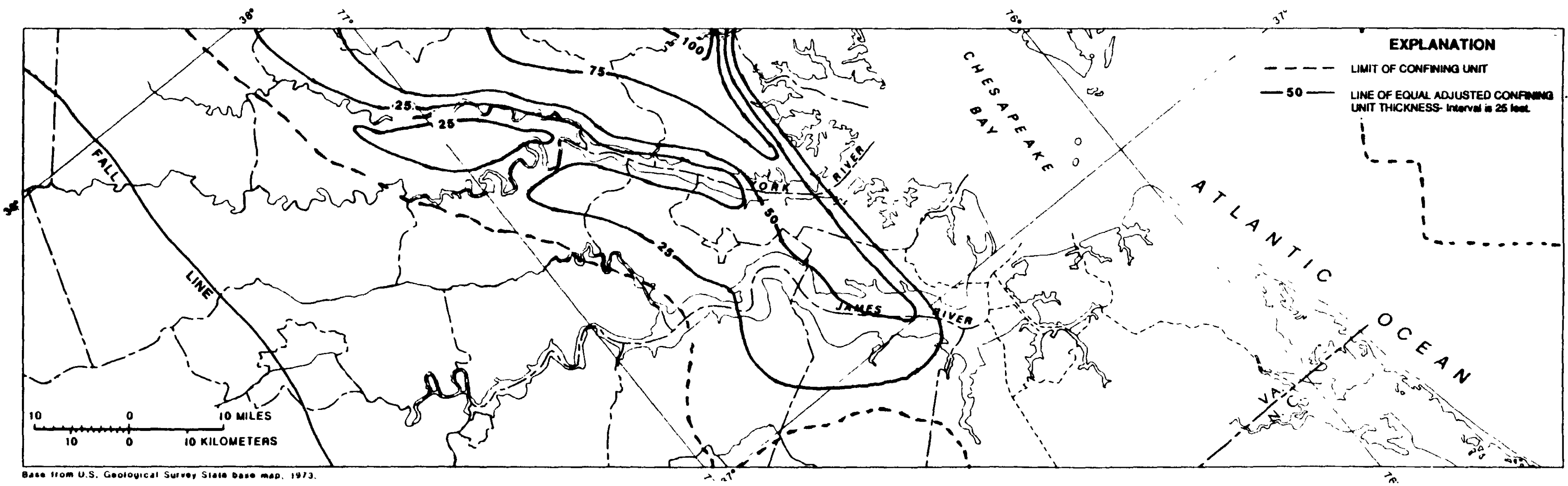
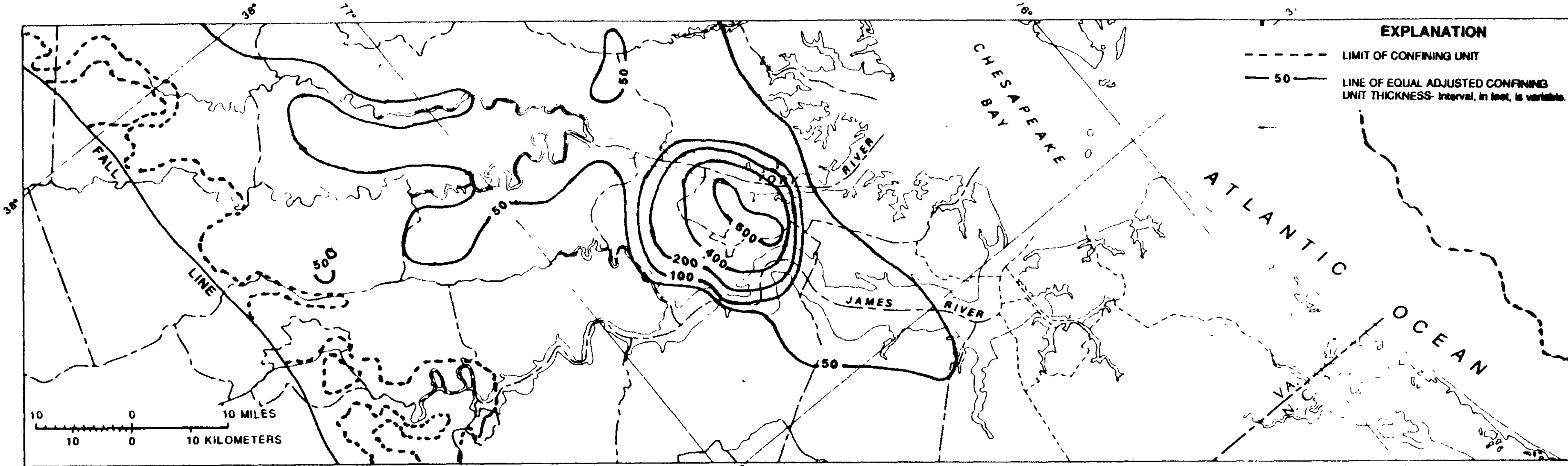
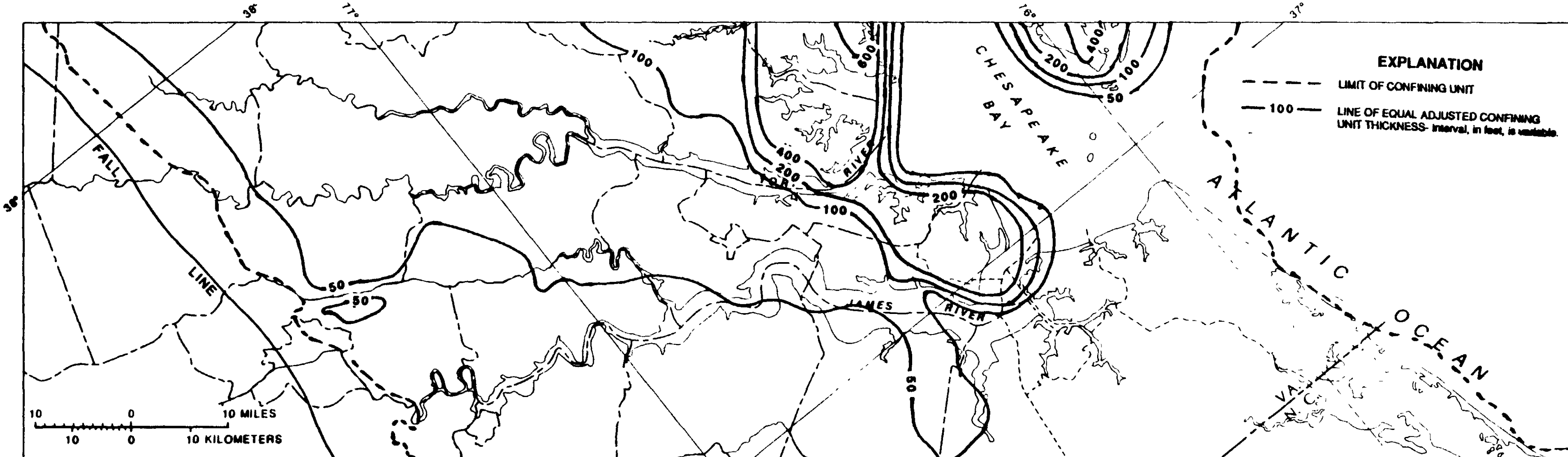


Figure 48. Adjusted thickness of St. Marys confining unit.



Base from U.S. Geological Survey State base map, 1973

Figure 49. Adjusted thickness of Calvert confining unit.



Base from U.S. Geological Survey State base map, 1973

Figure 50. Adjusted thickness of Nanjemoy-Marlboro confining unit.

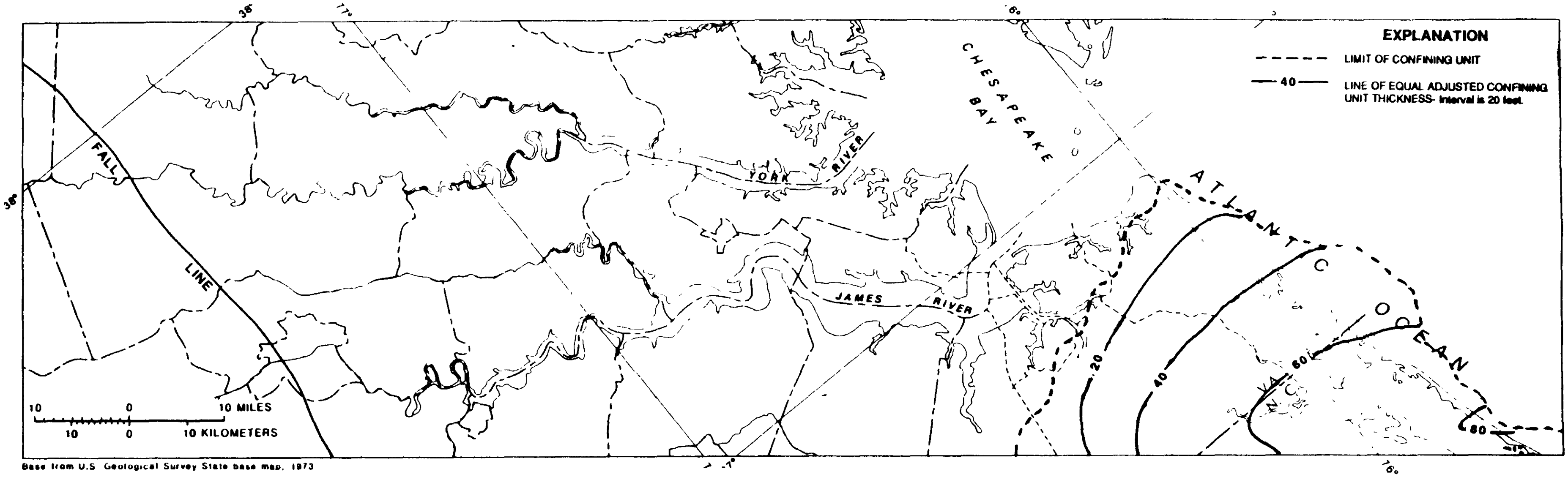


Figure 51. Adjusted thickness of Virginia Beach confining unit.

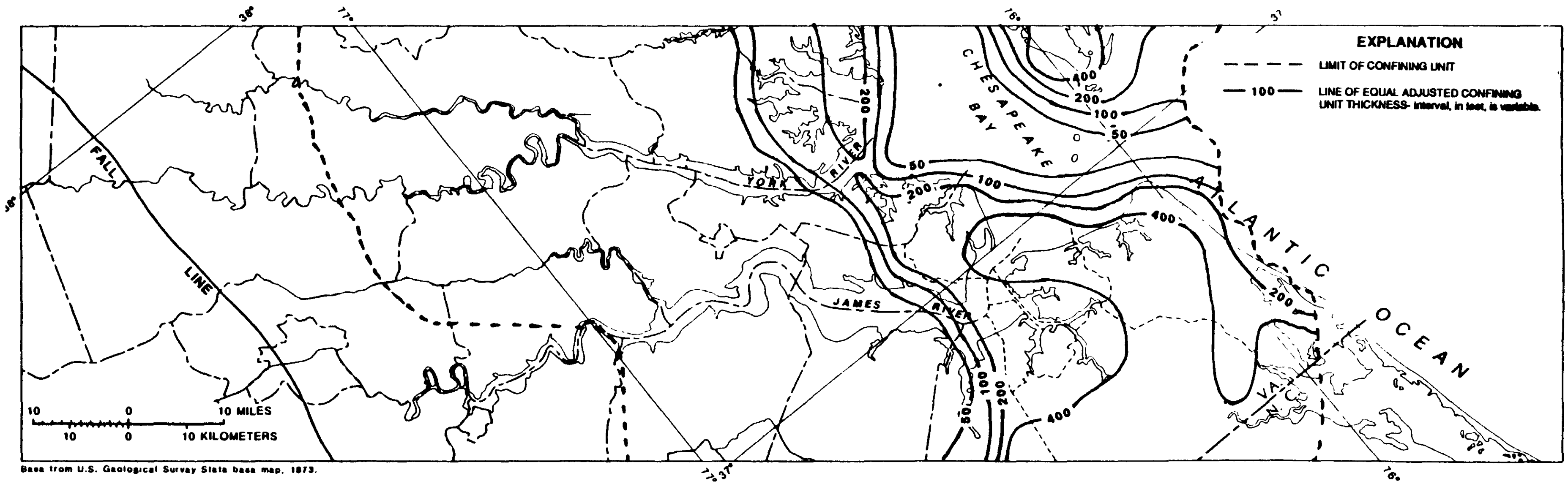


Figure 52. Adjusted thickness of upper Potomac confining unit.

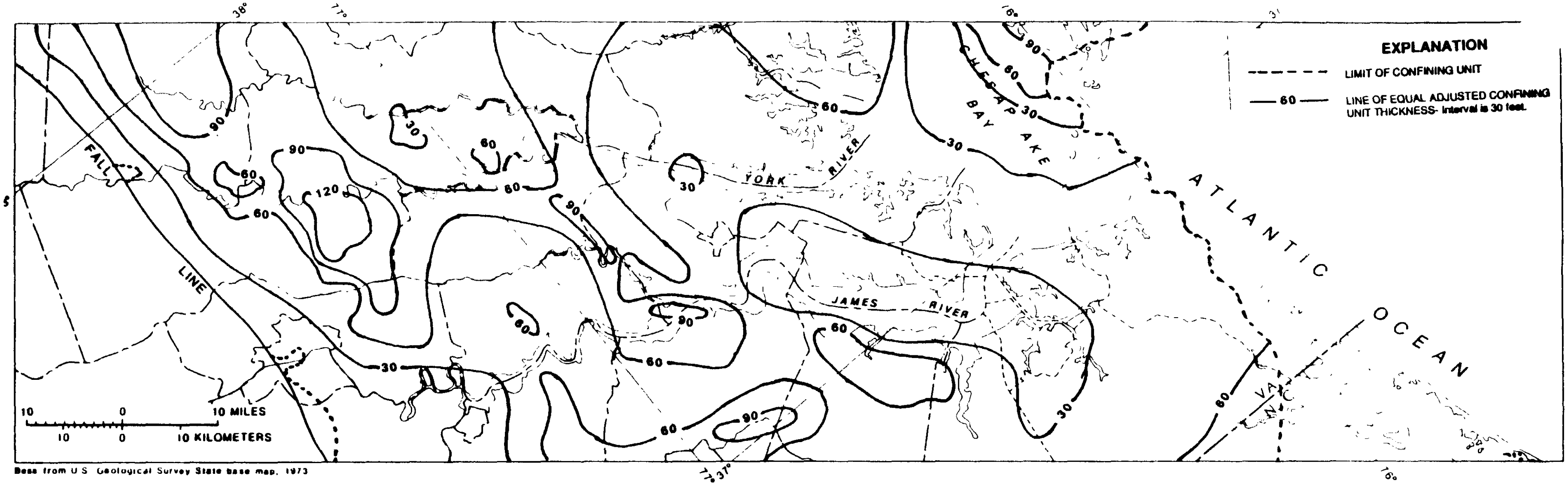


Figure 53. Adjusted thickness of middle Potomac confining unit.

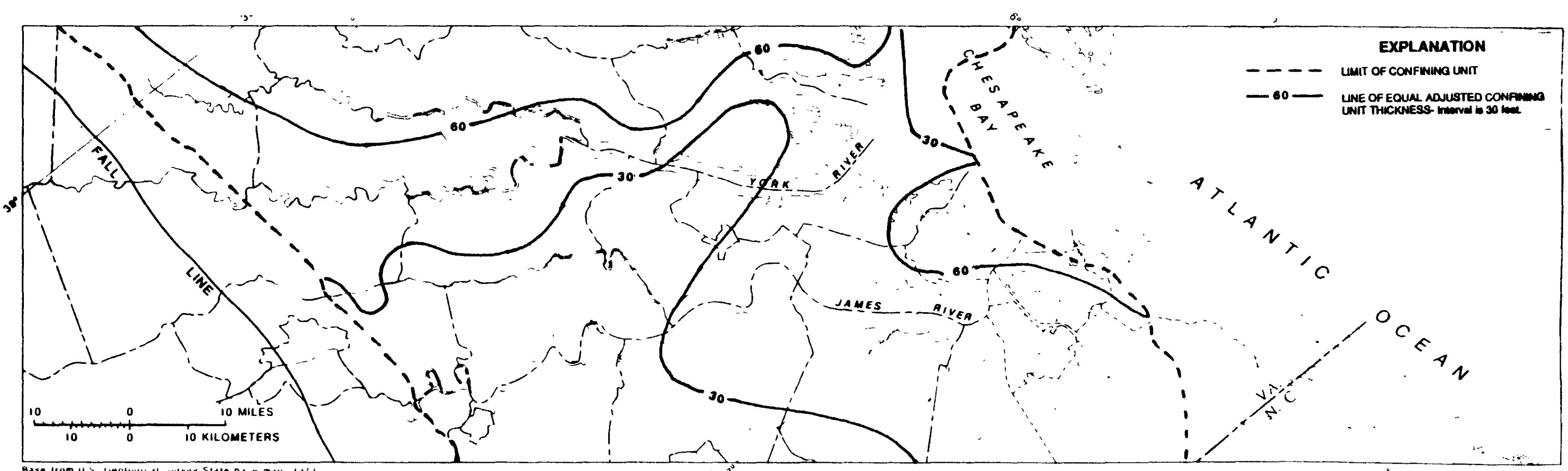


Figure 54. Adjusted thickness of lower Potomac confining unit.

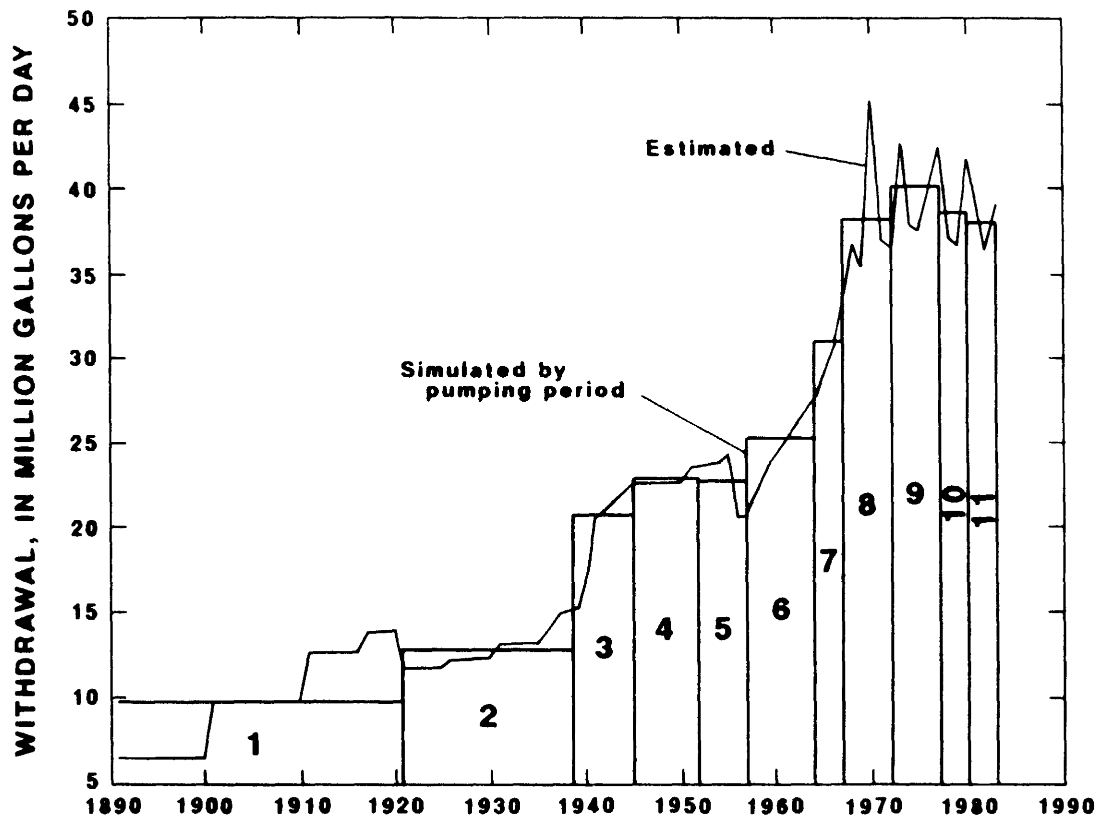


Figure 55. Simulated ground-water withdrawal from model area.

Table 23--Withdrawals for each pumping period by aquifer

[Values, in millions of gallon per day, are not intended to imply accuracy to precision shown]

Aquifer	Pumping period										
	1	2	3	4	5	6	7	8	9	10	11
	1891-1920	1921-39	1940-45	1946-52	1953-57	1958-64	1965-68	1969-72	1973-78	1979-80	1981-83
Columbia	0.000	0.000	0.000	0.000	0.000	0.007	0.019	0.046	0.088	0.102	0.128
Yorktown-Eastover	.000	.054	.169	.229	.246	.332	.785	1.337	1.781	1.621	1.403
Chickahominy-Piney Point	.025	.127	.305	.457	.568	.657	.787	1.247	1.840	1.977	2.641
Aquia	.077	.330	1.373	1.660	1.414	1.066	1.165	1.528	1.600	1.451	1.003
Virginia Beach	.000	.000	.000	.000	.000	.000	.000	.037	.094	.008	.006
Upper Potomac	5.252	6.141	10.837	10.983	9.652	10.772	13.189	16.177	14.929	14.495	13.644
Middle Potomac	3.947	5.322	6.612	7.864	8.883	10.536	12.987	15.773	16.215	16.149	15.150
Lower Potomac	.524	.888	1.370	1.726	1.959	1.944	2.099	2.081	3.685	2.865	4.135
Totals	9.825	12.862	20.866	22.919	22.722	25.314	31.031	38.226	40.232	38.668	38.110

Lateral-Boundary Flux

Lateral-boundary flux, water flowing into and out of aquifers across the northeastern and southwestern boundaries of the model, was calculated by multiplying water-level (hydraulic-head) gradients which were computed by the regional-flow model of Harsh and Laczniak (1986) by the harmonic mean of transmissivity across grid blocks defining the boundary. Model-simulated lateral-boundary fluxs for each pumping period are listed by aquifer in table 24.

Ground-Water Recharge

Ground-water recharge is precipitation that infiltrates into the water-table aquifer and is not evaporated or transpired. Average annual precipitation for the study area is 43 in/yr (inches per year) (National Oceanic and Atmospheric Administration, 1980). Approximately 10 to 15 inches are estimated to recharge the water-table aquifer throughout the Coastal Plain of Virginia (Geraghty and Miller, 1978; Harsh, 1980; Johnston, 1977). The remaining precipitation is lost to surface runoff or evapotranspiration. An average annual recharge rate of 15 in/yr is assigned to all grid blocks that simulate water-table conditions. Ground-water recharge varies over the model area, but data are inadequate to define these areal variations. The higher rate of 15 in/yr was used because preliminary low-flow analyses of stream flow in the York-James Peninsula indicate baseflows representative of the higher recharge rates (Hayes, D.C., U.S. Geological Survey, oral commun., 1986). A constant recharge rate of 15 in/yr was considered acceptable because water levels in the deeper confined aquifers upon which this study focuses are fairly insensitive to any seasonal changes in recharge.

Streambed Leakance

Streambed leakance, defined as the hydraulic conductivity divided by the thickness of the streambed sediment, controls the amount of water flowing through the streambed into and out of the water-table (unconfined) aquifer. Ground water that flows into the stream is referred to as stream baseflow. Assuming full saturation, stream baseflow is the product of streambed leakance and the difference between the water level in the water-table aquifer and stage of the stream. Prepumped baseflow was computed for each grid block intersecting a stream as the estimated ground-water recharge minus the simulated prepumped flow from the water-table aquifer into the underlying confined aquifer (Leahy and Martin, 1986; Harsh and Laczniak, 1986). Streambed leakance for each respective grid block was calculated by dividing the computed baseflow by the difference between the estimated water level in the water-table aquifer and the stage of the stream. Values of streambed leakance were assumed constant throughout the history of ground-water pumpage.

Simulation of Flow Conditions before Pumping

Prepumping flow conditions describe the ground-water flow system before the withdrawal of ground water and were assumed to exist within the study area prior to 1890. During this time, ground water existed in an approximate state of hydraulic equilibrium (inflow equals outflow). Therefore, prepumping flow conditions could be simulated by the steady-state solution of the ground-water flow equation. The simulation of prepumping flow conditions provided initial water levels for the simulation of pumping flow conditions and served as a

Table 24-- Lateral-boundary flux for each pumping period by aquifer

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

Aquifer	Pumping period: Prepumping Into	Out of	Net	1 (1891-1920) Into	Out of	Net	2 (1921-39) Into	Out of	Net	3 (1940-45) Into	Out of	Net	4 (1946-52) Into	Out of	Net	5 (1953-57) Into	Out of	Net
Columbia	0.42	0.51	-0.09	0.42	0.51	0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	.42	.51	-.09
Yorktown-Eastover	2.20	1.23	.97	2.20	1.23	.97	2.20	1.23	.97	2.20	1.23	.97	2.20	1.23	.98	2.20	1.23	.97
Chickahominy-Piney Point	.48	.83	-.35	.49	.77	-.29	.48	.72	-.23	.49	.59	-.09	.49	.51	-.02	.49	.48	.01
Aquia	.51	.77	-.25	.56	.73	-.17	.55	.71	-.16	.63	.68	-.05	.67	.67	.02	.68	.70	-.02
Virginia Beach	.12	.00	.12	.14	.00	.14	.14	.00	.14	.15	.00	.15	.15	.00	.15	.15	.00	.15
Upper Potomac	.39	.68	-.29	1.03	.32	.71	1.09	.16	.93	1.90	.07	1.83	2.04	.07	1.97	1.78	.08	1.70
Middle Potomac	3.06	4.25	1.19	5.09	3.70	1.39	5.23	3.44	1.78	6.23	3.32	2.91	6.19	3.37	2.82	5.19	3.60	1.59
Lower Potomac	.77	1.10	-.33	1.26	.74	.52	1.32	.88	.45	1.38	.87	.52	1.20	1.05	.15	1.16	1.23	-.07
Totals	9.36	7.95	-1.41	11.18	8.00	3.18	11.44	7.65	5.85	13.41	7.26	6.15	13.37	7.43	5.93	12.08	7.82	4.26

Aquifer	Pumping period: 6 (1958-64) Into	Out of	Net	7 (1965-68) Into	Out of	Net	8 (1969-72) Into	Out of	Net	9 (1973-77) Into	Out of	Net	10 (1978-80) Into	Out of	Net	11 (1981-83) Into	Out of	Net
Columbia	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09
Yorktown-Eastover	2.20	1.23	.97	2.20	2.17	.95	2.17	1.22	.95	2.18	1.22	.96	2.17	1.22	.95	2.18	1.22	.95
Chickahominy-Piney Point	.49	.43	.06	.49	.50	.13	.51	.28	.23	.55	.27	.28	.54	.27	.27	.54	.27	.27
Aquia	.74	.73	.01	.74	.79	.01	.90	.81	.09	.91	.83	.08	.89	.84	.06	.87	.80	.07
Virginia Beach	.16	.00	.16	.16	.00	.16	.20	.00	.20	.22	.00	.22	.19	.00	.19	.18	.00	.18
Upper Potomac	2.00	.17	1.83	2.34	.38	1.96	3.33	.36	2.08	3.23	.37	2.85	3.10	.36	2.73	3.06	.20	2.86
Middle Potomac	5.27	5.32	-.04	5.78	5.84	-.06	6.32	6.12	.20	6.34	6.28	.06	6.25	6.96	-.71	6.07	6.53	-.46
Lower Potomac	1.44	1.88	-.44	1.79	2.27	-.48	2.13	2.95	-.82	2.48	2.79	.31	2.22	2.87	-.65	2.44	2.72	-.28
Totals	12.73	10.26	3.82	13.95	11.37	3.99	15.97	12.25	5.77	16.32	12.27	6.26	15.78	13.02	2.75	15.76	12.25	3.52

comparison in order to determine the effects of withdrawal on ground-water flow conditions.

Simulated prepumping water levels for the confined aquifers are shown as potentiometric surfaces in figures 56-61. Available measured water levels are included on the maps to show agreement with simulated values. Because measured water levels were sparse, simulated potentiometric surface maps also were compared to prepumping maps published by Bal (1978), Siudyla and others (1977), and Harsh and Laczniak (1986). Water-level gradients indicate that the regional flow of ground water was from the Fall Line toward Chesapeake Bay and the Atlantic Ocean, and that local flow was toward major river systems. These maps show simulated water levels to be consistent with measured values, and simulated flow directions to be in agreement with the conceptualization of ground-water flow during prepumping flow conditions.

The model-computed water budget for prepumping flow conditions is shown in table 25. Sources of water were recharge from precipitation (about 3,237 Mgal/d) and lateral-boundary inflow (about 8 Mgal/d). Discharges were flow to surface water (about 3,236 Mgal/d) and lateral-boundary outflow (about 9 Mgal/d).

The direction of flow into and out of the aquifers through the overlying confining units is shown in figures 62-67. The general direction of flow was downward in the western part of the model area toward Chesapeake Bay and the Atlantic Ocean and upward in the eastern part. In the shallow aquifers, the direction of flow was influenced strongly by major river systems to which ground water discharged. Flow of water into and out of aquifers through the overlying confining units is given in table 26.

Simulation of Flow Conditions during Pumping

The withdrawal of ground water affected ground-water flow conditions in the prepumping flow system. The response of the flow system to the withdrawal of ground water was simulated by the transient solution of the ground-water flow equation. The solution superimposes the effects of withdrawal on prepumping flow conditions. Simulated withdrawals for each pumping period are listed, by aquifer, in table 23. Lateral-boundary flux across the northeastern and southwestern model boundaries, computed from water-level gradients simulated by the regional model of Harsh and Laczniak (1986), are listed for each pumping period, by aquifer, in table 24. The minimum and maximum storage coefficients of each aquifer are listed in table 20. All other hydraulic characteristics and hydrologic stresses were equivalent to those simulating prepumping flow conditions.

Simulated water levels are compared to measured water levels at 15 observation wells in figure 68. Hydrographs show close agreement between measured and simulated values. Locations of these observation wells are shown on figure 69. The observation wells selected have the longest available water-level record in the study area. Water levels of 126 other observation wells, located throughout the model area, show similar agreement with model results, but are not presented because most either have only short-term water-level record available or are outside the limits of the study area.

Simulated water levels for 1983 are shown as potentiometric surfaces in figures 70-75. Measured water levels are included on the maps to show

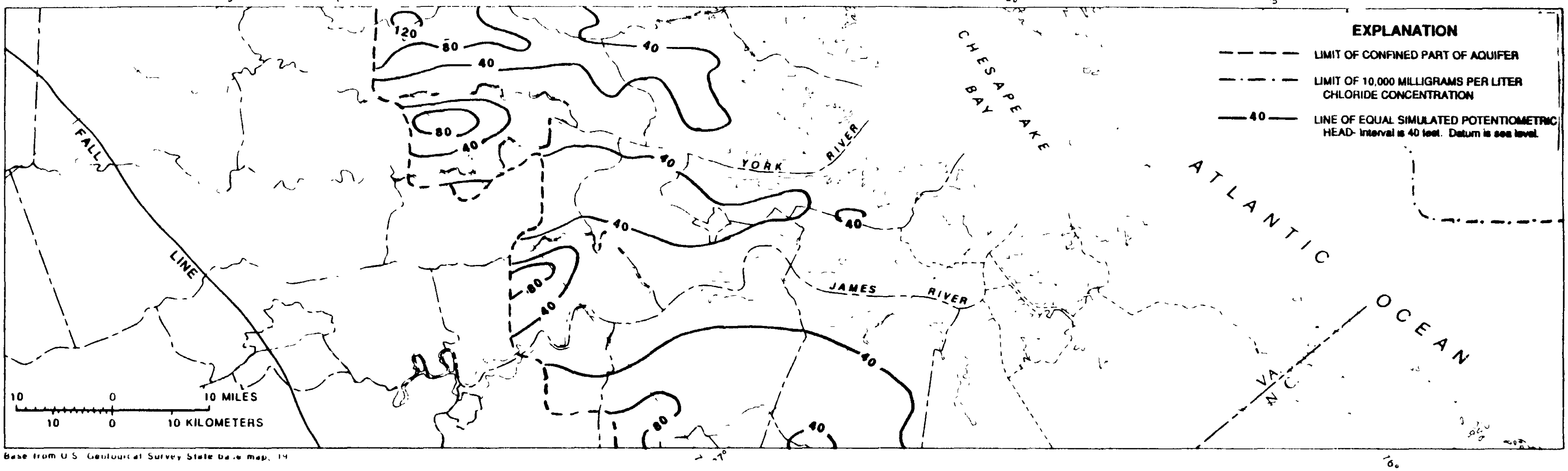


Figure 56. Prepumping potentiometric surface of Yorktown-Eastover aquifer.

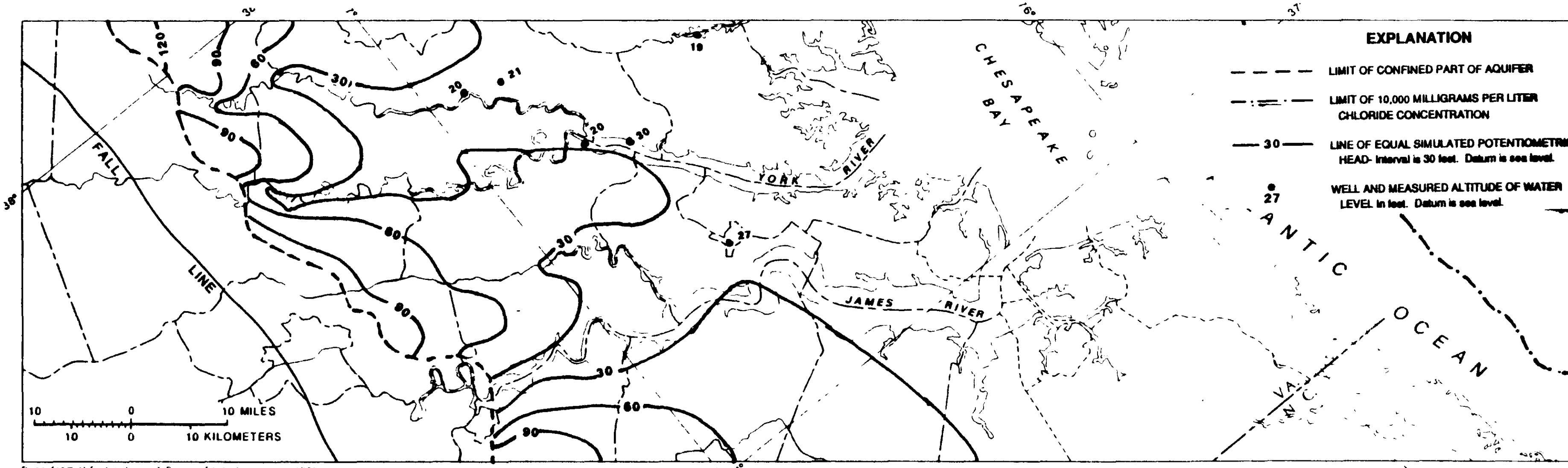


Figure 57. Prepumping potentiometric surface of Chickahominy-Piney Point aquifer.

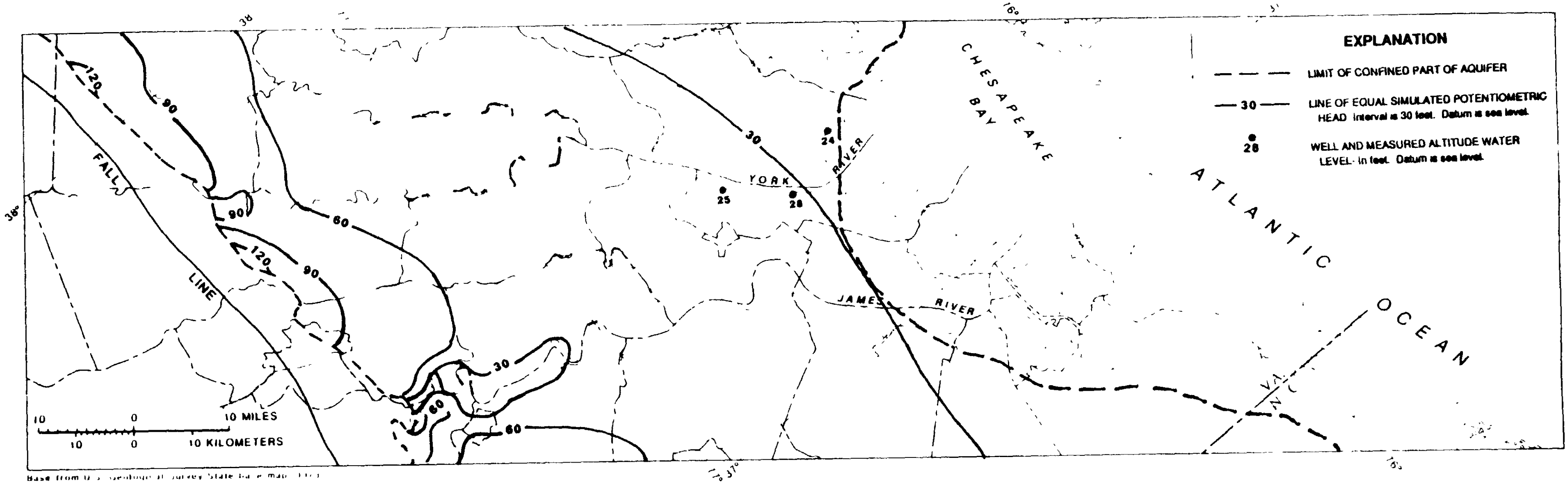


Figure 58. Prepumping potentiometric surface of Aquia aquifer.

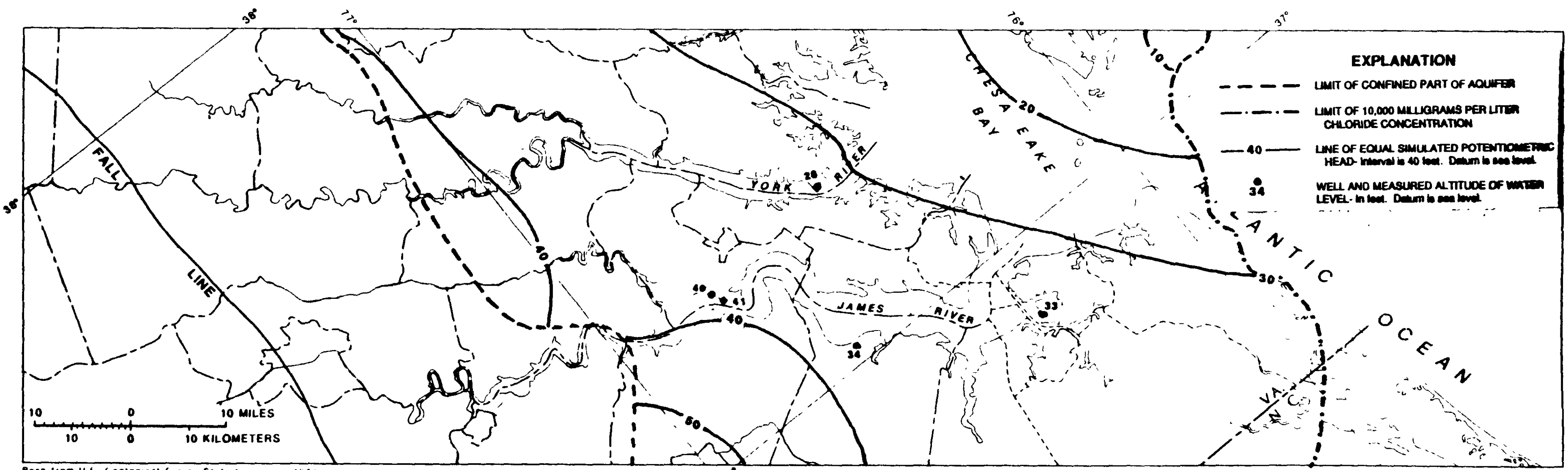


Figure 59. Prepumping potentiometric surface of upper Potomac aquifer.

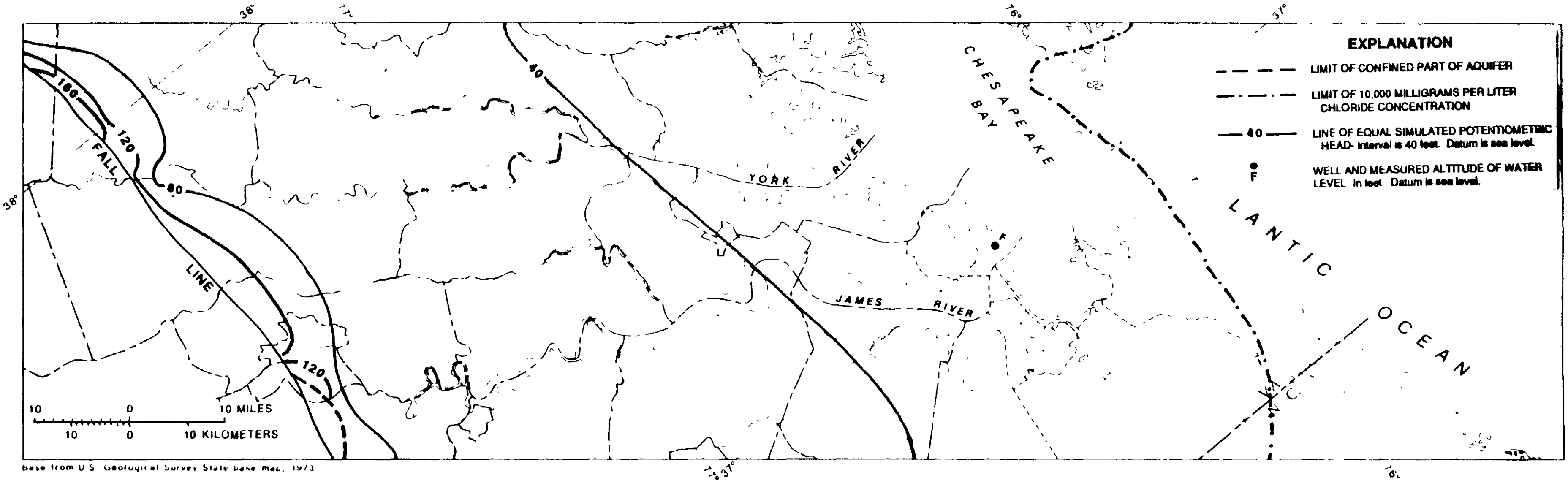


Figure 60. Prepumping potentiometric surface of middle Potomac aquifer.

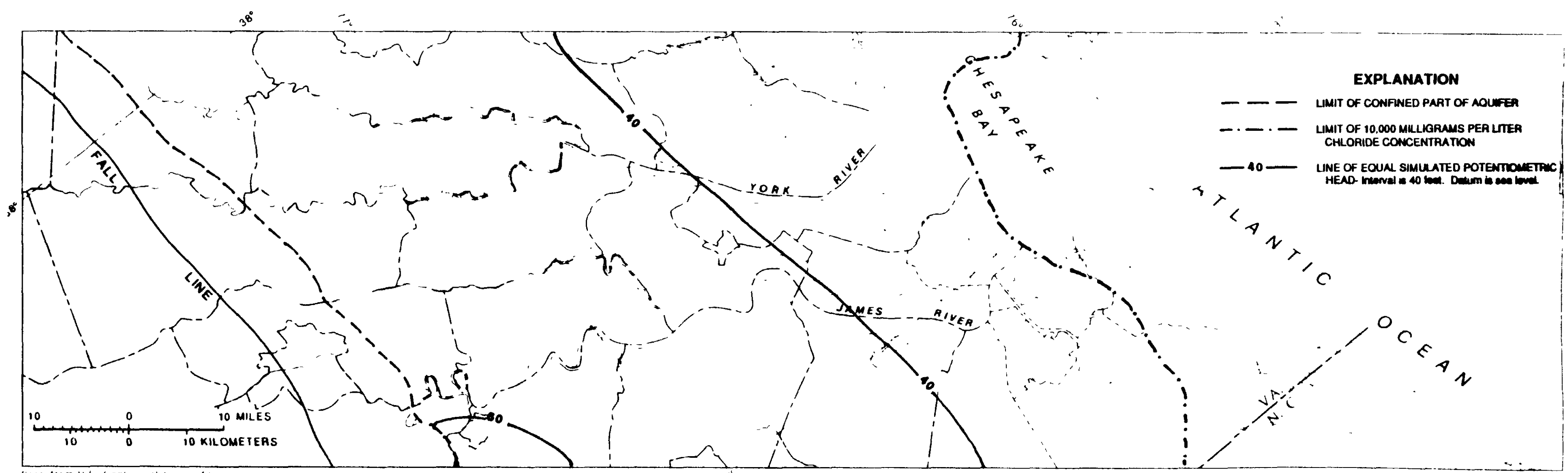


Figure 61. Prepumping potentiometric surface of lower Potomac aquifer.

Table 25.--Model-computed ground-water budget throughout history of ground-water development

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

		Pumping period										
		1	2	3	4	5	6	7	8	9	10	11
	Prepumped flow	1891-1920	1921-39	1940-45	1946-52	1953-57	1958-64	1965-68	1969-72	1973-78	1979-80	1981-83
SOURCES												
Water released from aquifer storage	0.00	0.00	0.00	2.10	1.38	1.36	1.77	3.96	3.66	2.09	1.04	0.21
Lateral-boundary inflow	7.95	11.18	11.44	13.41	13.37	12.08	12.73	13.95	15.97	16.32	15.78	15.76
Recharge from precipitation to water-table aquifer	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85	3236.85
Flow from surface water	.00	.00	.00	.00	.00	.00	.21	.44	.95	1.19	1.28	1.29
DISCHARGES												
Water entering aquifer storage	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Lateral-boundary outflow	9.35	8.00	7.65	7.26	7.43	7.82	10.26	11.37	12.25	12.27	13.02	12.25
Withdrawal from wells	.00	9.83	12.08	20.87	22.92	22.72	25.31	31.03	38.23	40.23	38.67	38.11
Flow to surface water	3235.88	3232.33	3230.33	3225.60	3222.38	3220.82	3217.14	3213.85	3208.16	3205.06	3204.53	3204.47

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

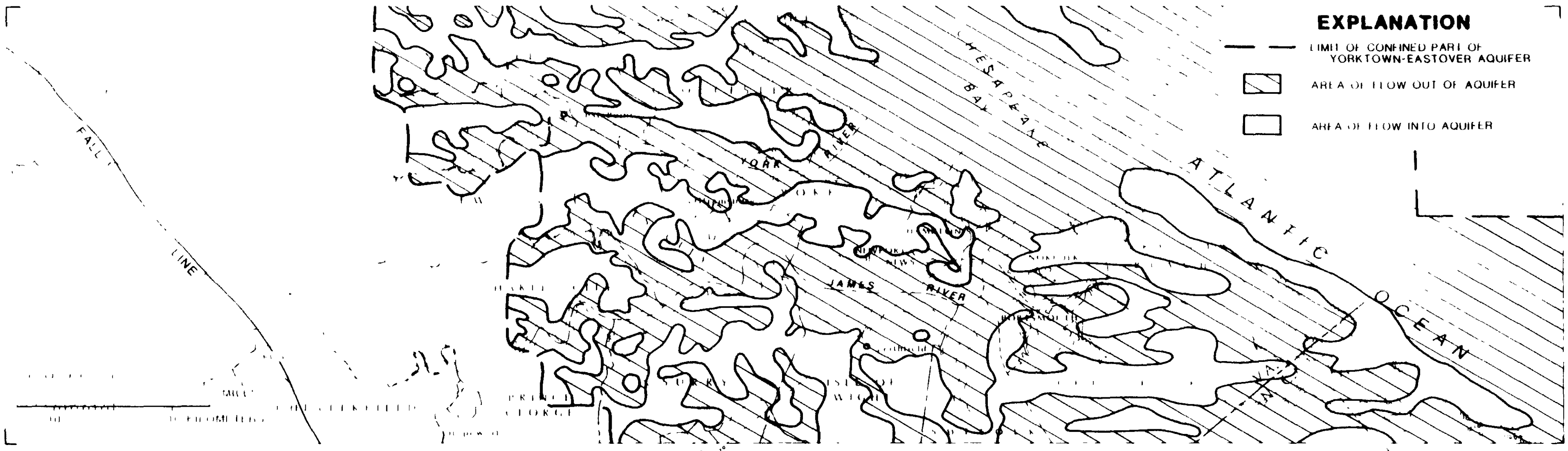


Figure 62. Prepumping direction of ground-water flow into and out of Yorktown-Eastover aquifer through overlying confining unit.

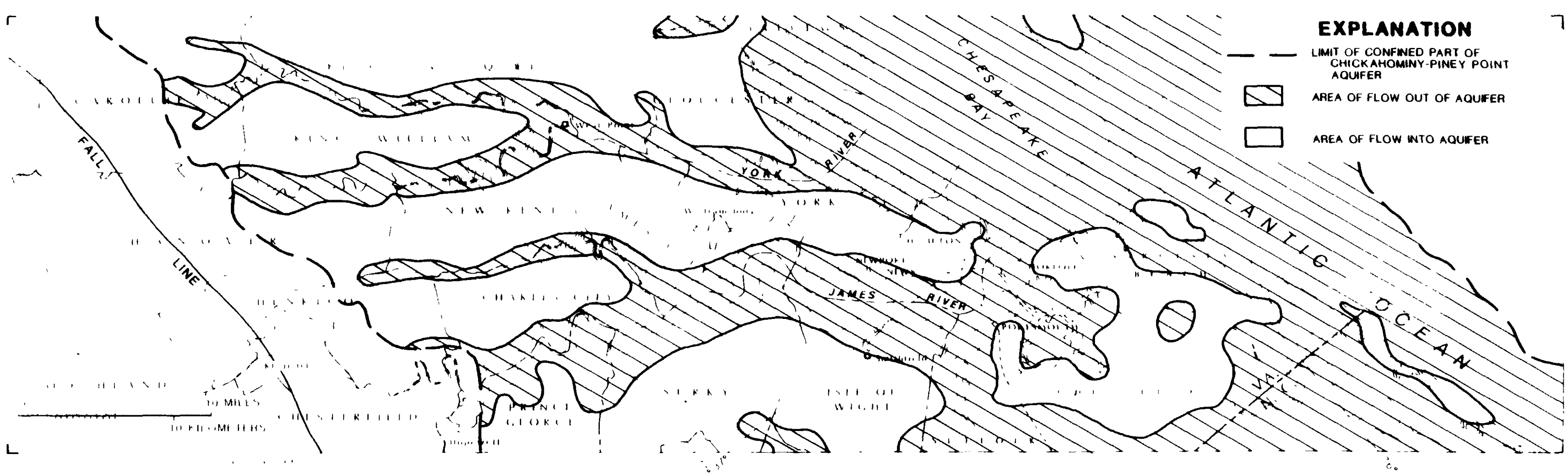


Figure 63. Prepumping direction of ground-water flow into and out of Chickahominy-Piney Point aquifer through overlying confining unit.

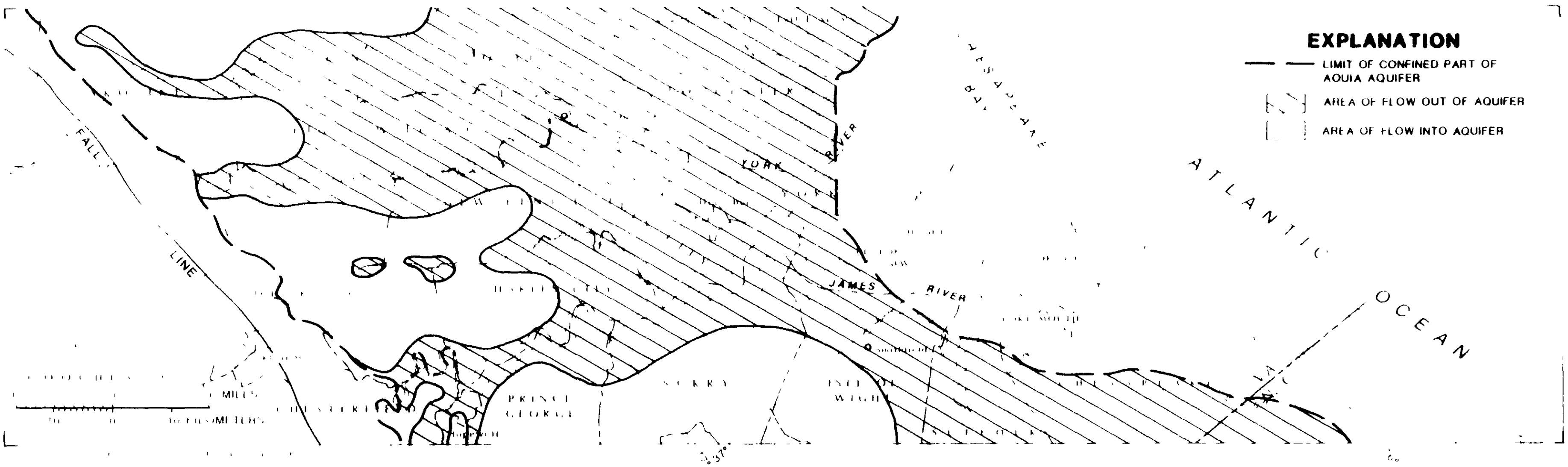


Figure 64. Prepumping direction of ground-water flow into and out of Aquia aquifer through overlying confining unit.

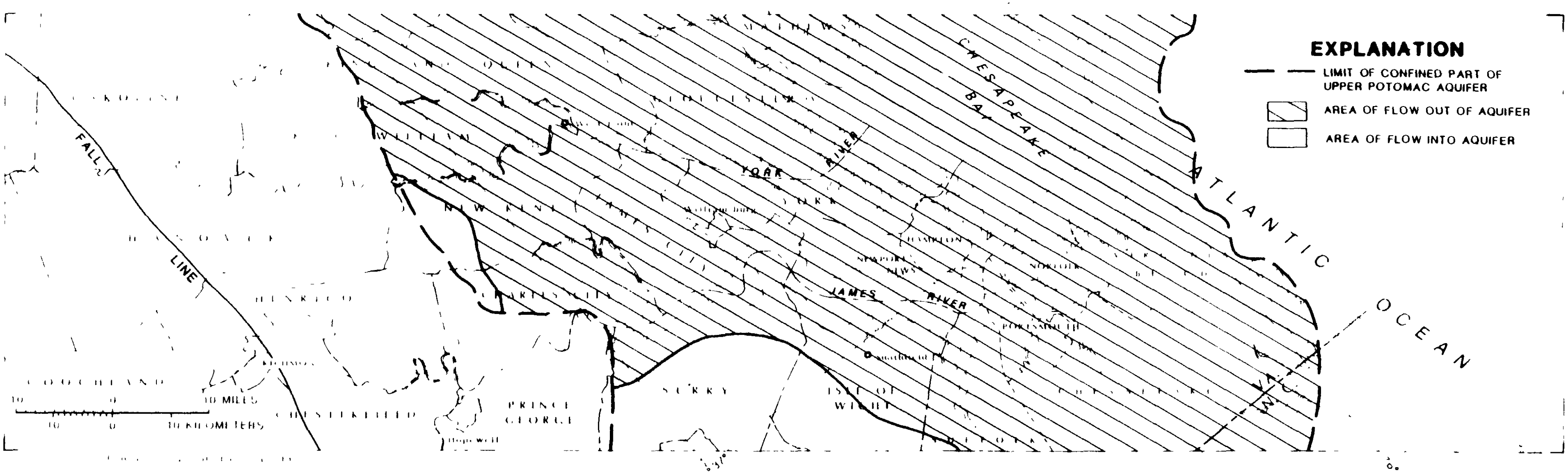


Figure 65. Prepumping direction of ground-water flow into and out of upper Potomac aquifer through overlying unit.

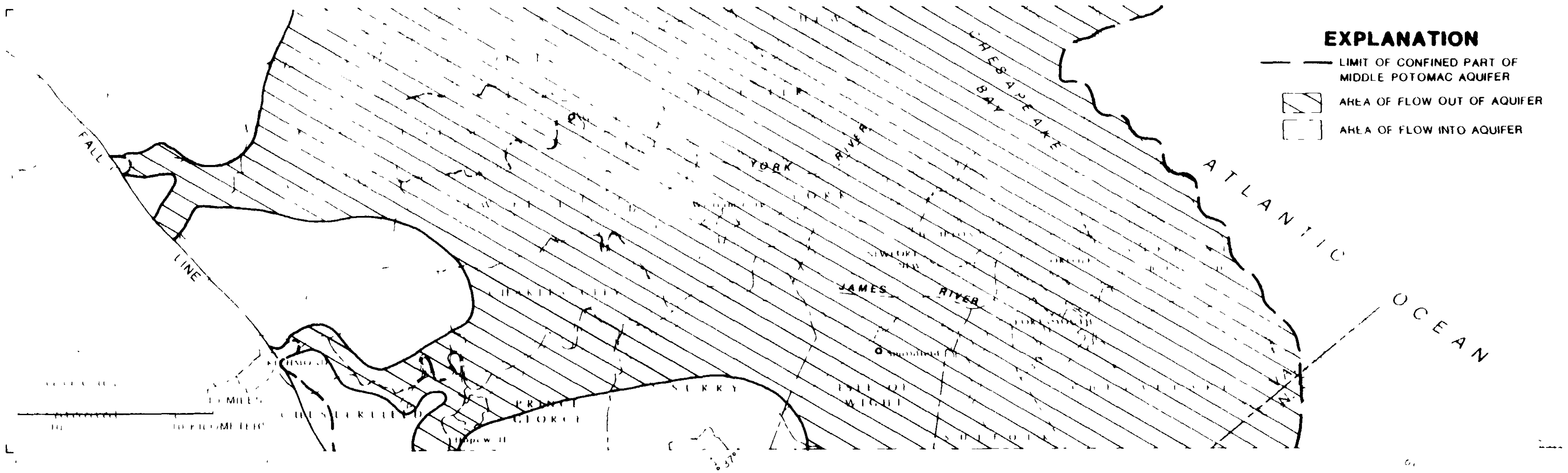


Figure 66. Prepumping direction of ground-water flow into and out of middle Potomac aquifer through overlying confining unit.

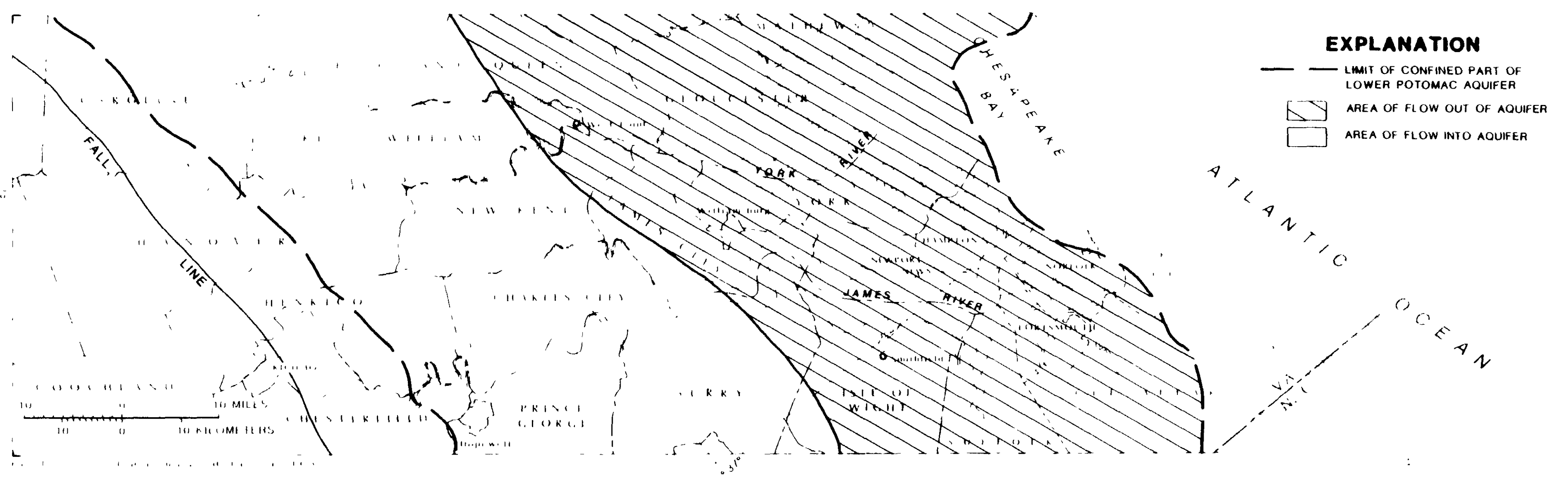


Figure 67. Prepumping direction of ground-water flow into and out of lower Potomac aquifer through overlying confining unit.

Table 26.--Flow into and out of aquifers through overlying confining unit throughout history of ground-water development

[Values in millions of gallons per day]

Aquifer	Pumping period																	
				1			2			3			4			5		
	Prepumping			1891-1920			1921-39			1940-45			1946-52			1953-57		
	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
Yorktown-Eastover	53.09	59.25	-6.16	53.68	57.88	-4.20	54.01	57.17	-3.16	55.09	54.89	0.20	55.57	53.83	1.75	55.76	53.40	2.36
Chickahominy-Piney Point	13.50	16.35	-2.85	14.50	14.82	-.32	15.06	14.03	1.03	16.95	11.85	5.10	17.95	10.78	7.17	18.42	10.32	8.10
Aquia	5.14	6.28	-1.14	6.05	4.52	1.53	6.71	3.94	2.77	9.42	3.12	6.30	10.88	2.79	8.09	11.49	2.63	8.86
Virginia Beach	.01	.40	-.39	.02	.32	-.30	.03	.29	-.26	.05	.22	-.17	.07	.17	-.10	.09	.15	-.05
Upper Potomac	.27	2.91	-2.64	.97	1.50	-.53	1.48	1.13	.35	3.57	.51	3.06	4.71	.25	4.46	5.49	.12	5.37
Middle Potomac	10.98	9.34	1.64	11.55	10.22	1.33	11.97	9.60	2.37	12.92	10.17	2.75	13.84	8.60	5.24	14.61	6.66	7.95
Lower Potomac	1.09	.62	.47	1.11	1.54	-.43	1.29	1.46	-.17	1.69	1.57	.12	2.11	1.04	1.07	2.21	.66	1.55

Aquifer	Pumping period																	
	6			7			8			9			10			11		
	1958-64			1965-68			1969-72			1973-77			1978-80			1981-83		
	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
Yorktown-Eastover	56.70	52.04	4.66	57.76	50.58	7.18	59.82	48.44	11.39	60.77	47.51	13.26	60.84	47.44	13.40	60.73	47.45	13.28
Chickahominy-Piney Point	20.17	9.30	10.87	22.05	8.60	13.45	25.55	7.34	17.81	27.06	7.48	19.66	27.38	7.34	20.03	27.43	7.37	20.07
Aquia	13.39	2.41	10.98	15.35	2.21	13.14	18.12	1.91	16.21	19.12	1.78	17.34	19.23	1.75	17.48	18.63	1.74	16.89
Virginia Beach	.18	.08	.10	.25	.05	.20	.46	.02	.44	.57	.01	.56	.56	.01	.55	.55	.01	.54
Upper Potomac	8.17	.02	8.15	10.34	.01	10.33	13.56	.01	13.55	14.45	.01	14.44	14.77	.01	14.76	14.52	.01	14.51
Middle Potomac	16.73	5.59	11.14	18.21	5.79	12.42	20.42	5.16	15.26	22.26	4.25	18.01	22.67	3.86	18.80	22.93	3.59	19.34
Lower Potomac	2.40	.66	1.74	2.36	1.00	1.36	2.67	1.00	1.67	3.65	.38	3.27	3.56	.44	3.11	4.34	.15	4.19

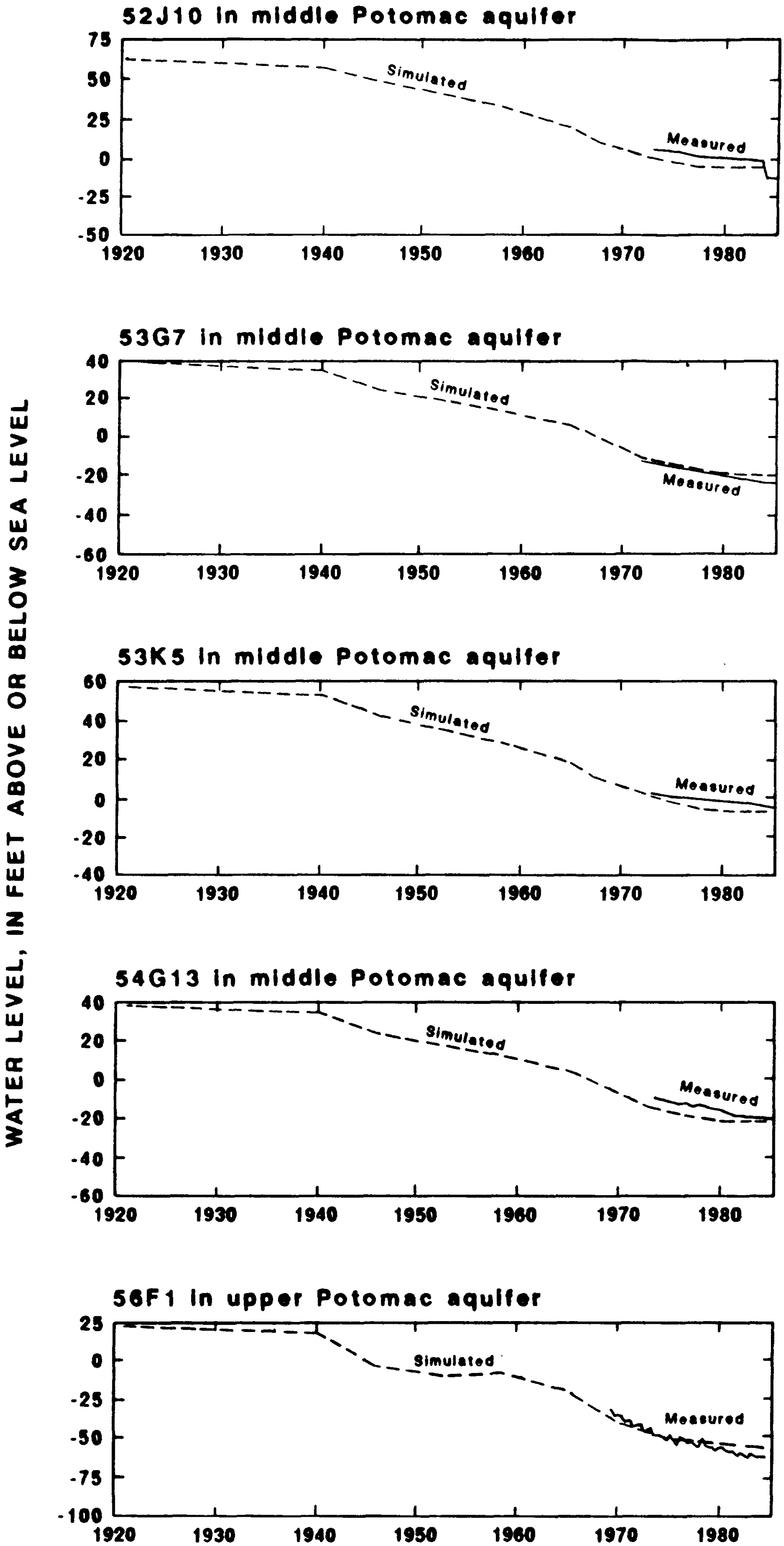


Figure 68. Simulated and measured water levels at selected observation wells.

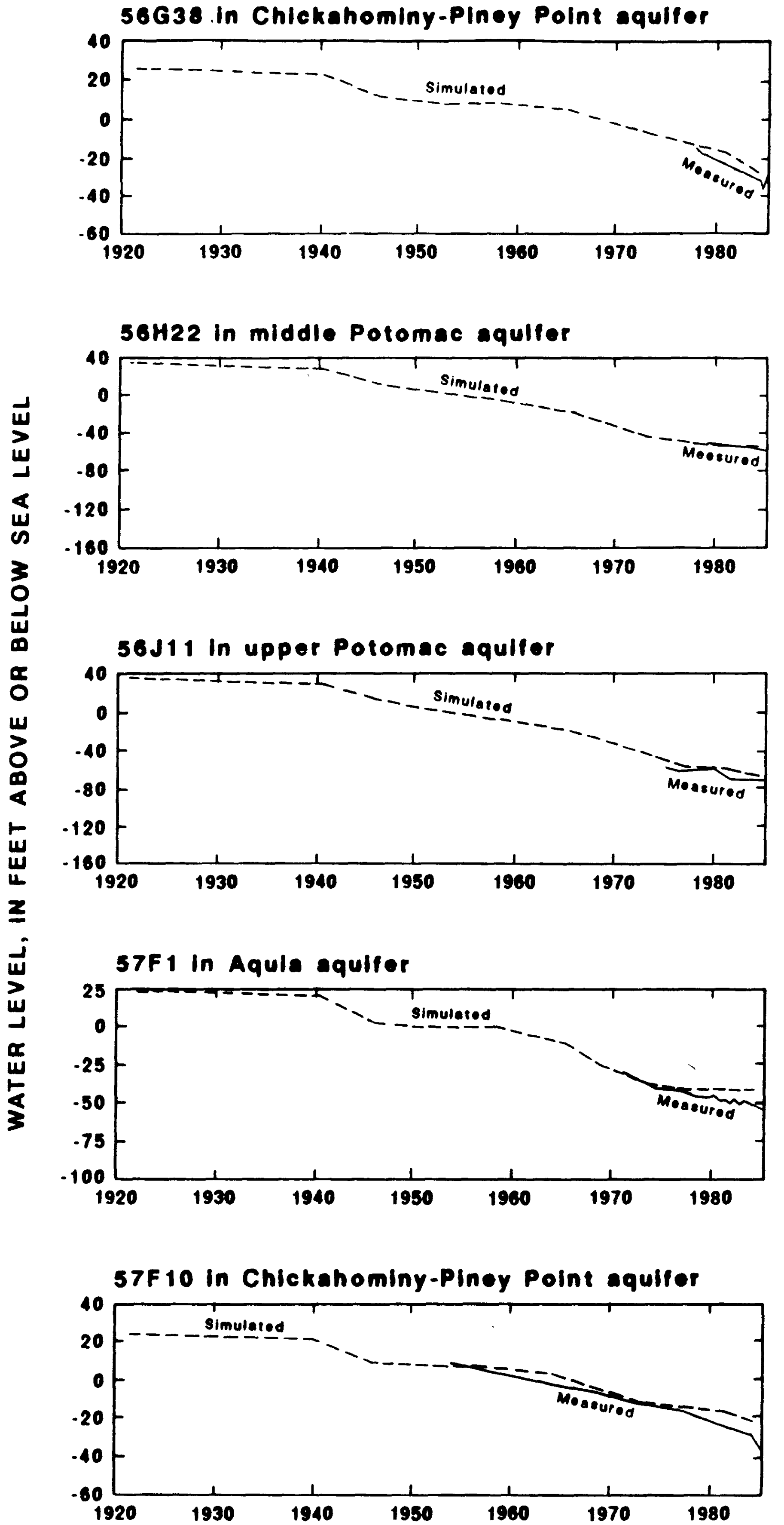


Figure 68. Continued

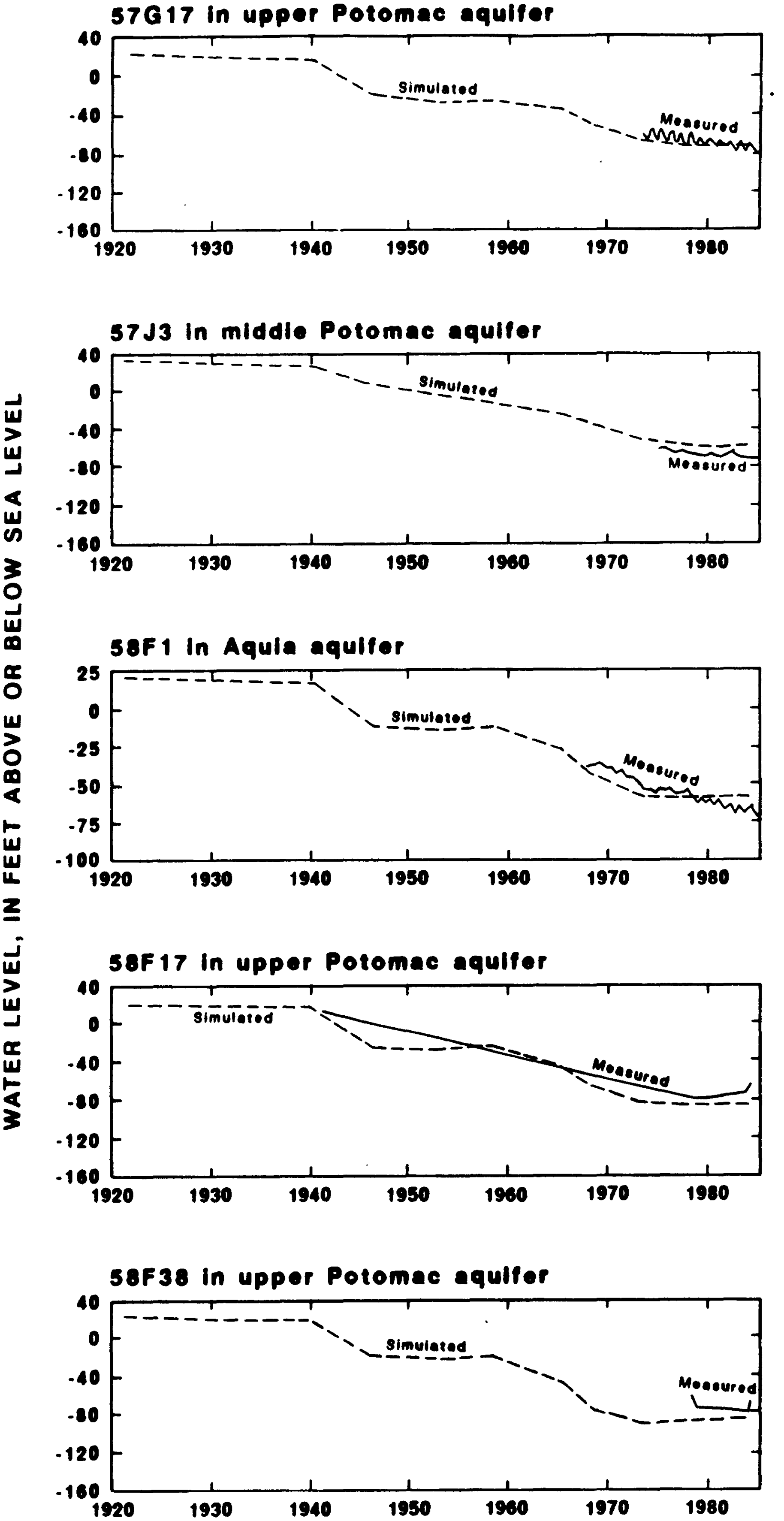


Figure 68. Continued

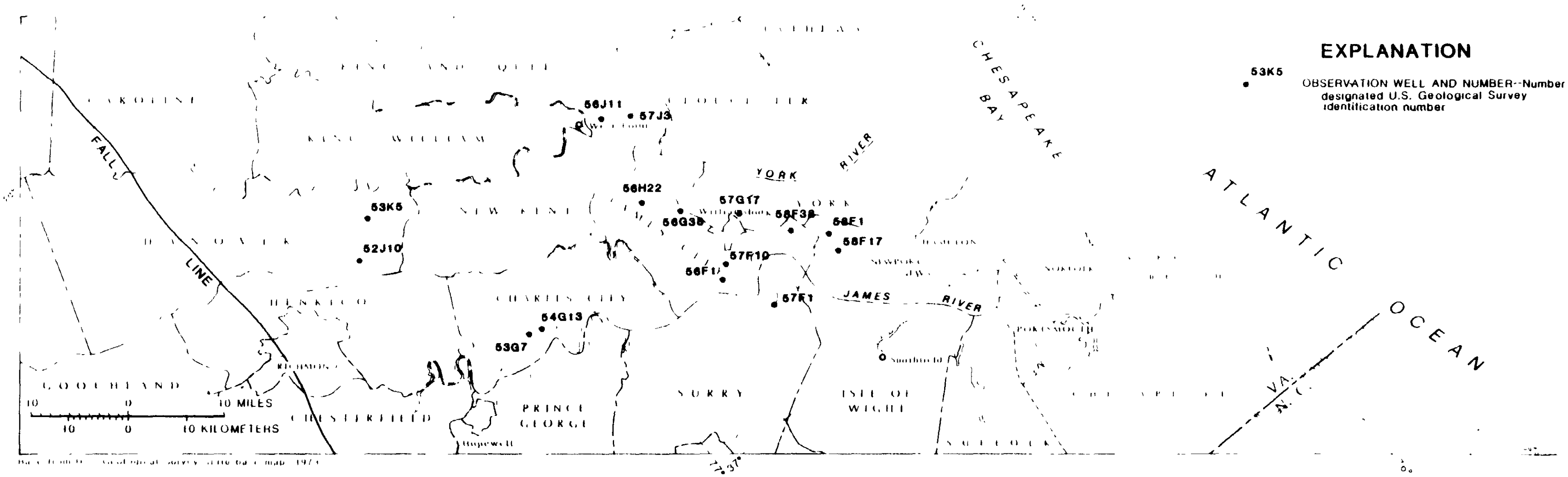


Figure 69. Location of selected observation wells comparing simulated to measured water levels.

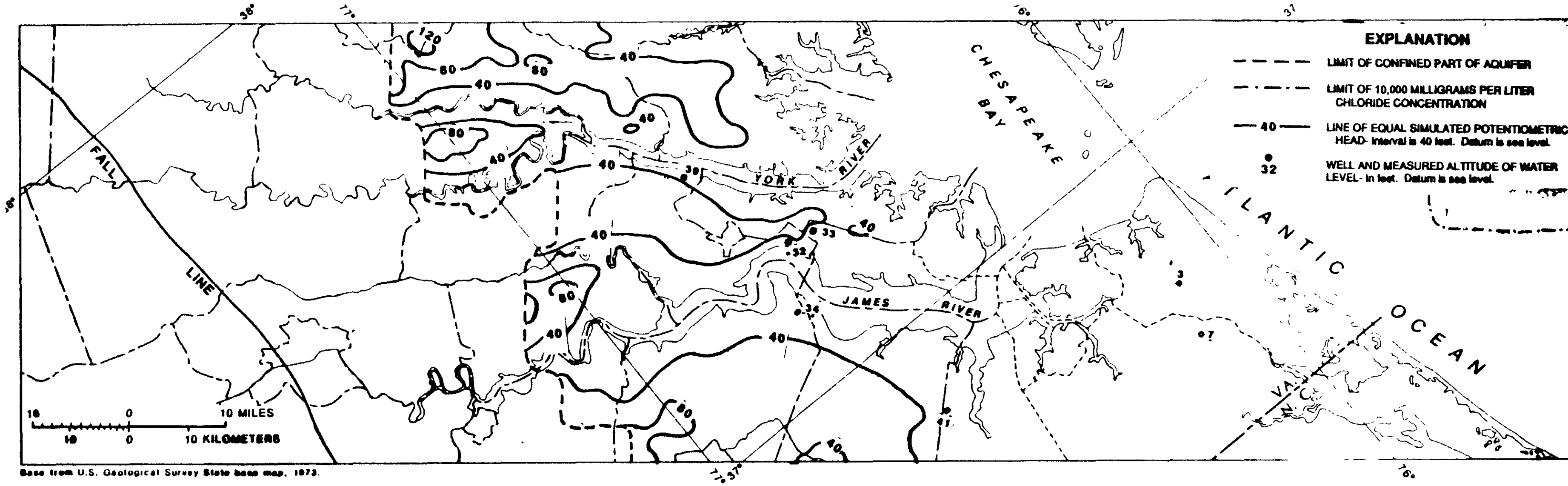


Figure 70. Potentiometric surface of Yorktown-Eastover aquifer, 1983.

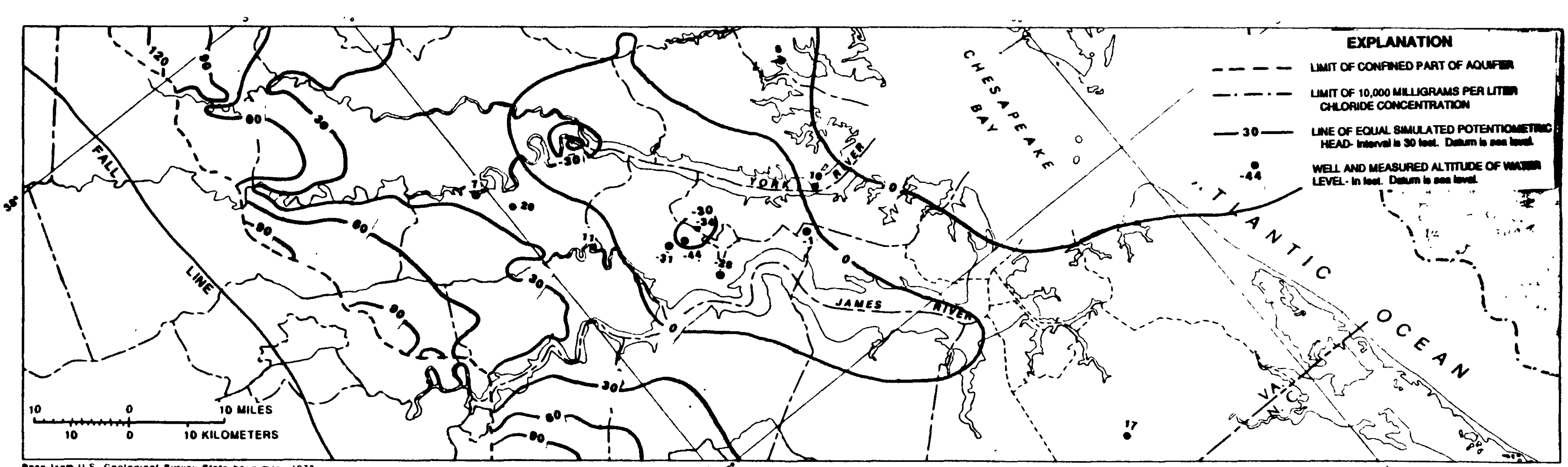


Figure 71. Potentiometric surface of Chickahominy-Piney Point aquifer, 1983.

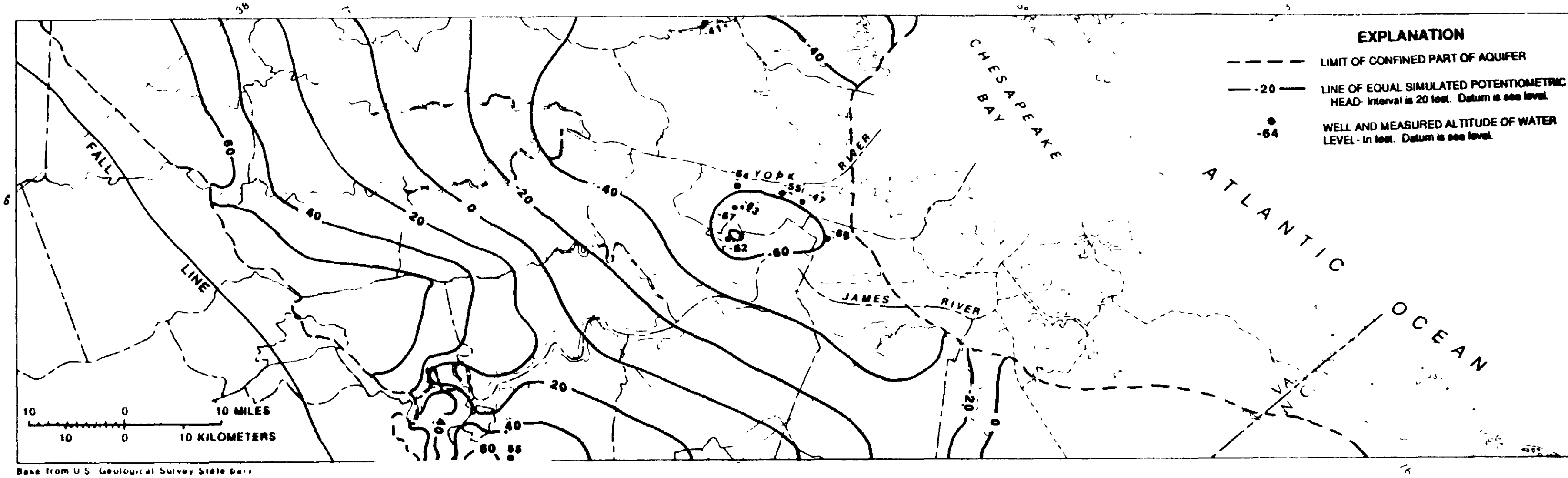


Figure 72. Potentiometric surface of Aquia aquifer, 1983.

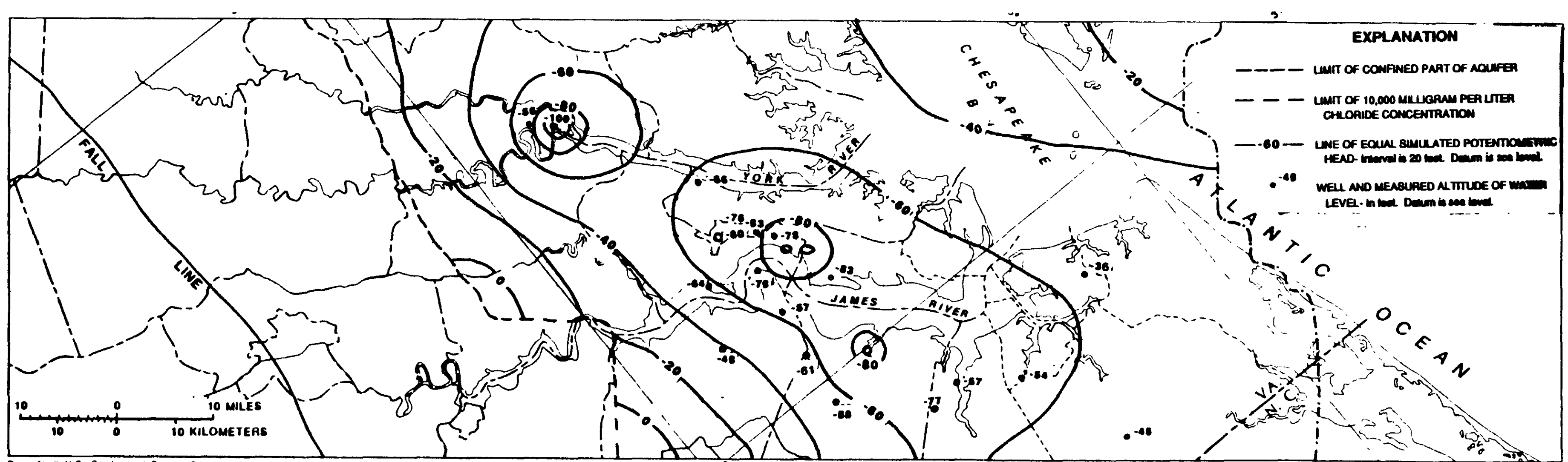


Figure 73. Potentiometric surface of upper Potomac aquifer, 1983.

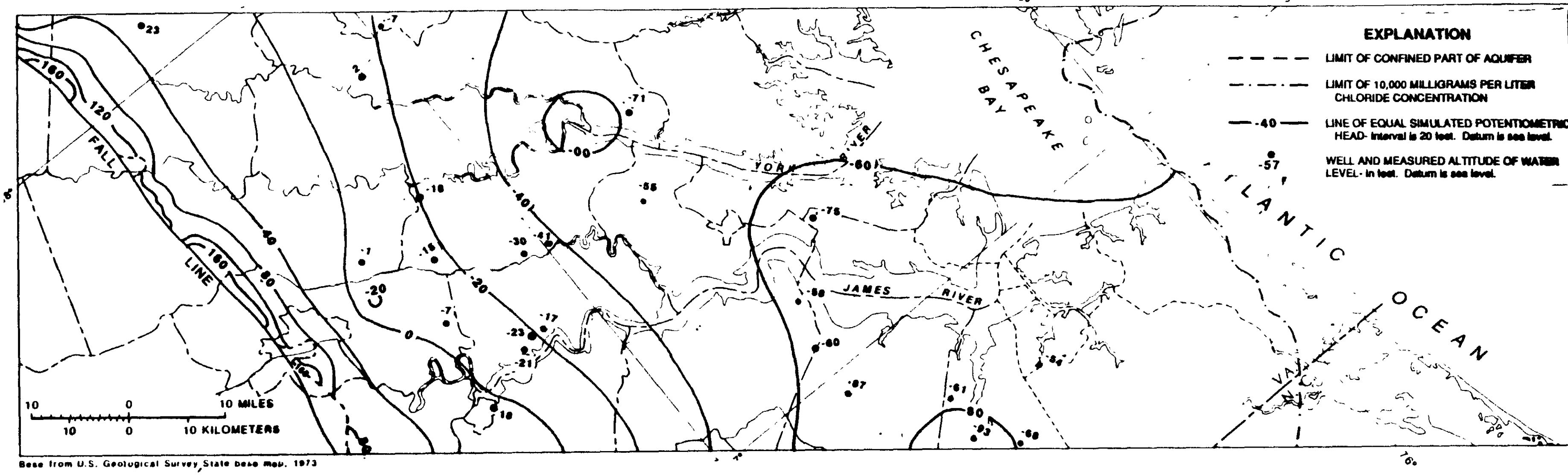


Figure 74. Potentiometric surface of middle Potomac aquifer, 1983.

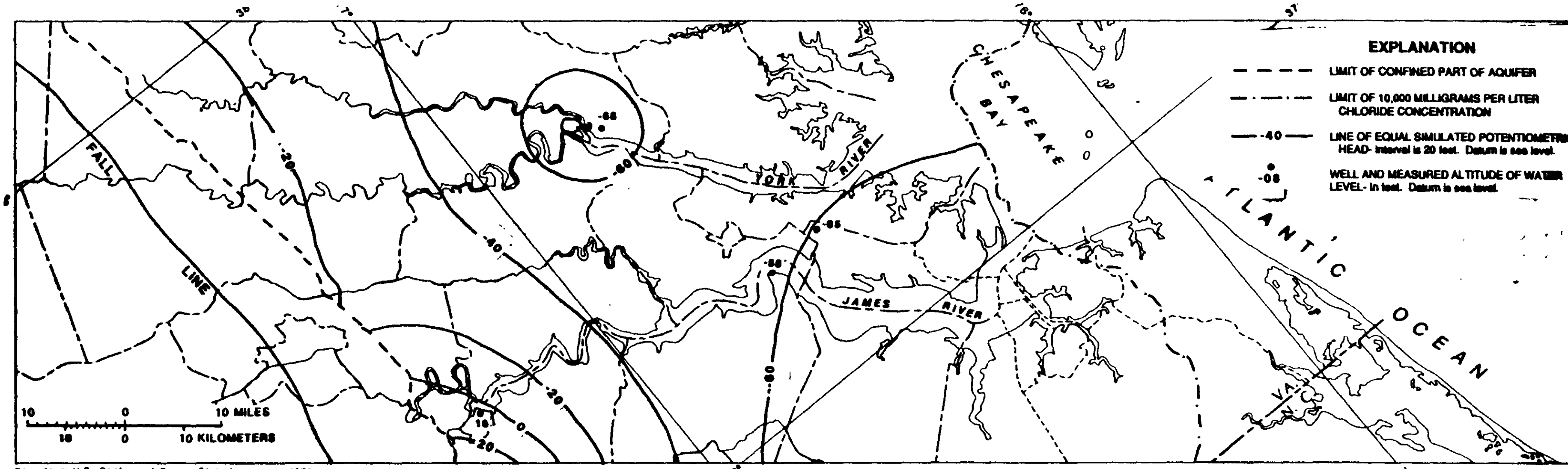


Figure 75. Potentiometric surface of lower Potomac aquifer, 1983.

agreement with simulated values. The deepest simulated water level, about 122 feet below sea level, was in the upper Potomac aquifer near the town of West Point (fig. 73). Comparison with prepumping flow maps indicates a substantial decline in water levels. The maximum water-level decline from prepumping flow conditions and the approximate location of the maximum decline are given for each aquifer in table 27. Areas of greatest water-level decline were centered at the major pumping centers. Maximum water-level decline, about 157 feet, was in the upper Potomac aquifer near the town of West Point (fig. 76). Other areas of substantial water-level decline coincided with other areas of concentrated ground-water withdrawal. These areas are (1) near the town of Smithfield, (2) in the eastern part of James City County, and (3) in the western part of the city of Newport News. Water-level gradients indicate that the regional flow of water in the deeper confined aquifers was toward major pumping centers. Comparison of simulated potentiometric surfaces and top of aquifer maps show that water levels in the Chickahominy-Piney Point aquifer are approaching the top of the aquifer near the town of West Point. Water levels were well above the top of respective aquifers elsewhere in the model area.

Model-computed water budgets for each pumping period are given in table 25. As the withdrawal of ground water increased, (1) ground-water flow to surface water was reduced, (2) surface-water flow to the ground water increased, and (3) lateral-boundary inflow and lateral-boundary outflow increased. Surface-water depletion, the sum of the reduced flow of water from the ground-water flow system to surface water and the induced flow of water to the ground-water flow system from surface water, replaced about 87 percent or 33 out of the 38 Mgal/d of water withdrawn in pumping period eleven (1981-83). Lateral-boundary flow, the net flow of water into the ground-water flow system through lateral-flux boundaries, accounted for about 12 percent or 4 Mgal/d. The remainder, about 1 percent, was replaced by water released from aquifer storage. The significance of surface-water depletion to lateral-boundary flow throughout the history of ground-water pumpage is shown in figure 77. Surface-water depletion accounted for the majority of water replacing that withdrawn after pumping period three (1940-45). Lateral-boundary flow begins to deviate from the trend in withdrawal during this same pumping period because large withdrawals from wells located outside the model area reduced lateral flow into the model area. Surface-water depletion, though negligible when compared to the total quantity of surface water, could be extremely important to local areas during periods of low-flow or drought conditions, because the quantity of ground water sustaining streamflow (baseflow) would be lessened. Also, increased surface-water recharge could pose serious water-quality problems in areas where aquifers are overlain by poor-quality surface water. Areas of simulated surface-water depletion greater than 0.4 in/yr from prepumping flow conditions and areas of simulated surface-water recharge to the ground-water flow system are shown in figure 78. Areas of greatest surface-water depletion coincide with major river systems in the western part of the model area. Here, the confined aquifers that supply much of the ground water withdrawn approach land surface and were incised by ancient and present-day rivers. Other areas of high surface-water depletion were centered at pumping centers that withdraw water from the Yorktown-Eastover aquifer in the southeastern part of the model area. The figure also shows that the majority of surface water recharging the ground-water flow system was from sources that contain salty water (Chesapeake Bay and Atlantic Ocean), but that this recharge was to parts of aquifers not used for freshwater supply and the rates of recharge were relatively slow.

Table 27--Maximum water-level decline from prepumped flow conditions for each aquifer, 1983

Aquifer	Maximum water-level decline (feet)	Approximate areal location
Yorktown-Eastover	7.1	City of Virginia Beach
Chickahominy-Piney Point	100.3	Town of West Point
Aquia	127.9	Town of West Point
Upper Potomac	156.8	Town of West Point
Middle Potomac	128.3	Town of Smithfield
Lower Potomac	125.6	Town of Smithfield

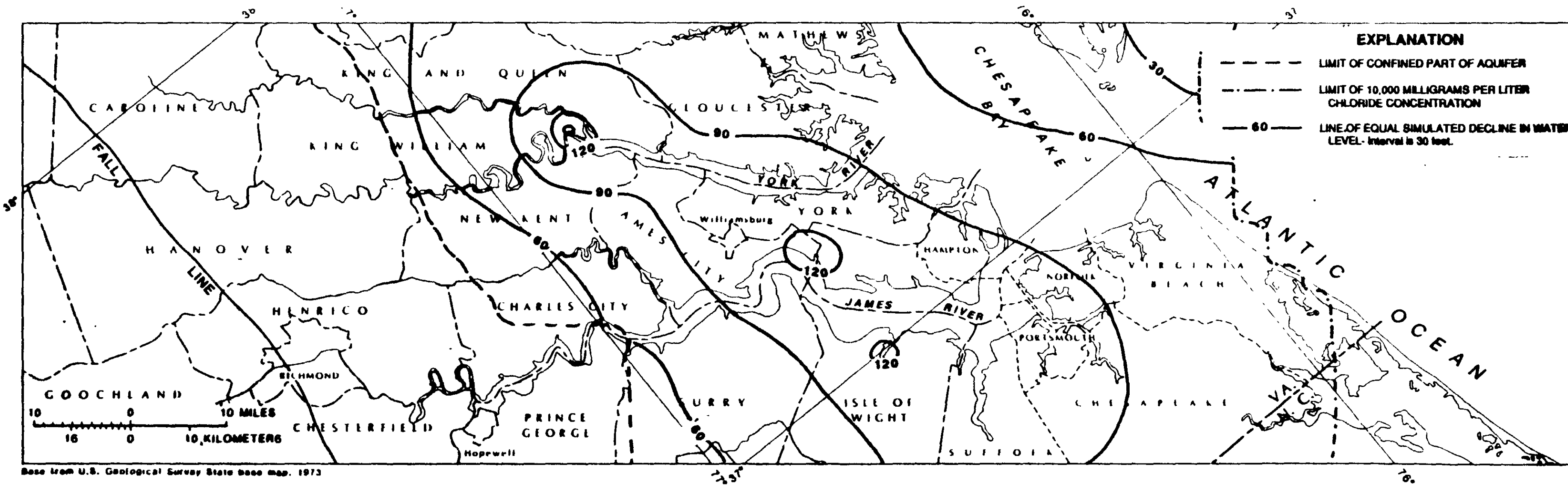


Figure 76. Water-level decline from prepumping-flow conditions in upper Potomac aquifer, 1983.

The withdrawal of ground water affected the flow of water into and out of the confined aquifers. Vertical leakage, the net flow into an aquifer through the overlying and underlying confining units (calculated from table 26), accounted for the majority of water replacing the water withdrawn. Lateral-boundary flow, the net flow across lateral-flow boundaries (calculated from table 24), accounted for most of the remaining water. A small percentage of water was replaced by water released from aquifer storage.

The significance of vertical leakage to lateral-boundary flow in the middle Potomac aquifer throughout the history of ground-water withdrawal is shown by figure 79. Vertical leakage was the major source replacing water withdrawn from the middle Potomac aquifer after pumping period three (1940-45). As in the overall model water budget, lateral-boundary flow to the middle Potomac aquifer begins to deviate from the trend in withdrawal during this same time period because withdrawal from wells located outside the model area reduced lateral-boundary flow into the aquifer. The direction of flow into and out of aquifers through the overlying confining unit in 1983 is shown in figures 80-85. Comparison with the prepumping flow maps indicates that the area of recharge into aquifers through the overlying confining unit increased from prepumping flow conditions; thus, more water was induced into the aquifers through the overlying confining unit.

Water-level declines from prepumping flow conditions and the inland lateral flow directions, suggested by 1983 simulated water-level gradients near the saltwater parts of the upper, middle, and lower Potomac aquifers, cause some question as to the validity of using a stationary no-flow boundary condition at the freshwater limit. Velocity, which is directly proportional

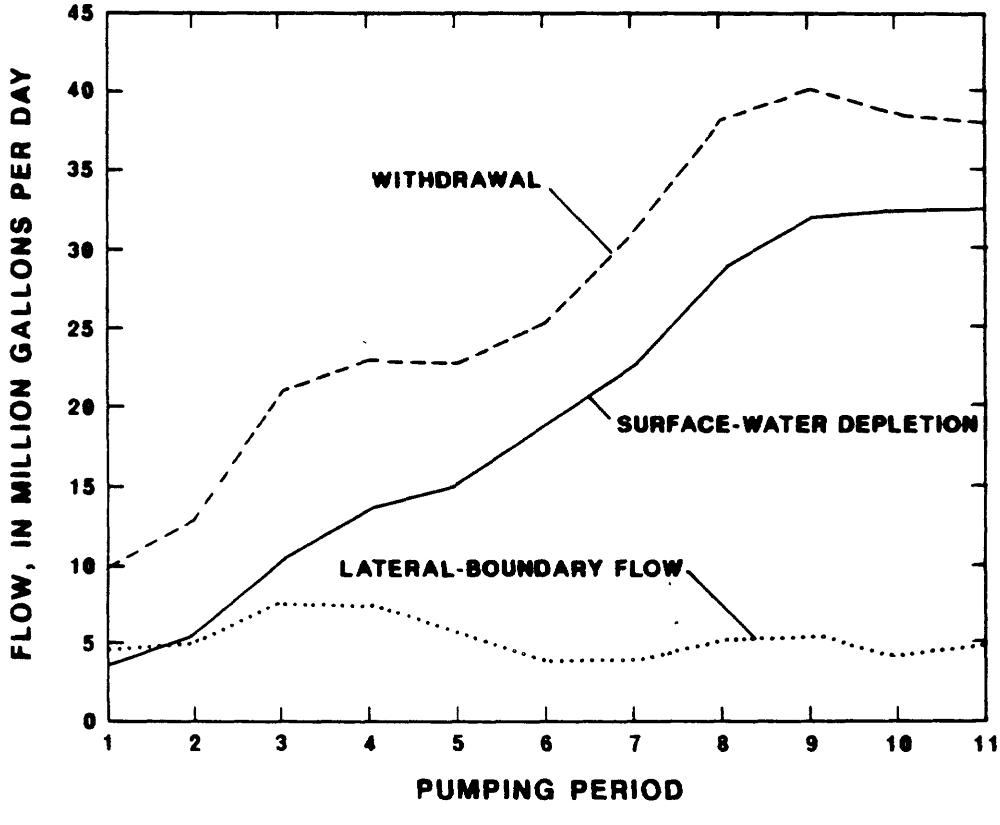


Figure 77. Change in major model water-budget flow components throughout history of ground-water development.

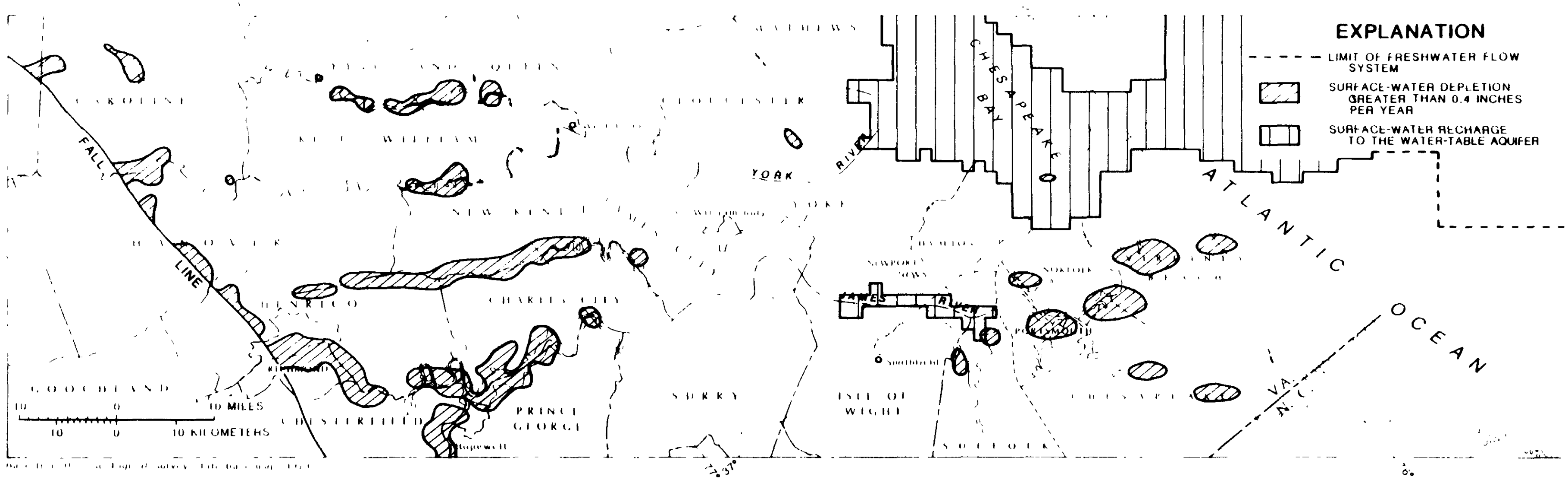


Figure 78. Areas of high surface-water depletion and surface-water recharge to ground-water flow system, 1983.

to the water-level gradient and the lateral hydraulic conductivity of the aquifer, can be calculated to determine the rate of ground-water movement. If it is assumed that chlorides move with ground water, then the magnitude of velocity can be used to determine the rate of inland movement of the freshwater limit. Because water-level declines have expanded out to the freshwater limit, simulated water levels are affected by the no-flow condition. Thus, computed velocities may be unrealistic. In order to test the validity of this boundary condition, the seaward limit of all aquifers was extended to the freshwater limit of the Yorktown-Eastover aquifer (fig. 62). Hydraulic characteristics for each grid block in the saltwater parts of aquifers and confining units were assumed equal to the furthest seaward grid block value in the corresponding grid column. The expanded grid allows velocities to be computed from simulated water-level gradients across the original freshwater limit. Velocities computed by this approach assume freshwater densities and, therefore, would be higher than true saltwater flow velocities.

Velocities for each grid block were calculated by substituting water-level gradients across adjacent grid blocks into Darcy's equation and dividing the resulting flow rate by an assumed porosity of 40 percent. Velocities calculated from simulated 1983 water levels were greatest in the middle Potomac aquifer (fig. 86). Magnitudes of velocity near the freshwater limit were less than 10 ft/yr (feet per year). Velocities of this magnitude would result in minimal inland movement of the freshwater limit relative to the spatial and temporal scale of simulation, but because of the effect of the no-flow condition at the freshwater limit, the expanded model was used to further analyze velocities in these areas. Water levels, simulated by the expanded model, were higher than those simulated in the calibrated model. For 1983,

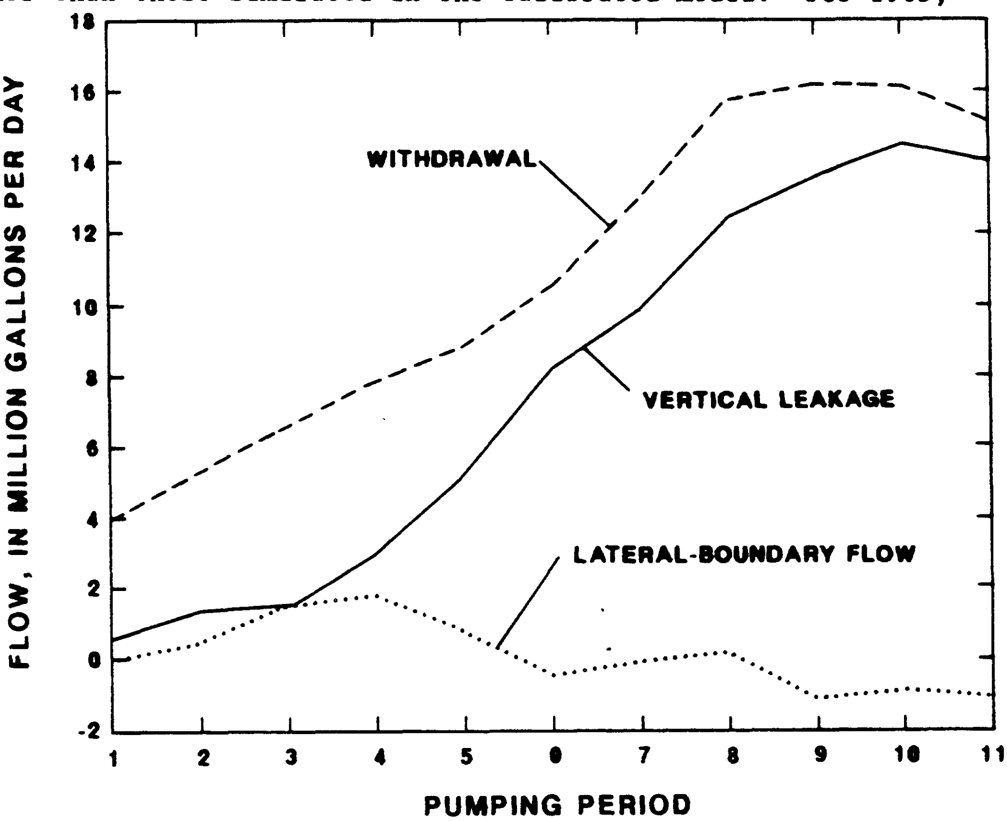


Figure 79. Change in water-flow components into and out of middle Potomac aquifer throughout history of ground-water development.

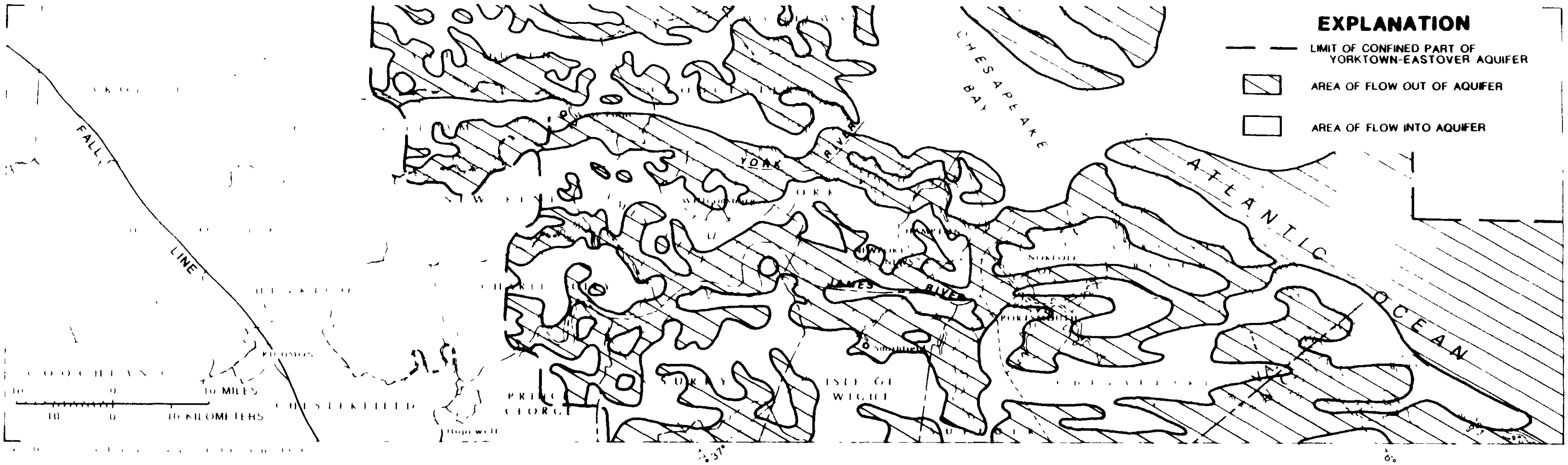


Figure 80. Direction of ground-water flow into and out of Yorktown-Eastover aquifer through overlying confining unit, 1983.

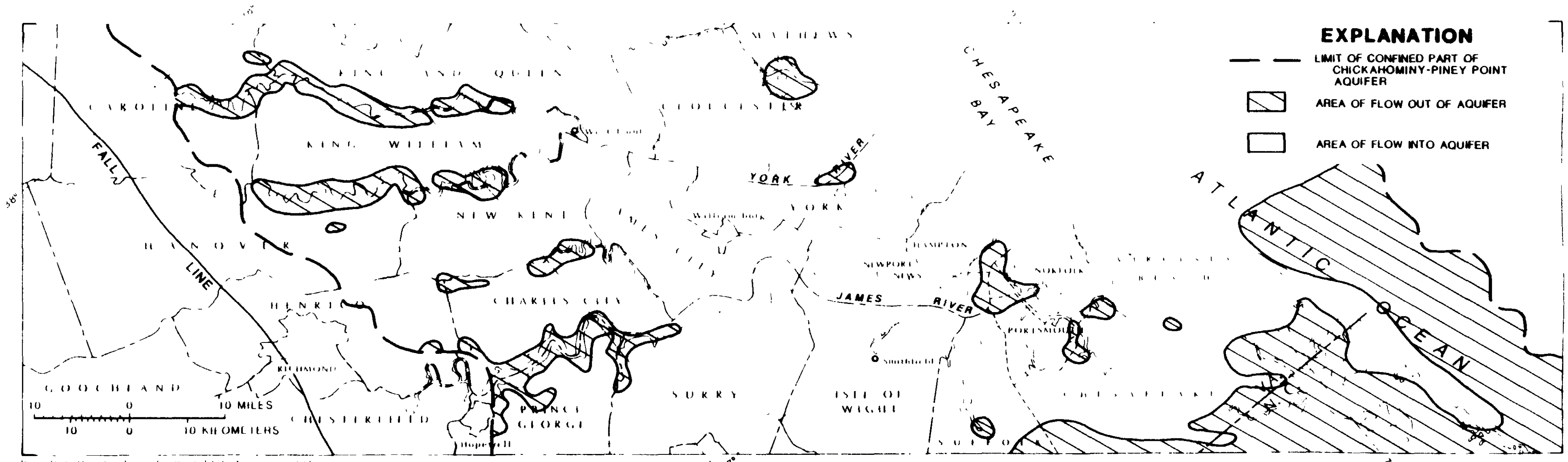


Figure 81. Direction of ground-water flow into and out of Chickahominy-Piney Point aquifer through overlying confining unit, 1983.

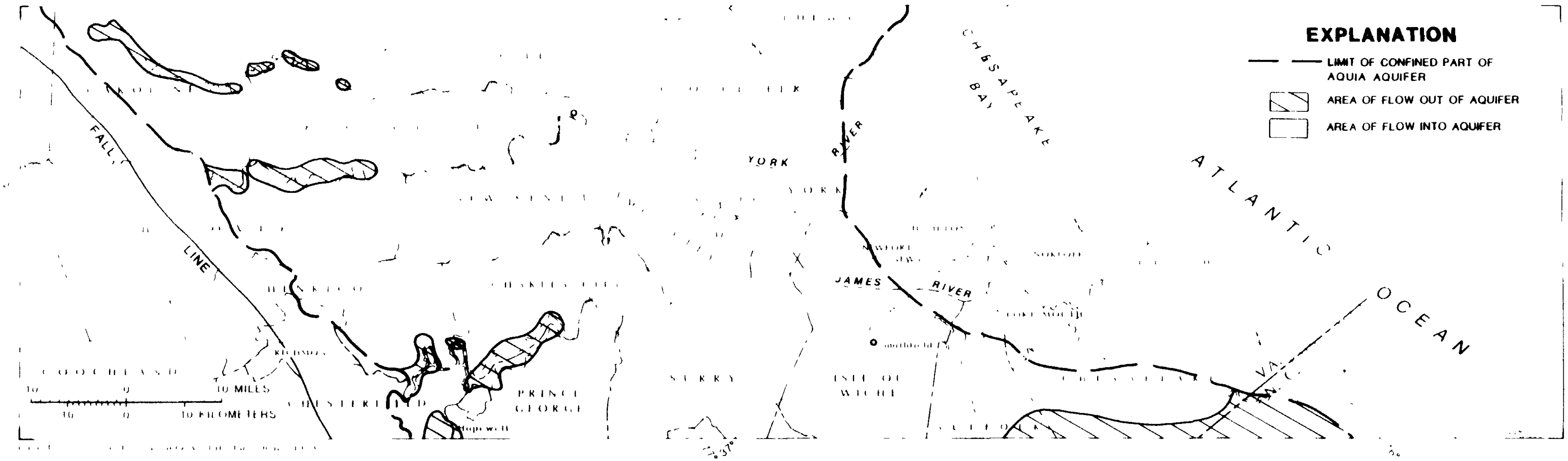


Figure 82. Direction of ground-water flow into and out of Aquia aquifer through overlying confining unit, 1983.

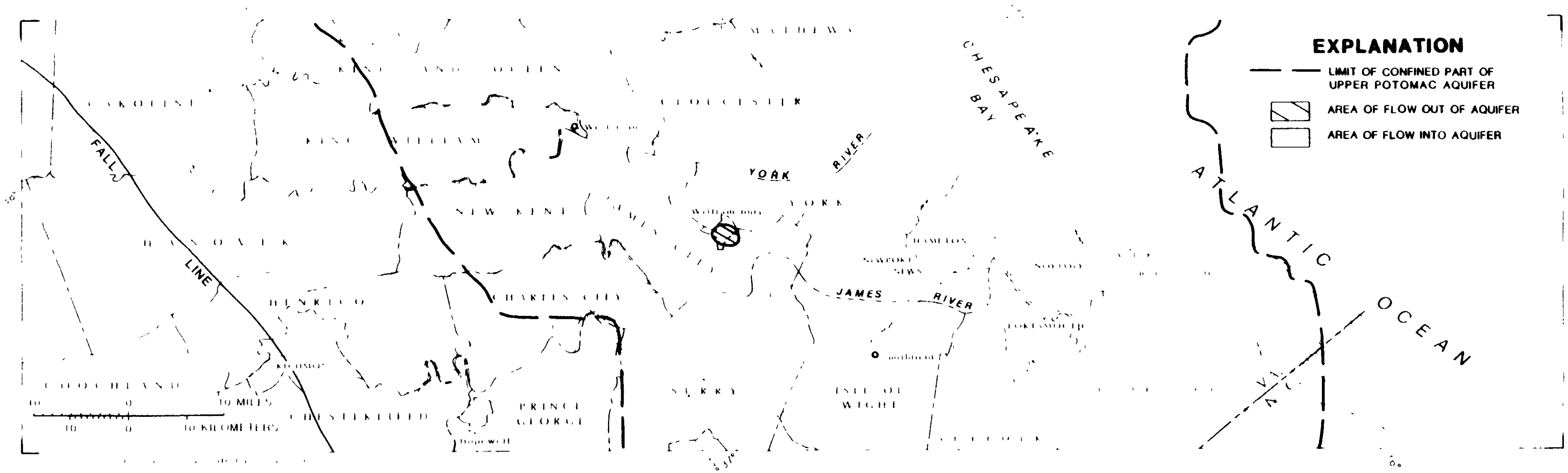


Figure 83. Direction of ground-water flow into and out of upper Potomac aquifer through overlying unit, 1983.

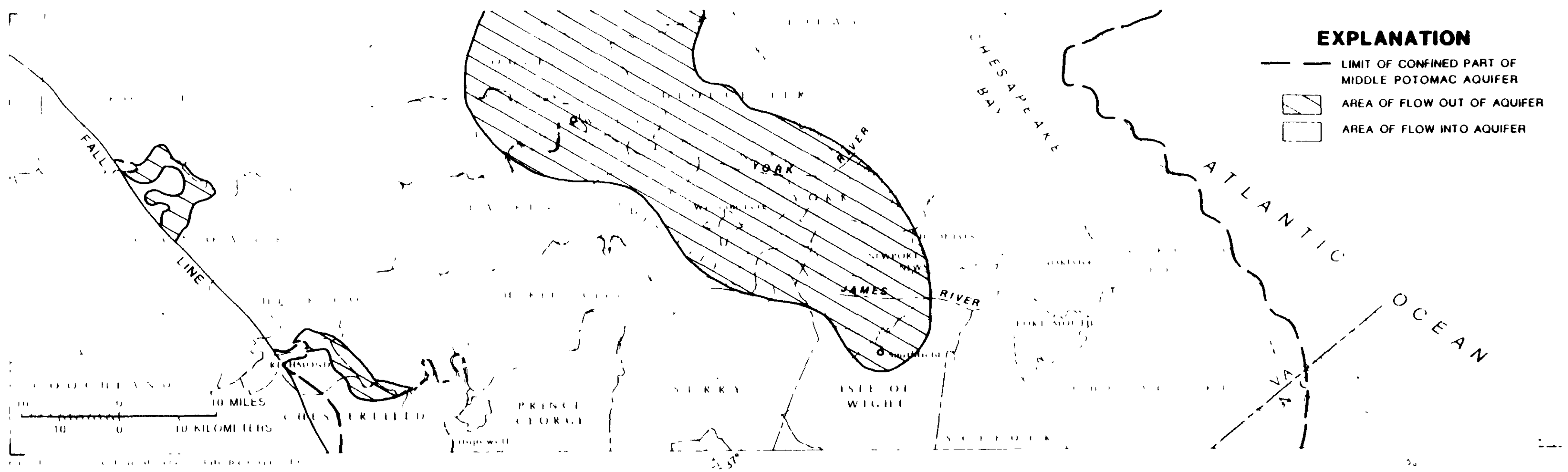


Figure 84. Direction of ground-water flow into and out of middle Potomac aquifer through overlying confining unit, 1983.

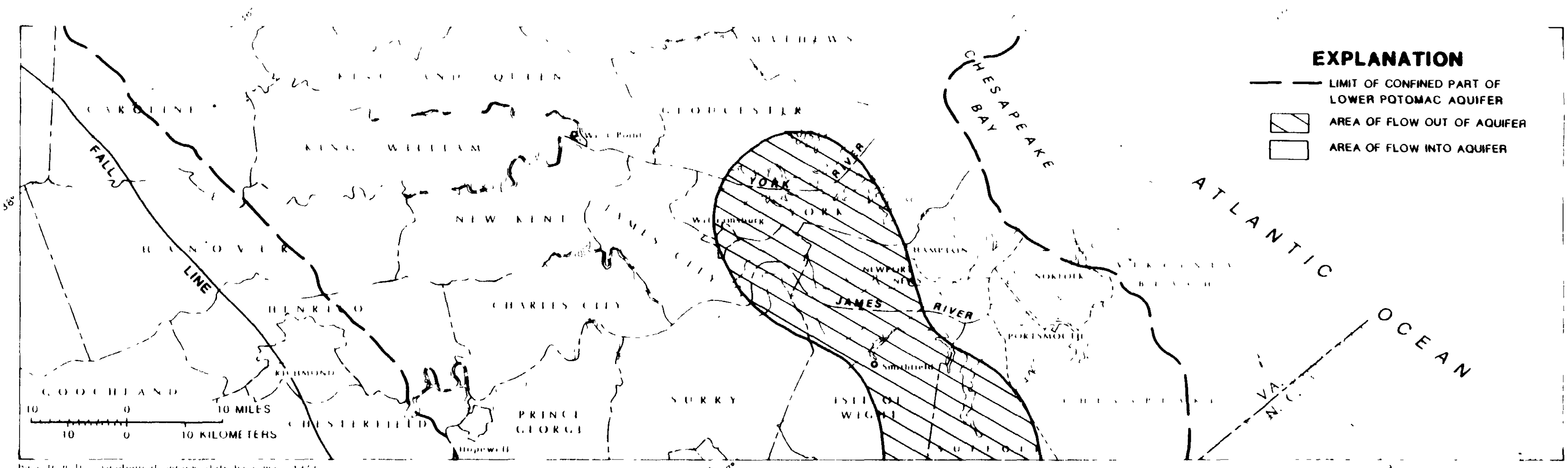


Figure 85. Direction of flow into and out of lower Potomac aquifer through overlying confining unit, 1983.

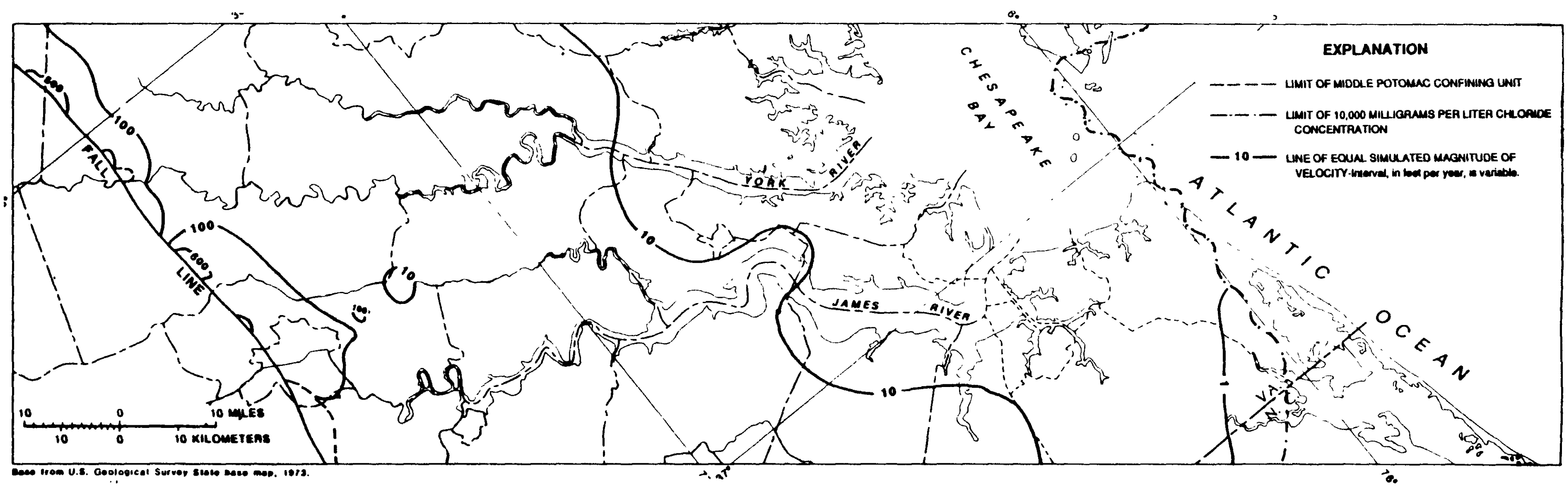


Figure 86. Magnitude of velocity of ground-water flow middle Potomac aquifer, 1983.

the maximum water-level difference along the freshwater limit was about 15 feet, but at pumping centers was less than 7 feet. Landward of the freshwater limit, velocity distributions for aquifers were similar in shape, but magnitudes were slightly higher than velocities calculated from calibrated water levels. Near the freshwater limit, magnitudes of velocity generally were less than 10 feet as in the calibrated simulation. The reason for the small differences between the two simulations in computed velocities near the freshwater limit is assumed to be because transmissivities decrease within the aquifers approaching this limit. Because of these small differences and slow rates, the stable positioning of a no-flow boundary at the freshwater limit is considered a sufficient approximation for the pumping conditions simulated.

Projected Effects of Increased Ground-Water Withdrawal

Four scenarios, referred to as projections I through IV, were simulated to forecast the effects of increased withdrawal on ground-water flow conditions in the York-James Peninsula. Each projection simulates a different increase in withdrawal. Projections are not intended to predict exact ground-water flow conditions at some future date but, instead, to provide information to evaluate the ground-water resource for meeting future water needs. Scenarios were simulated with the steady-state solution of the ground-water flow equation, thus results are indicative of flow under equilibrium conditions. Withdrawals simulated for each projection are listed by aquifer in table 28. Lateral-boundary fluxes across the northeastern and southwestern model boundaries, were computed from water-level gradients simulated by the regional model of Harsh and Laczniak (1986) and are given by aquifer, for each projection, in table 29. Aquifer and confining-unit characteristics and ground-water recharge were equivalent to those simulating pumping flow conditions.

Projection I--Doubling Ground-Water Withdrawal

Projection I doubled withdrawal from all wells located in the Coastal Plain of Virginia. Withdrawal from the model area was increased by 38 Mgal/d and totaled about 76 Mgal/d (table 28). A withdrawal of this magnitude is within the range projected by local planners to meet near future water needs of the peninsula (York-James Peninsula Project Advisory Committee Meeting, oral commun., 1985).

Projected water levels in the confined aquifers are shown as potentiometric surfaces in figures 87-92. The deepest projected water level, about 277 feet below sea level, was in the upper Potomac aquifer near the town of West Point (fig. 90). Water levels remained well above the top of respective aquifers, except in the Chickahominy-Piney Point aquifer (fig. 88) near the town of West Point. A decline in water level below the top of an aquifer would cause a change within the aquifer from confined to unconfined (water-table) flow conditions and would result in the dewatering of the aquifer material. Dewatering could cause land subsidence and decreases in aquifer yields. The model was not developed to simulate the effects of this change, but it does provide the knowledge needed to avoid its occurrence. Maximum water-level declines from 1983 flow conditions and the location of these declines are listed for each aquifer in table 30. The maximum water-level decline, about 155 feet, was in the upper Potomac aquifer near the town of West Point. The areal distribution of water-level decline from 1983 flow con-

Table 28--Withdrawal by aquifer for projections I, II, III, and IV

[Values in millions of gallons per day]

Aquifer	Pumping period	Projection			
	11	I	II	III	IV
Columbia	0.128	0.256	0.128	0.128	0.128
Yorktown-Eastover	1.403	2.806	4.406	1.403	4.406
Chickahominy-Piney Point	2.641	5.282	5.214	4.439	4.164
Aquia	1.003	2.006	1.685	1.685	1.410
Virginia Beach	.006	.012	.006	.006	.006
Upper Potomac	13.644	27.228	21.814	17.702	19.066
Middle Potomac	15.150	30.300	28.415	19.502	25.548
Lower Potomac	4.135	8.270	9.588	5.251	8.317
Total	38.110	76.220	71.253	50.110	63.042

ditions in the upper Potomac aquifer is shown in figure 93. The extent of water-level decline suggests that increasing withdrawal from established pumping centers is an impractical means of meeting future water needs.

The model-computed water budget is included in table 31. The difference between the projected and 1983 budget flow components is the change in ground-water inflows and outflows. Changes from 1983 flow conditions in surface-water depletion (sum of reduced flow to surface water and induced flow from surface water), lateral-boundary flow (net flow across lateral-flow boundaries), and withdrawal are compared for each projection in figure 94. About 85 percent of the additional 38 Mgal/d of water withdrawn in projection I was replaced by surface-water depletion. The remainder of water was replaced by lateral-boundary flow. The lesser quantity of water replaced by lateral-boundary flow was because large pumping centers located outside the model area reduced lateral flow into the model area. Areas of simulated high surface-water depletion (greater than 0.4 in/yr from prepumping conditions) and areas of surface-water recharge into the ground-water flow system are shown in figure 95. Both areas increased from 1983 flow conditions. Increased areas of surface-water recharge primarily were from sources containing salty water (Chesapeake Bay and Atlantic Ocean).

Table 29.--Lateral-boundary flux by aquifer for projections I, II, III, and IV

[Values, in millions of gallon per day, are not intended to imply accuracy to precision shown]

Aquifer	Pumping period			Projection											
	11			I			II			III			IV		
	In	Out	Net	In	Out	Net	In	Out	Net	In	Out	Net	In	Out	Net
Columbia	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09	0.42	0.51	-0.09
Yorktown-Eastover	2.18	1.22	.95	2.15	1.22	.93	2.18	1.22	.96	2.18	1.22	.95	2.18	1.22	.96
Chickahominy-Piney Point	.54	.27	.27	1.12	.27	.85	.80	.23	.57	.67	.24	.42	.70	.24	.47
Aquia	.87	.80	.07	1.36	.95	.42	1.11	.79	.32	.98	.80	.18	1.03	.78	.25
Virginia Beach	.18	.00	.18	.25	.01	.24	.20	.00	.20	.19	.00	.19	.19	.00	.19
Upper Potomac	3.06	.20	2.86	6.19	.27	5.93	4.65	.05	4.60	3.88	.12	3.76	4.10	.09	4.01
Middle Potomac	6.07	6.53	-.46	10.57	10.35	.21	10.63	4.72	5.91	8.02	5.87	2.16	9.18	5.10	4.08
Lower Potomac	2.44	2.72	-.28	5.31	5.31	.41	4.40	1.79	2.60	3.17	2.39	.79	3.79	2.00	1.79
Totals	15.76	12.25	3.52	27.36	18.46	8.90	24.39	9.31	15.07	19.51	11.14	8.37	21.59	9.94	11.66

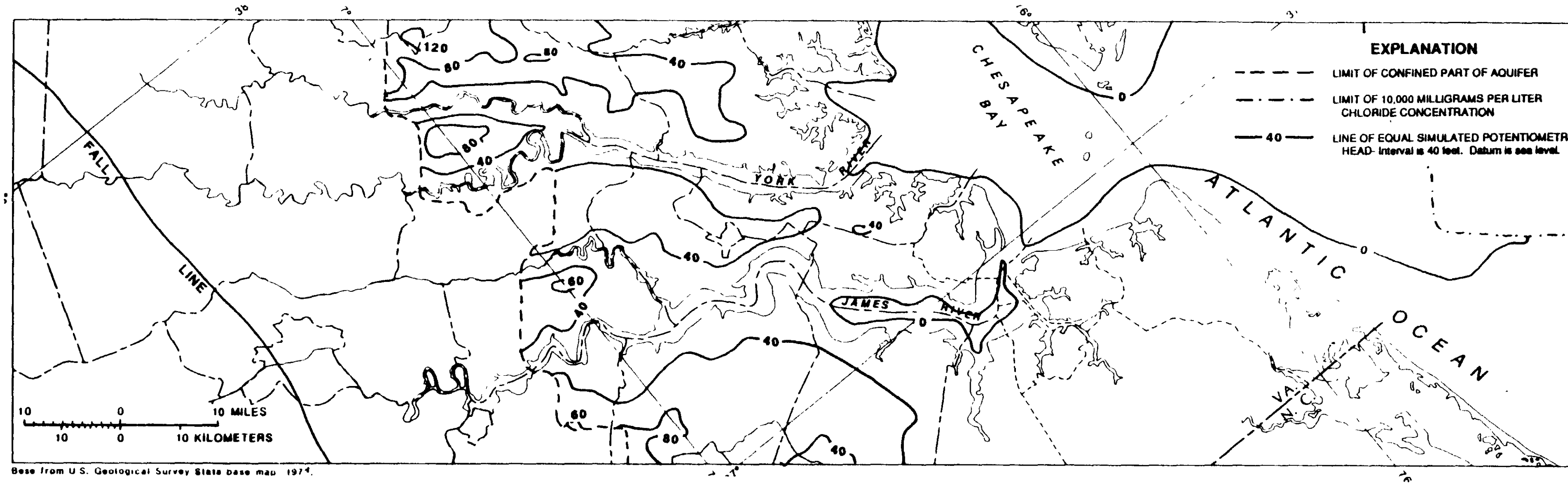


Figure 87. Potentiometric surface of Yorktown-Eastover aquifer, projection I.

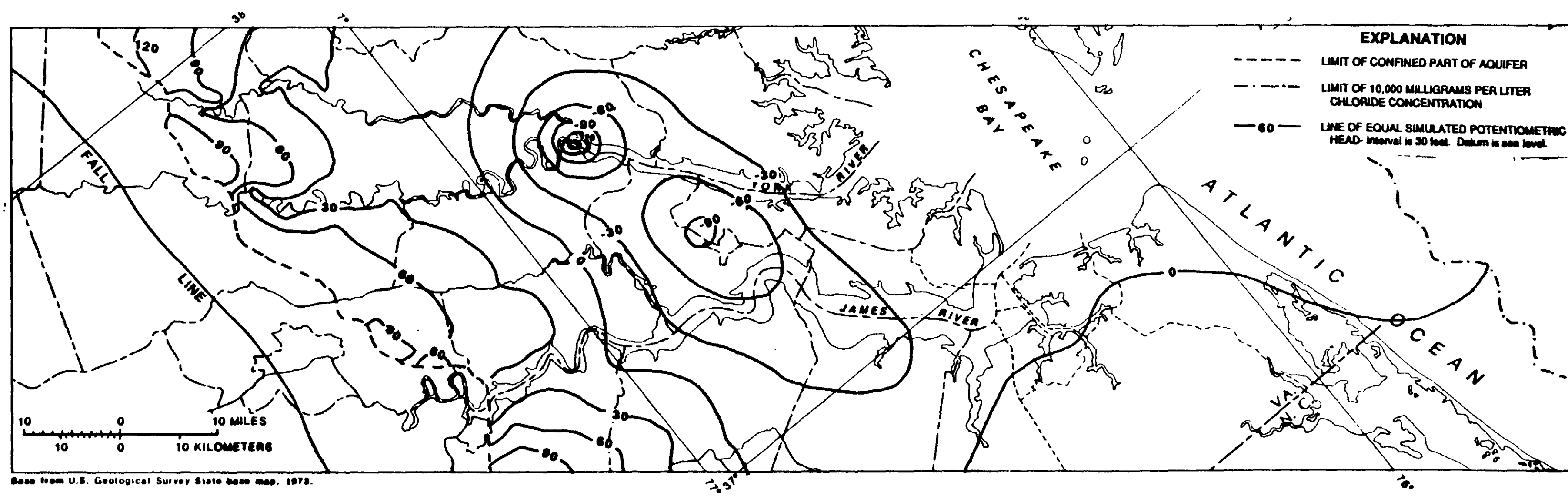


Figure 88. Potentiometric surface of Chickahominy-Piney Point aquifer, projection I.

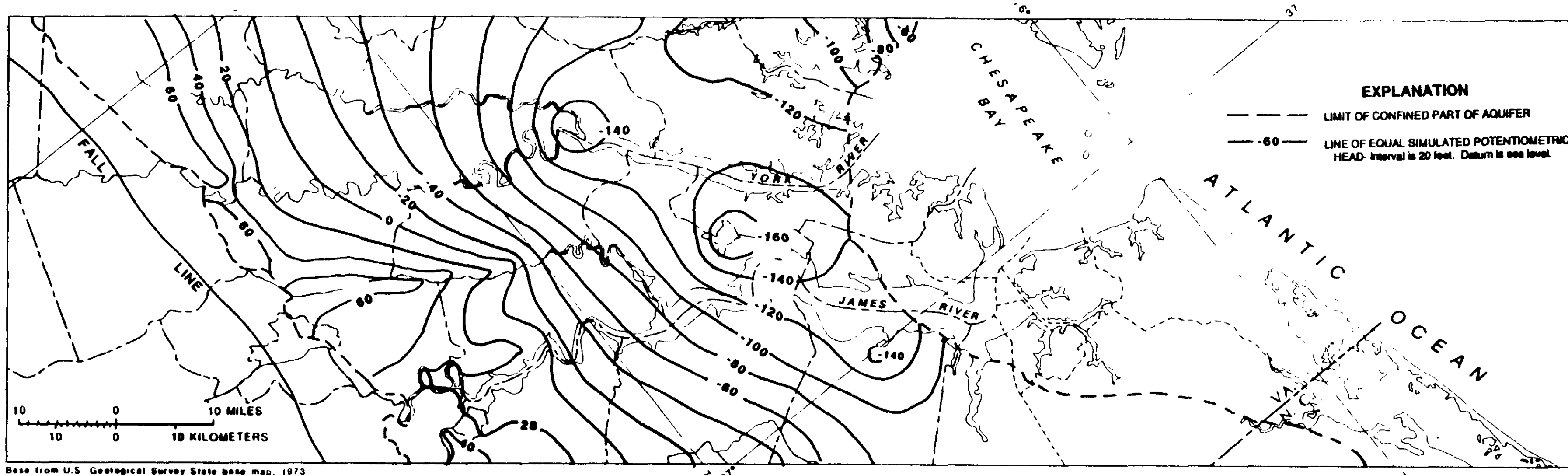


Figure 89. Potentiometric surface of Aquia aquifer, projection I.

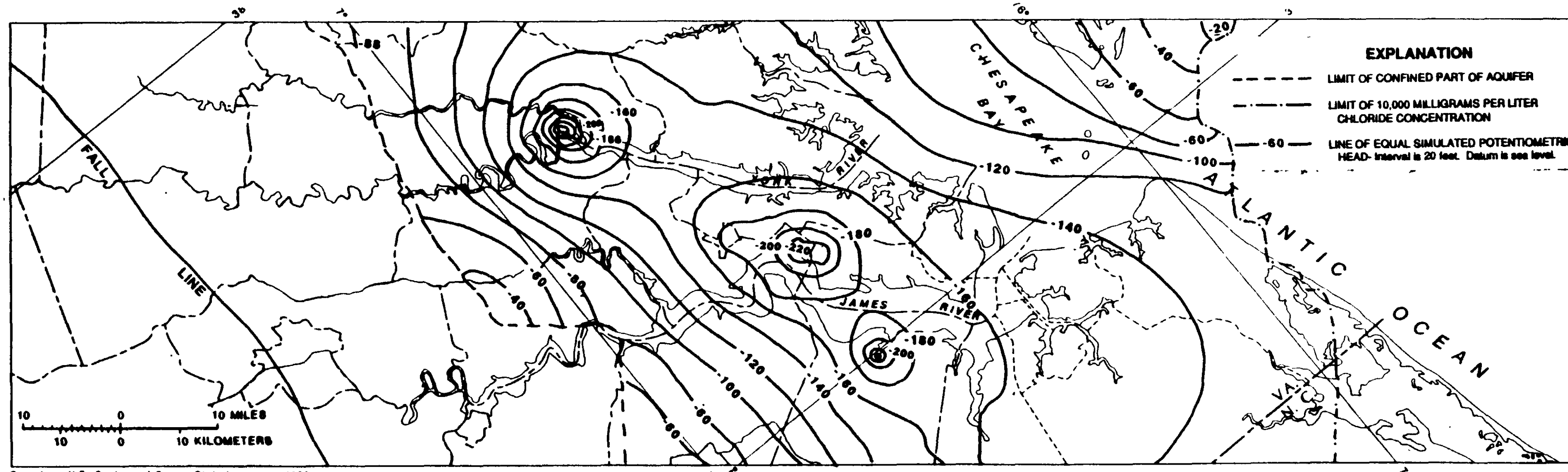


Figure 90. Potentiometric surface of upper Potomac aquifer, projection I.

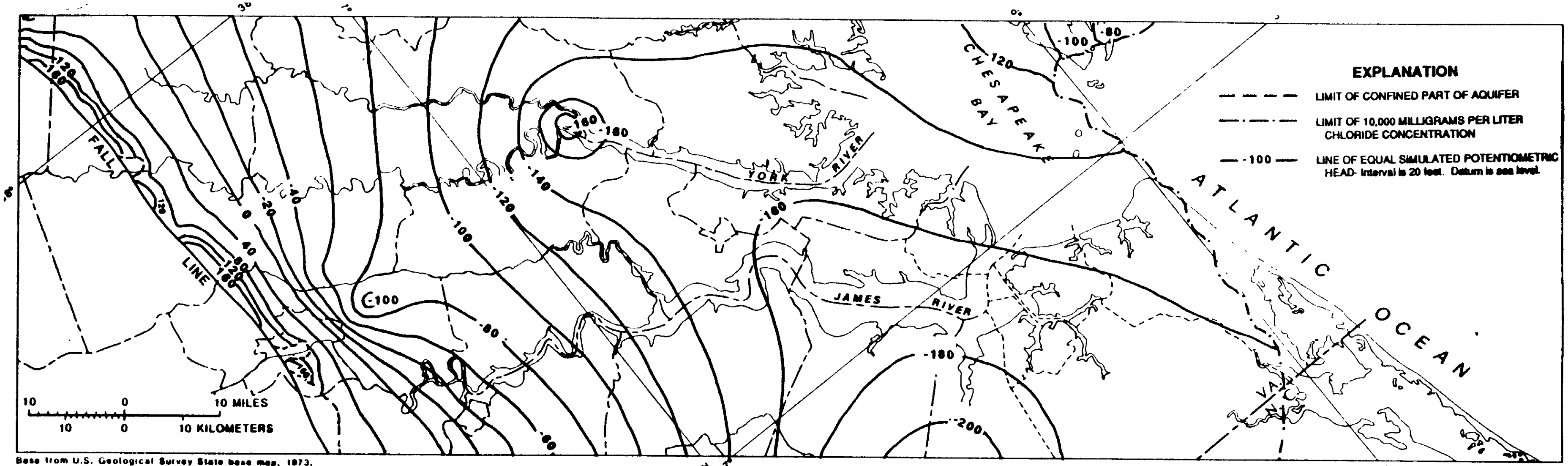


Figure 91. Potentiometric surface of middle Potomac aquifer, projection I.

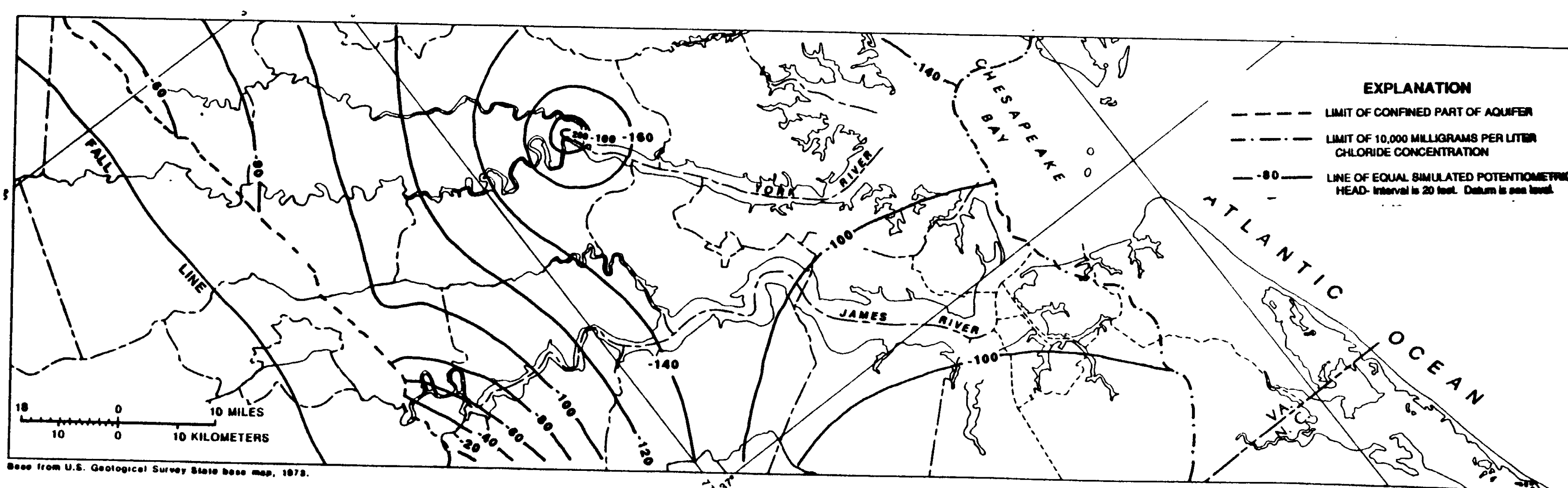


Figure 92. Potentiometric surface of lower Potomac aquifer, projection I.

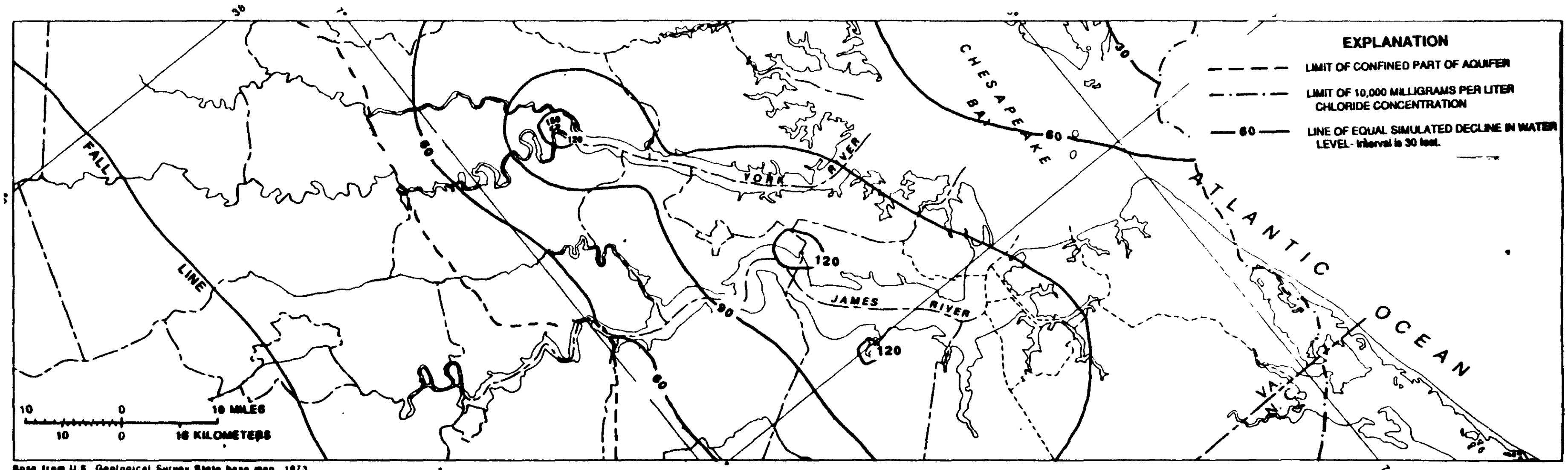


Figure 93. Water-level decline from 1983 flow conditions in upper Potomac aquifer, projection I.

Table 30.--Maximum water-level decline from 1983 flow conditions for each aquifer, projection I

Aquifer	Decline (feet)	Grid row	Grid column	Approximate areal location
Yorktown-Eastover	7.15	27	10	City of Richmond
Chickahominy-Piney Point	99.92	50	29	Town of West Point
Aquia	126.49	64	20	City of Williamsburg
Upper Potomac	155.23	49	30	Town of West Point
Middle Potomac	127.11	84	1	Town of Suffolk
Lower Potomac	122.61	50	30	Town of West Point

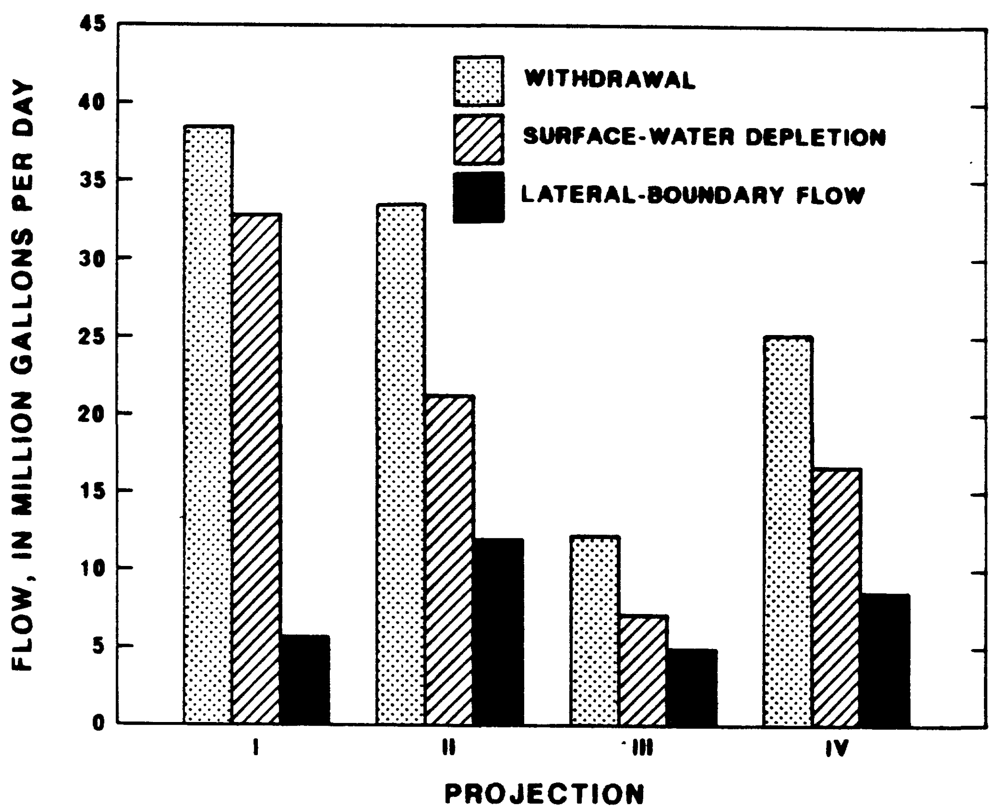


Figure 94. Change in major model water-budget flow components for projections I, II, III, and IV.

Table 31--Model-computed ground-water budget for projections I, II, III, and IV

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

	Pumping period	Projection			
	11	I	II	III	IV
SOURCES					
Water released from aquifer storage	0.21	0.00	0.00	0.00	0.00
Lateral-boundary inflow	15.76	27.36	24.38	19.51	21.59
Recharge from precipitation to water-table aquifer	3236.85	3236.85	3236.85	3236.85	3236.85
Flow from surface water	1.29	4.34	2.31	1.71	1.99
DISCHARGES					
Water entering aquifer storage	.00	.00	.00	.00	.00
Lateral-boundary outflow	12.25	18.22	9.00	11.01	9.61
Withdrawal from wells	38.11	76.22	71.26	50.12	63.06
Flow to surface water	3204.47	3175.20	3184.44	3197.88	3188.83

Footnote: Small error between sources and discharges is due to numerical truncation error of digital simulation.

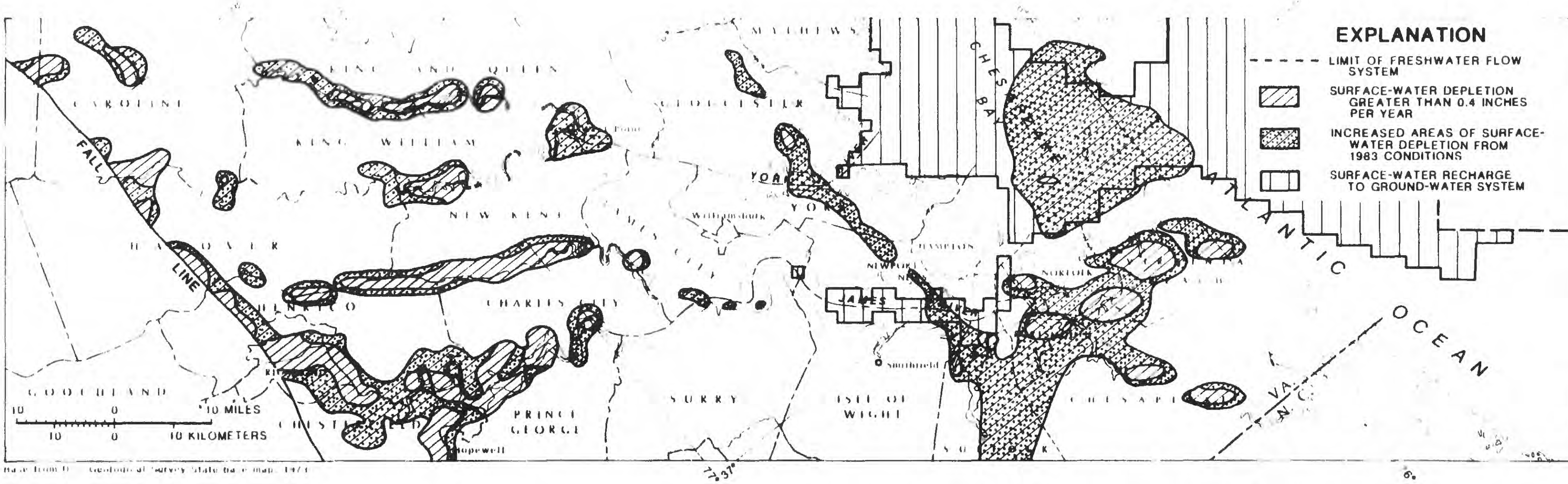


Figure 95. Areas of high surface-water depletion and surface-water recharge, projection I, II, III, and IV.

Flow of water into and out of aquifers through the overlying confining units are listed for each aquifer in table 32. Comparison with 1983 values shows that flow into all aquifers through the overlying confining units increased and that flow out of all aquifers, except the lower Potomac aquifer, decreased. Changes in vertical leakage (net flow into an aquifer through the overlying and underlying confining units) from 1983 flow conditions, lateral-boundary flow (net flow into or out of an aquifer across lateral-flux boundaries), and withdrawal for the middle Potomac aquifer are compared in figure 96. About 90 percent of the additional water withdrawn was replaced by vertical leakage and the remainder by lateral-boundary flow. The direction of flow into and out of each aquifer through the overlying confining unit is shown in figures 97-102. Comparison with 1983 maps gives the change in area of recharge into and discharge out of an aquifer through the overlying confining unit. The area of recharge into all confined aquifers increased from 1983 flow conditions.

Comparison of computed velocities with 1983 values indicates that magnitudes increased within all aquifers. As in the 1983 simulation, magnitudes were greatest in the middle Potomac aquifer (fig. 103). Because simulated water-level declines near saltwater parts of the Potomac aquifers increased from 1983 flow conditions, the validity of the no-flow condition at the freshwater limit again was tested by simulating equivalent flow conditions with the expanded model. Water levels simulated by the expanded model were higher by as much as 25 feet near the freshwater limit, but at pumping centers differences were less than 10 feet. Computed velocities also were slightly higher

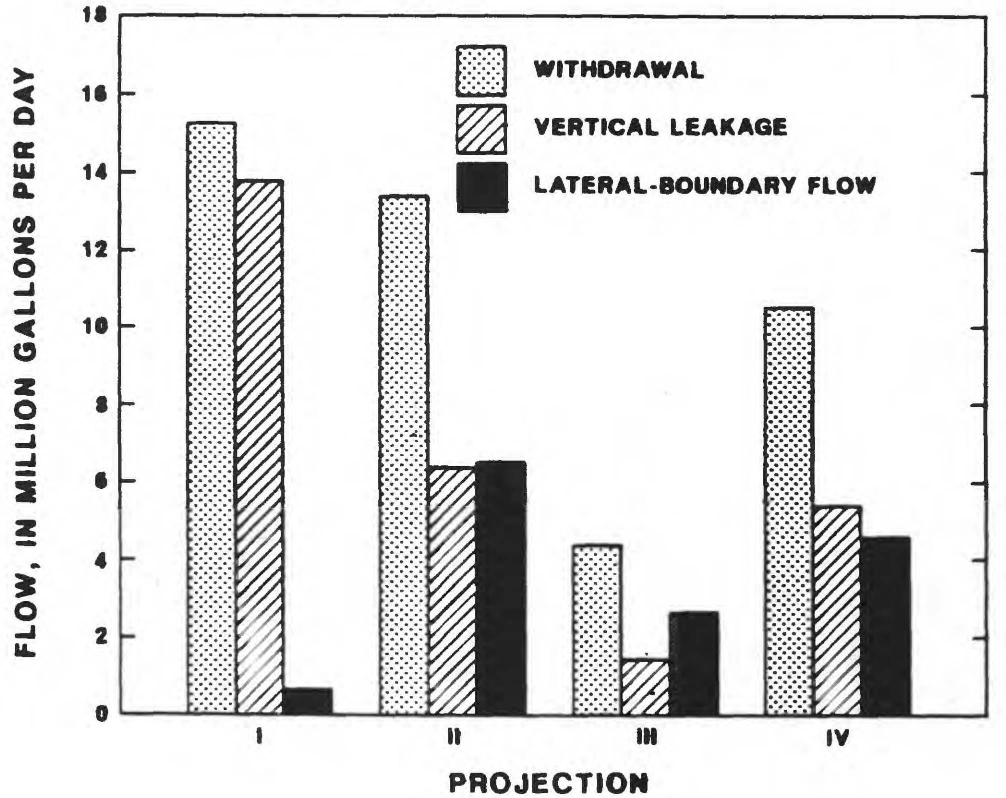


Figure 96. Changes in major water-flow components for projections I, II, III, and IV.

Table 32.--Flow into and out of aquifers through overlying confining units for projections I, II, III, and IV

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

Aquifer	Pumping period 11			Projection I			Projection II			Projection III			Projection IV		
	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net	Into	Out of	Net
Yorktown	60.73	47.45	13.28	72.11	39.62	32.49	68.61	43.06	25.55	63.14	45.30	17.84	66.84	44.31	22.53
Chickahominy-Piney Point	27.43	7.37	20.07	47.34	4.73	42.61	38.23	5.42	32.80	32.26	6.53	25.73	34.80	5.83	28.97
Aquia	18.63	1.74	16.89	35.36	.85	34.51	28.31	1.02	27.29	22.07	1.45	20.62	25.75	1.11	24.64
Virginia Beach	.55	.01	.54	1.46	.00	1.46	.75	.01	.74	.64	.01	.63	.69	.01	.68
Upper Potomac	14.52	.01	14.51	31.38	.01	31.37	22.55	.01	22.54	17.50	.01	17.49	20.24	.01	20.23
Middle Potomac	22.93	3.59	19.34	39.34	2.82	36.52	31.47	3.36	28.11	25.02	4.09	20.93	29.71	2.99	26.72
Lower Potomac	4.34	.15	4.19	7.92	.19	7.73	6.80	.14	6.66	4.73	.34	4.39	6.31	.08	6.23

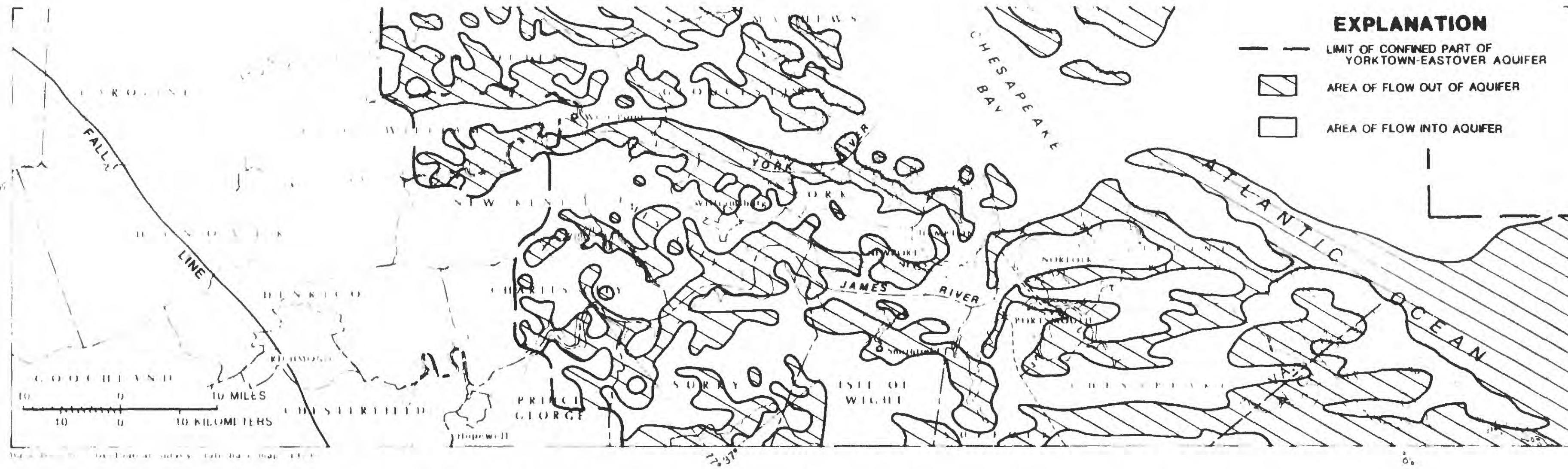


Figure 97. Direction of ground-water flow into and out of Yorktown-Eastover aquifer through overlying confining unit, projection I.

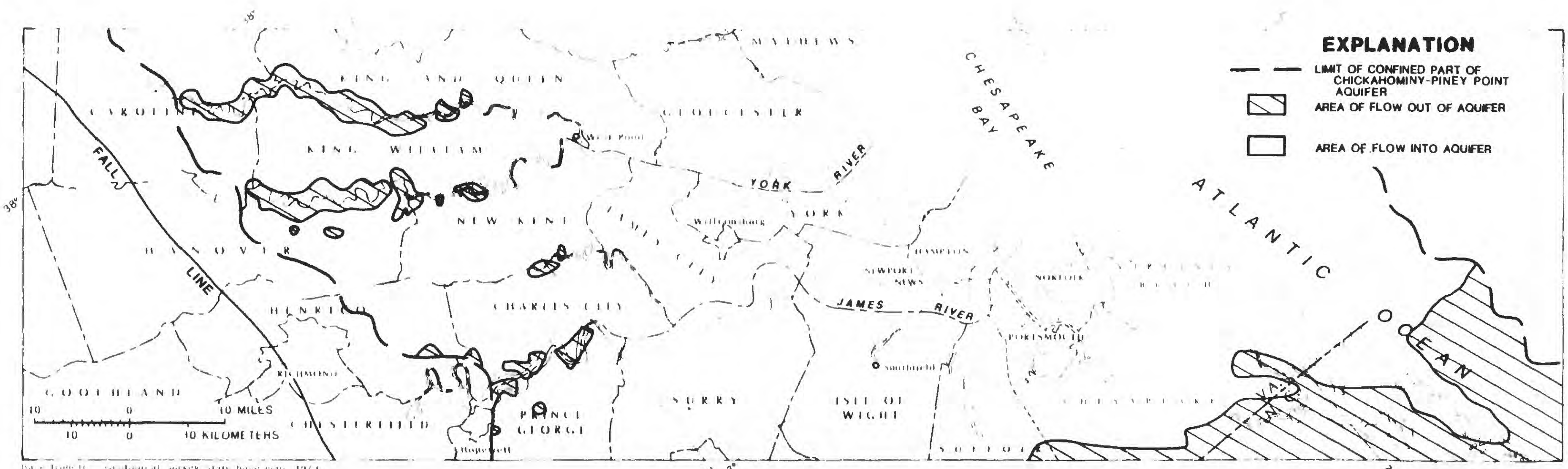


Figure 98. Direction of ground-water flow into and out of Chickahominy-Piney Point aquifer through overlying confining unit, projection I.

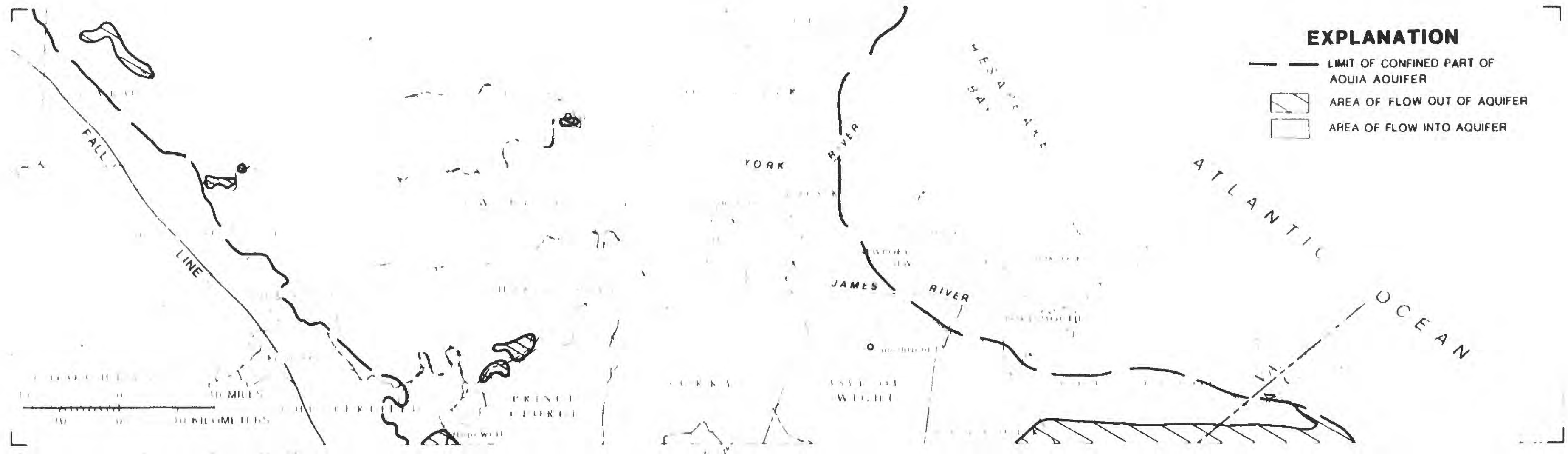


Figure 99. Direction of ground-water flow into and out of Aquia aquifer through overlying confining unit, projection I.

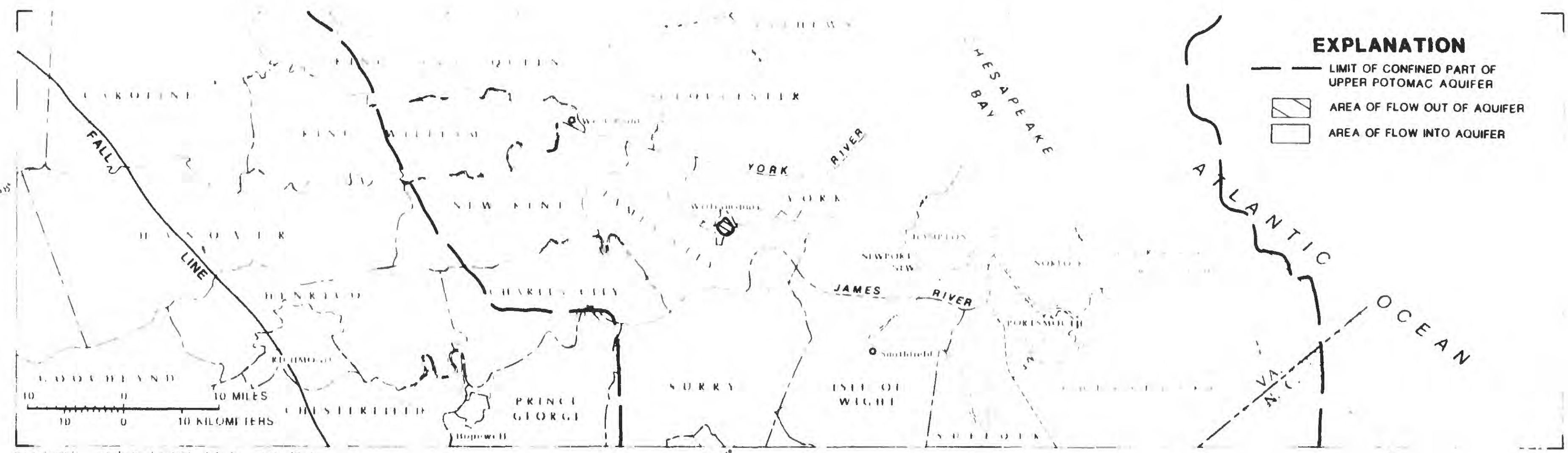


Figure 100. Direction of ground-water flow into and out of upper Potomac aquifer through overlying unit, projection I.

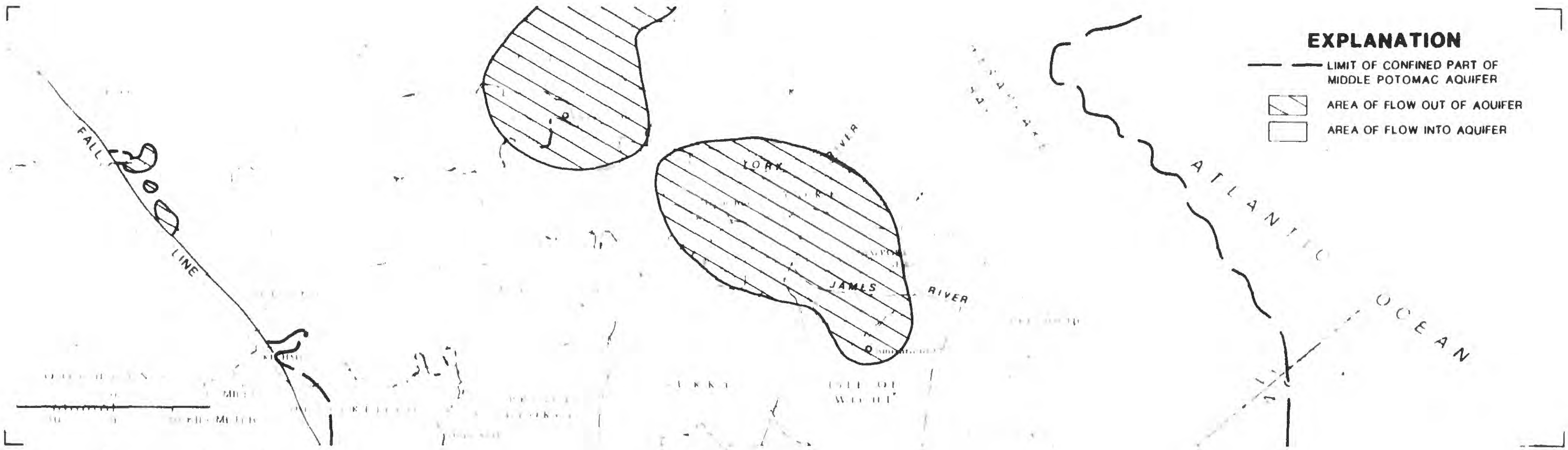


Figure 101. Direction of ground-water flow into and out of middle Potomac aquifer through overlying confining unit, projection I.

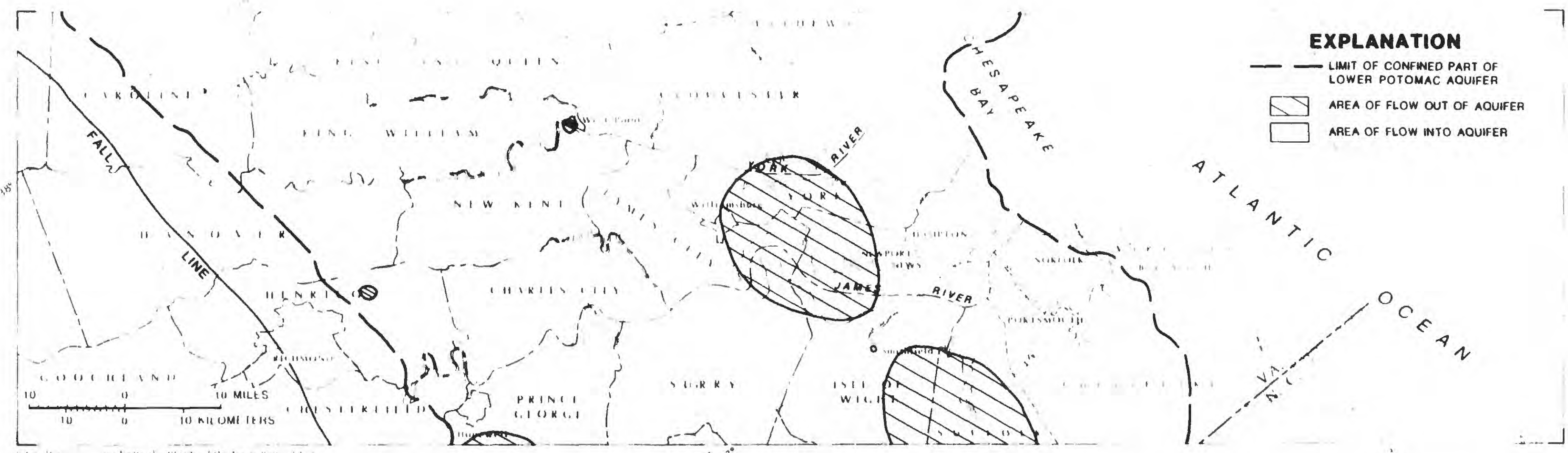


Figure 102. Direction of ground-water flow into and out of lower Potomac aquifer through overlying confining unit, projection I.

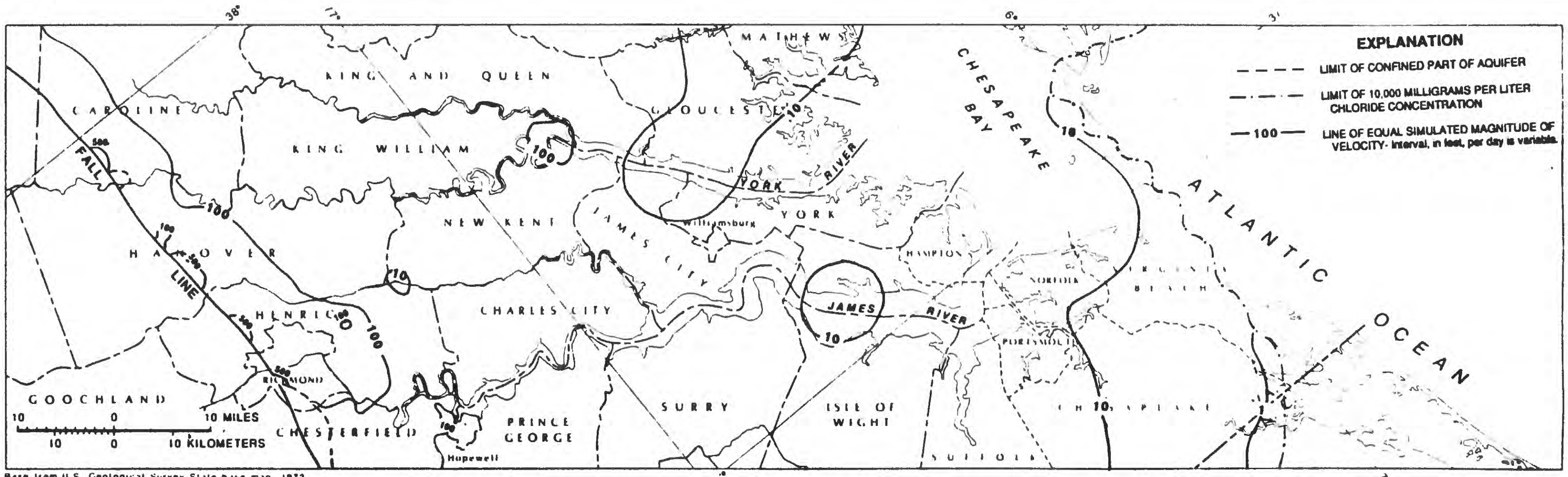


Figure 103. Magnitude of velocity of ground-water in middle Potomac aquifer, projection I.

than those computed by the calibrated model, but again magnitudes across the freshwater limit were less than 10 ft/yr. The small differences between the two simulations and the slow computed velocities again justified the use of the no-flow condition for this simulation, but it should be noted that as water levels decline near saltwater parts of aquifers this boundary condition becomes a less accurate representation of real hydrologic conditions. Because water-level declines near saltwater parts of aquifers were greater in this projection than in the following projections discussed in this report, the stable positioning of the no-flow boundary at the freshwater limit also was considered a sufficient approximation for these other projections.

Projection II--Future Municipal Water Needs

Projection II withdraws ground water to supply near-future municipal water needs of the peninsula. Future municipal water needs were estimated by local planners from the various localities participating in the study (York-James Project Advisory Committee Meeting, written commun., 1985). The locations of future withdrawal wells, as provided by local planners, are shown on figure 104. Withdrawal rates and source aquifers for wells are listed in table 33. Withdrawal from wells located outside the model area was not increased from 1983 flow conditions. Withdrawal from wells located within the model area was increased by about 33 Mgal/d and totaled about 71 Mgal/d (table 28). About 3 Mgal/d of water was withdrawn from the Yorktown-Eastover aquifer in eastern York County to evaluate this aquifer as a potential source for municipal water supply. The Yorktown-Eastover aquifer is the only local source of potable water available to this area.

Projected water levels in the confined aquifers are shown as potentiometric surfaces in figures 105-110. The deepest water level, about 202 feet below sea level, was in the upper Potomac aquifer in the western part of James City County (fig. 108). Water levels remained well above the top of respective aquifers, except in the Chickahominy-Piney Point aquifer near the town of West Point and in the Yorktown-Eastover aquifer in eastern York County. Major cones of depression developed in James City County. The maximum water-level decline from 1983 flow conditions and the approximate location of the maximum decline are listed for each aquifer in table 34. The maximum decline, about 155 feet, was in the upper Potomac aquifer in the western part of James City County. The areal distribution of water-level decline in the upper Potomac aquifer is shown in figure 111. The area of maximum water-level decline shifted away from the town of West Point to James City County. Water-levels declined a maximum of about 15 feet in the Yorktown-Eastover aquifer. This decline was a result of direct withdrawal from the aquifer in eastern York County. The severity of decline was much less than in other aquifers and the areal extent of the decline was relatively small, however, the impact probably would affect many more ground-water users than in other aquifers because of the large number of domestic users supplied by the aquifer. Also, because the top of the aquifer is less than 50 feet below sea level and water levels generally are less than 50 feet above sea level, large declines in water level could result in the dewatering of confined parts of the aquifer. Thus, it is unlikely that the Yorktown-Eastover aquifer would be a reliable source for meeting industrial or municipal water needs in eastern York County.

The model-computed water budget is listed in table 31. Changes from 1983 flow conditions in surface-water depletion, lateral-boundary flow, and

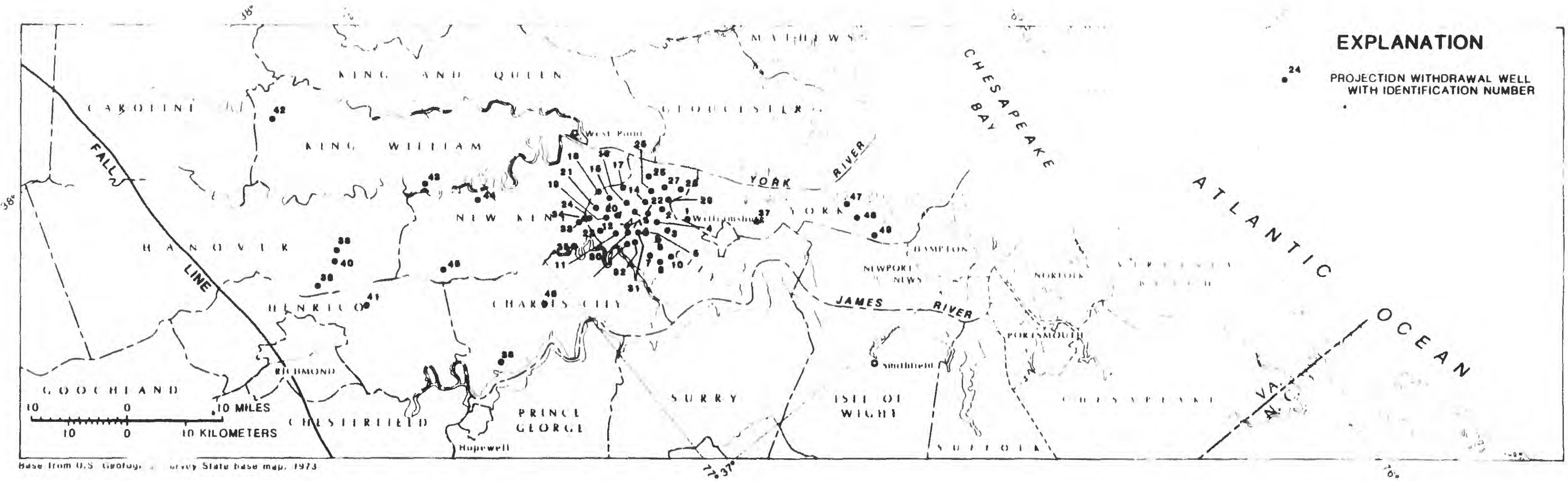


Figure 104. Location of projected ground-water withdrawals.

Table 33.--Additional withdrawal and source aquifers for projections II, III, and IV

[Mgal/d is million gallons per day]

Well number	[1]Source aquifer(s)	Projection (Mgal/d)		
		II	III	IV
1	7, 6, 3, 2	0.414	0.414	0.250
2	7, 6, 3, 2	.414	.414	.250
3	7, 6, 3, 2	.414	.414	.250
4	7, 6, 3, 2	.414	.414	.250
5	7, 3, 2, 1	.414	.414	.250
6	7, 6, 3, 2	.414	.414	.250
7	7, 3, 2, 1	.414	.414	.250
8	7, 6, 3, 2	.414	.414	.250
9	7, 3, 2, 1	.414	.414	.250
10	7, 6, 3, 2	.414	.414	.250
11	7, 3, 2, 1	.414	.414	.250
12	7, 3, 2, 1	.414	.414	.250
13	7, 3, 2, 1	.414	.414	.250
14	7, 3, 2, 1	.414	.414	.250
15	7, 3, 2, 1	.414	.414	.250
16	7, 3, 2, 1	.414	.414	.250
17	7, 3, 2, 1	.414	.414	.250
18	7, 3, 2, 1	.414	.414	.250
19	7, 3, 2, 1	.414	.414	.250
20	7, 3, 2, 1	.414	.414	.250
21	7, 3, 2, 1	.414	.414	.250
22	7, 3, 2, 1	.414	.414	.250
23	7, 3, 2, 1	.414	.414	.250
24	7, 3, 2, 1	.414	.414	.250
25	7, 3, 2, 1	.414	.414	.250
26	7, 6, 3, 2	.414	.414	.250
27	7, 6, 3, 2	.414	.414	.250
28	7, 6, 3, 2	.414	.414	.250
29	7, 6, 3, 2	.414	.414	.250
30	7, 3, 2, 1	1.500	0	.750
31	7, 3, 2, 1	1.500	0	.750
32	7, 3, 2, 1	1.500	0	.750
33	7, 3, 2, 1	1.500	0	.750
34	7, 3, 2, 1	1.500	0	.750
35	7, 3, 2, 1	.250	0	.750
36	2, 1	1.000	0	1.000
37	3	.500	0	.500
38	2, 1	.500	0	.500
39	2, 1	1.000	0	1.000
40	2	1.000	0	1.000
41	2, 1	1.000	0	1.000
42	2, 1	1.000	0	1.000
43	3, 2, 1	1.000	0	1.000
44	3, 2, 1	1.000	0	1.000
45	2, 1	1.000	0	1.000
46	3, 2, 1	1.000	0	1.000
47	9	1.000	0	1.000
48	9	1.000	0	1.000
49	9	1.000	0	1.000

[1]Explanation

9 Yorktown-Eastover aquifer
7 Chichahominy-Piney Point aquifer
6 Aquia aquifer
3 Upper Potomac aquifer
2 Middle Potomac aquifer
1 Lower Potomac aquifer

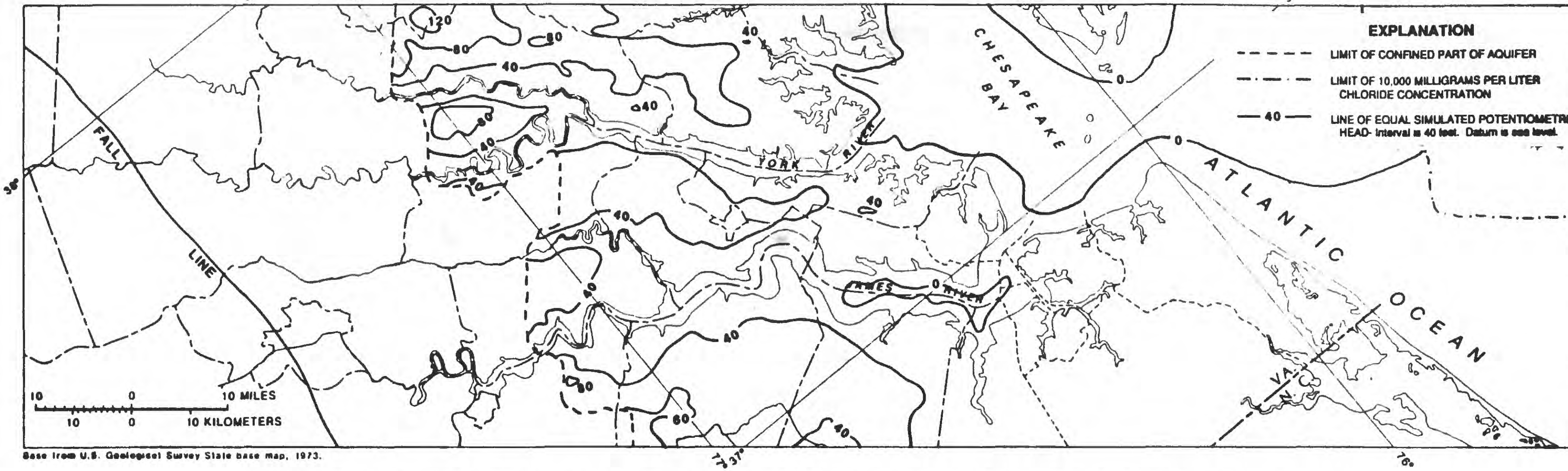


Figure 105. Potentiometric surface of Yorktown-Eastover aquifer, projection II.

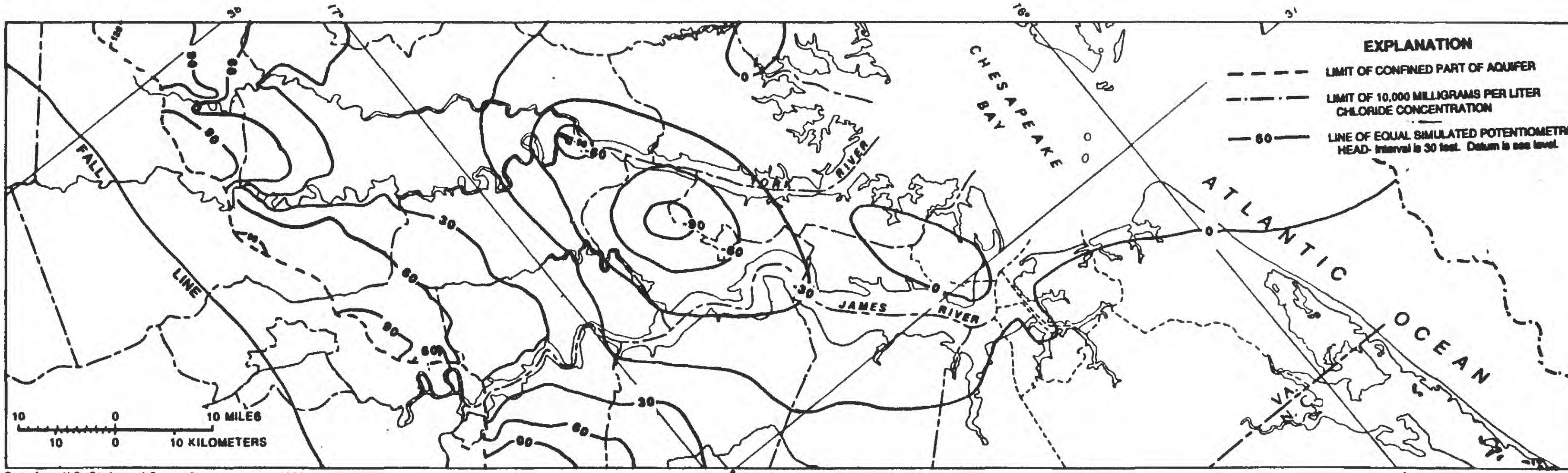
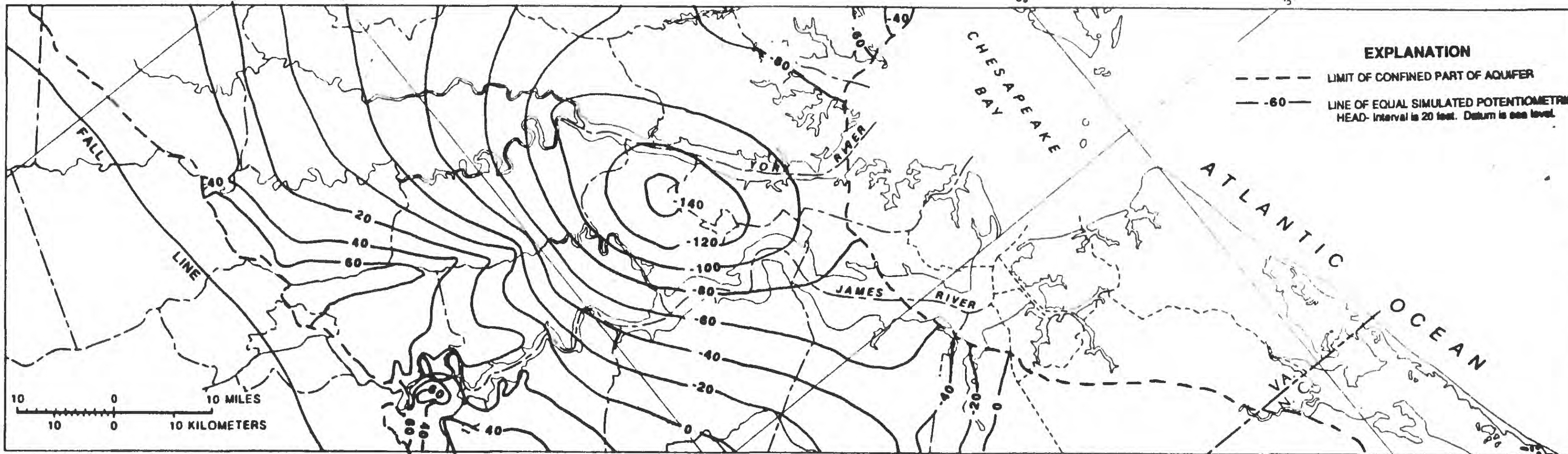
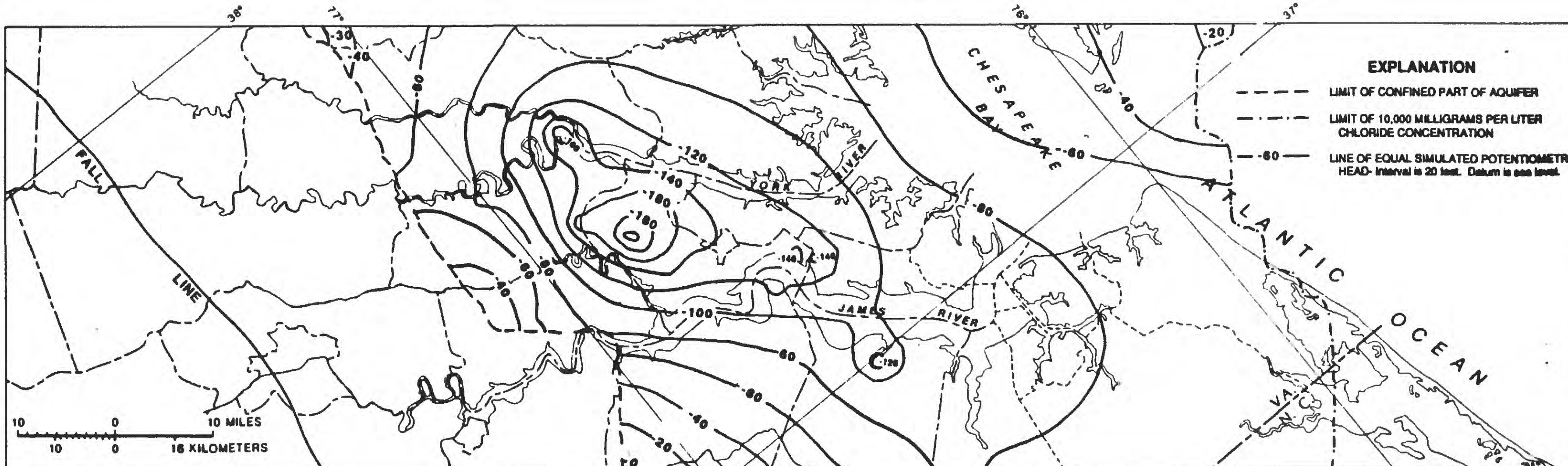


Figure 106. Potentiometric surface of Chickahominy-Piney Point aquifer, projection II.



Base from U.S. Geological Survey State base map, 1973.

Figure 107. Potentiometric surface of Aquia aquifer, projection II.



Base from U.S. Geological Survey State base map, 1973.

Figure 108. Potentiometric surface of upper Potomac aquifer, projection II.

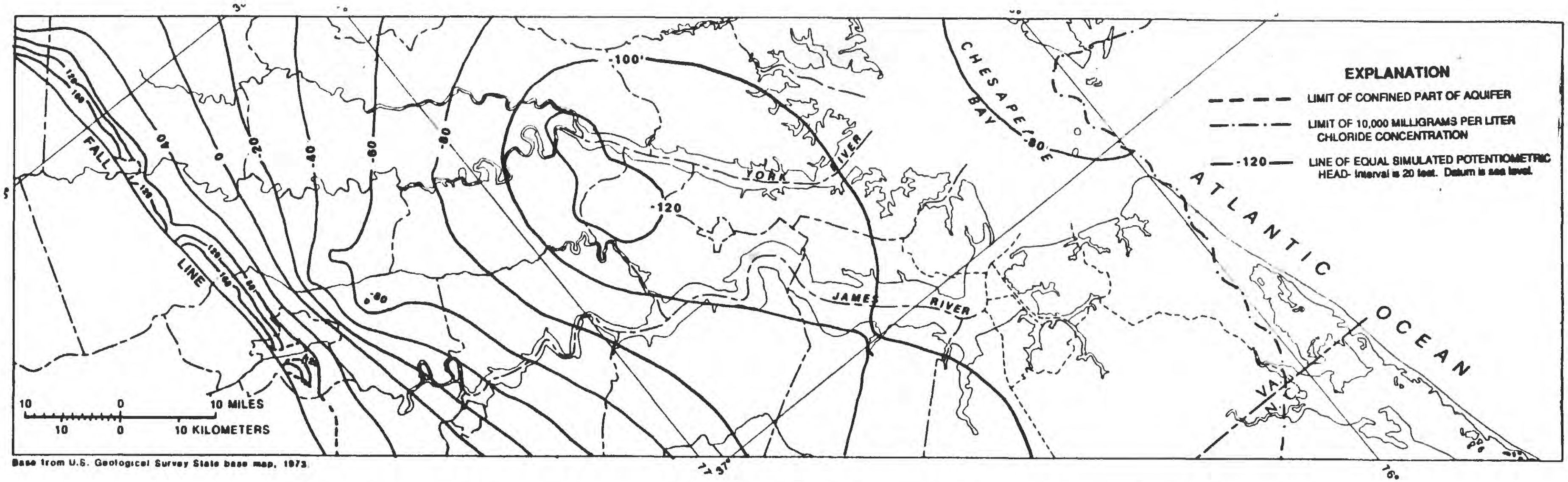


Figure 109. Potentiometric surface of middle Potomac aquifer, projection II.

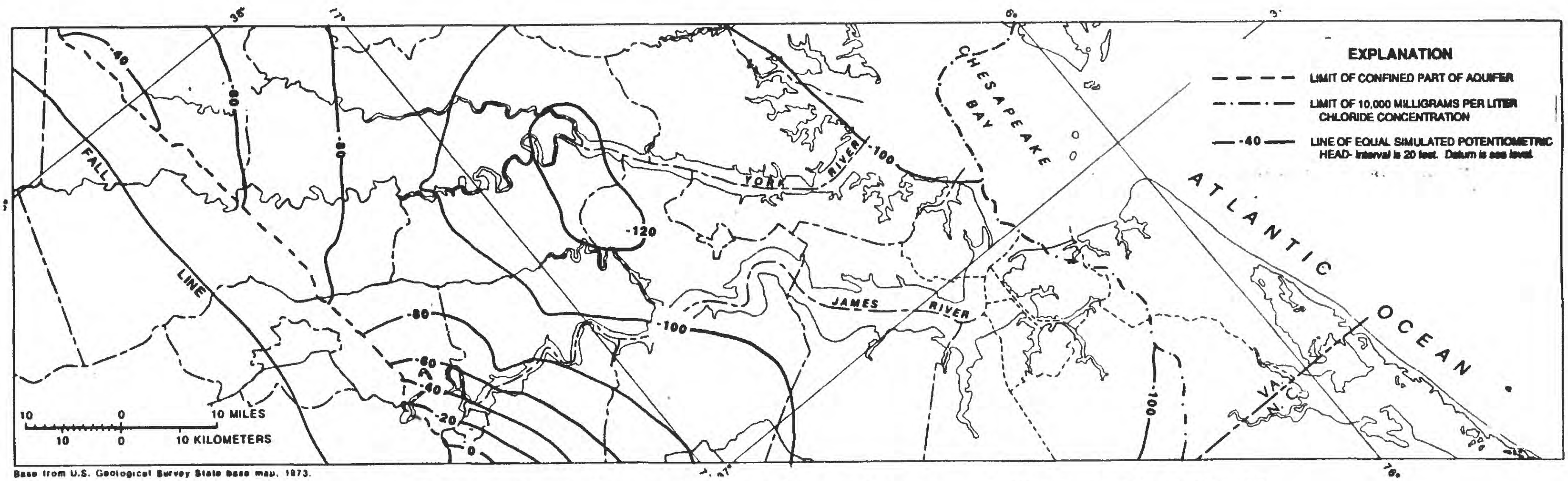


Figure 110. Potentiometric surface of lower Potomac aquifer, projection II.

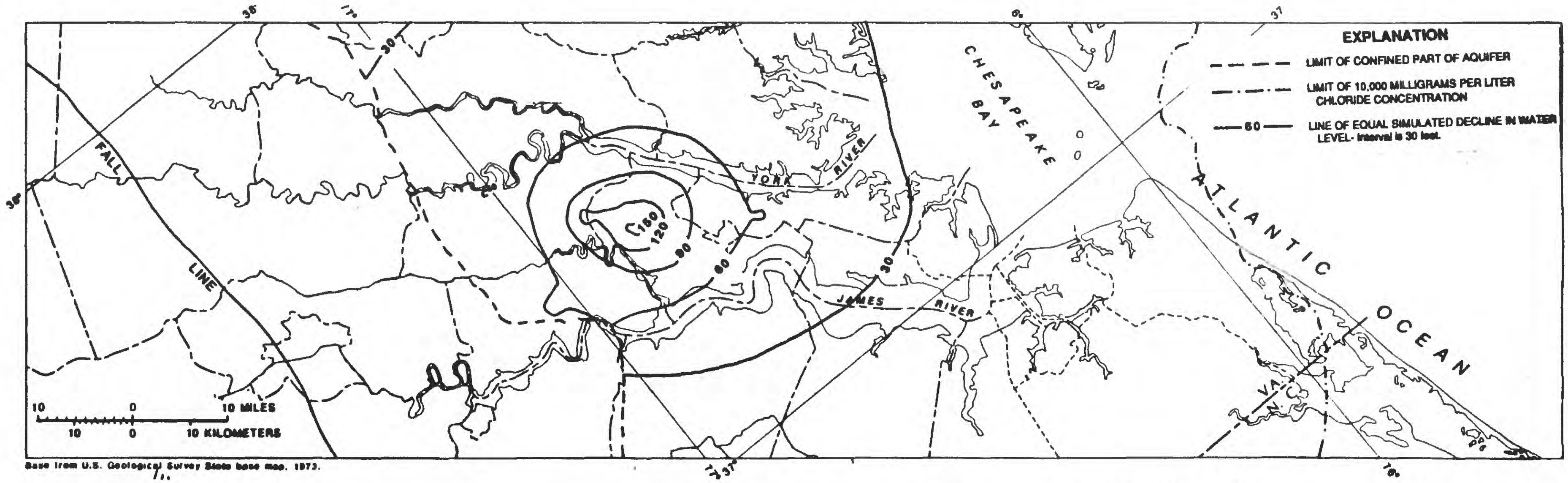


Figure 111. Water-level decline from 1983 ground-water flow conditions in upper Potomac aquifer, projection II.

Table 34.--Maximum water-level decline from 1983 flow conditions for each aquifer, projection II

Aquifer	Decline (feet)	Grid row	Grid column	Approximate areal location
Yorktown-Eastover	14.02	75	23	York County
Chickahominy-Piney Point	74.96	56	21	Central James City County
Aquia	99.19	58	22	Central James City County
Upper Potomac	155.40	55	21	Western James City County
Middle Potomac	76.39	55	21	Western James City County
Lower Potomac	74.19	51	22	Western James City County

withdrawal are compared in figure 94. About 63 percent of the additional 33 Mgal/d of water withdrawn was replaced by surface-water depletion and the remainder by lateral-boundary flow. The higher percentage replaced by lateral-boundary flow than simulated in projection I was because no additional water was withdrawn from wells located outside the model area. Areas of high simulated surface-water depletion (greater than 0.4 in/yr from prepumping conditions) and areas of simulated surface-water recharge are shown in figure 112. Both areas increased from 1983 flow conditions, but increases were much less than the increases simulated by projection I.

Flow of water into and out of aquifers through the overlying confining unit are listed in table 32. Flow into all aquifers through the overlying confining units increased from 1983 flow conditions, whereas flow out of all aquifers through the overlying confining units either decreased or remained the same. Changes from 1983 flow conditions in vertical leakage, lateral-boundary flow, and withdrawal for the middle Potomac aquifer are compared in figure 96. About 50 percent of the additional water withdrawn was replaced by vertical leakage and about 50 percent was replaced by lateral-boundary flow. The direction of flow into and out of each aquifer through the overlying confining unit is shown in figures 113-118. Increased areas of flow into confined aquifers coincided with the location of the larger municipal pumping centers. In eastern York County, where water was withdrawn from the Yorktown-Eastover aquifer, the area of flow into the Yorktown-Eastover aquifer through the overlying Yorktown confining unit increased from 1983 flow conditions. Because the source of some of this additional recharge is salty surface water (Chesapeake Bay and local estuaries), the potential for saltwater contamination is increased. This increased potential for saltwater contamination of the aquifer further supports the conclusion that the Yorktown-Eastover aquifer is an unlikely source for large water supplies in eastern York County.

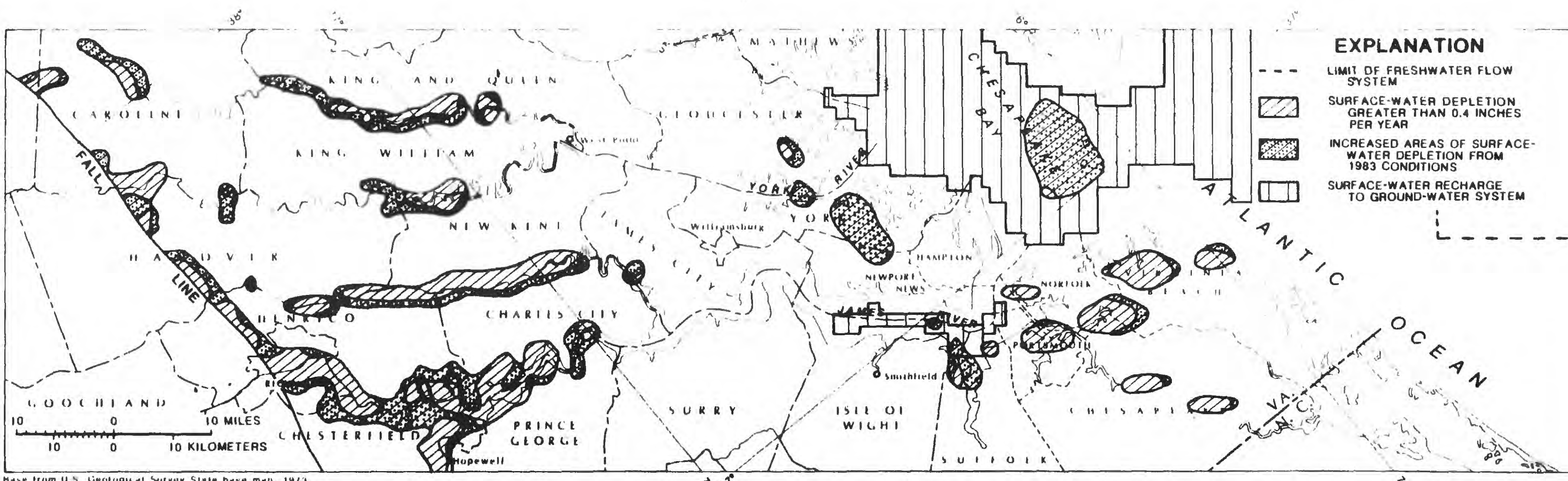


Figure 112. Areas of high surface-water depletion and surface-water recharge, projection II.

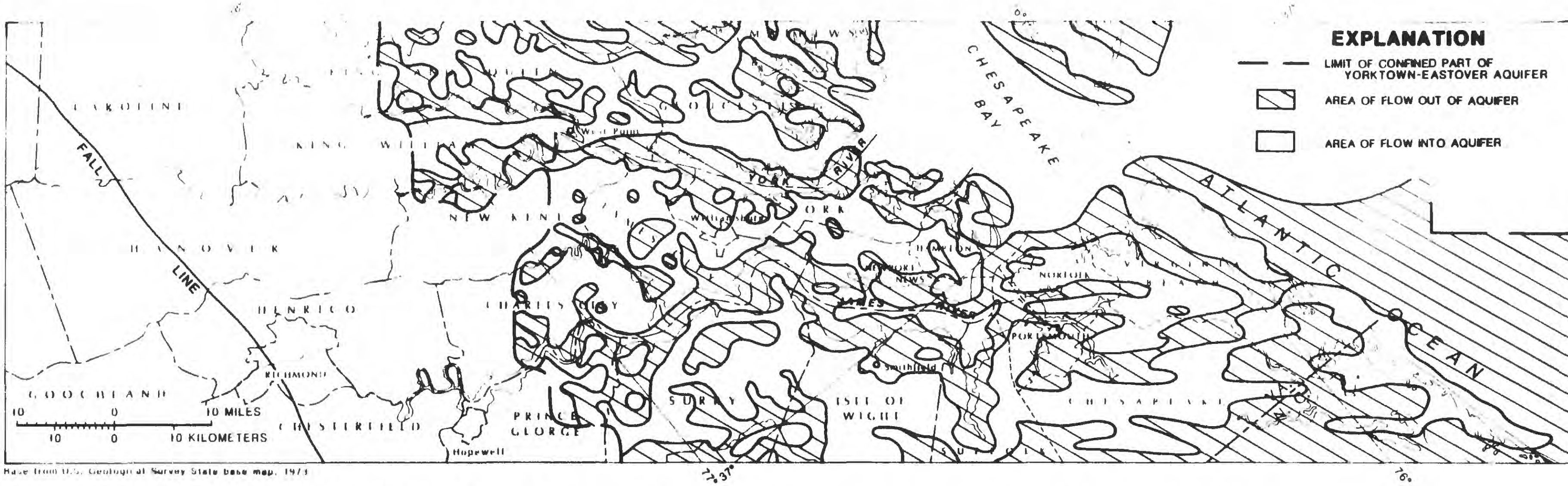


Figure 113. Direction of ground-water flow into and out of Yorktown-Eastover aquifer through overlying confining unit, projection II.

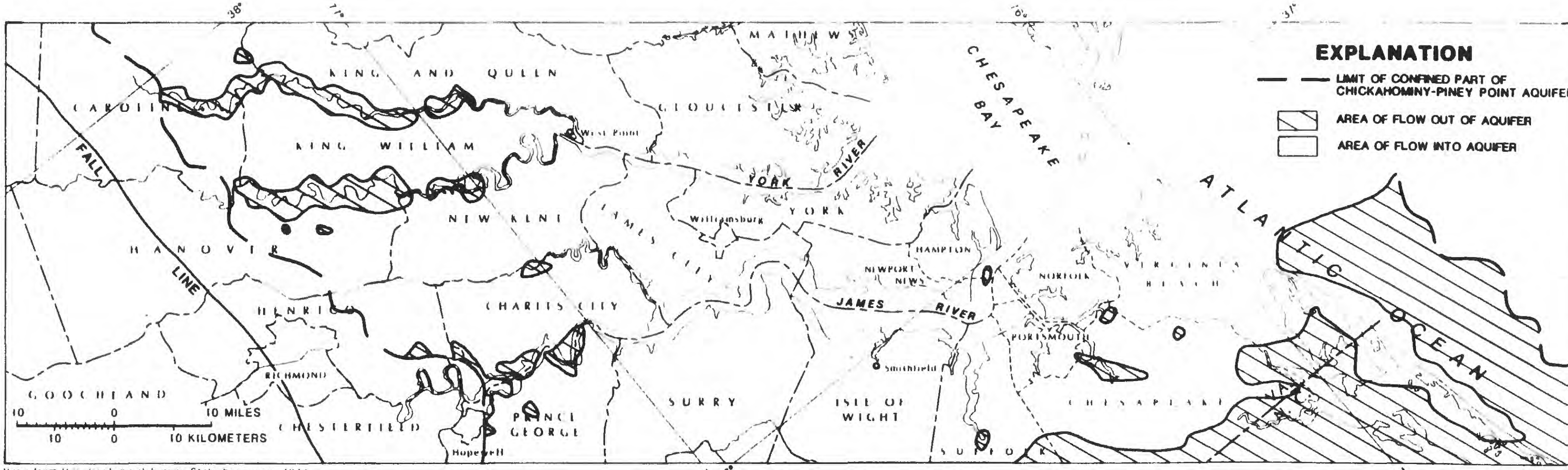


Figure 114. Direction of ground-water into and out of Chickahominy-Piney Point aquifer through overlying confining unit, projection II.

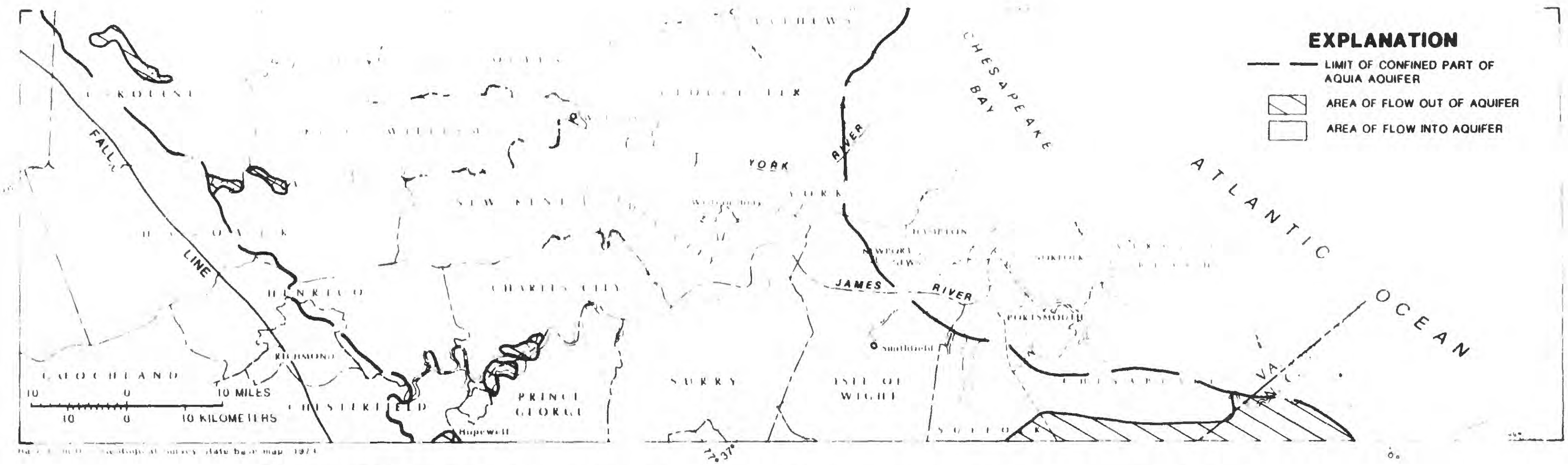


Figure 115. Direction of ground-water flow into and out of Aquia aquifer through overlying confining unit, projection II.

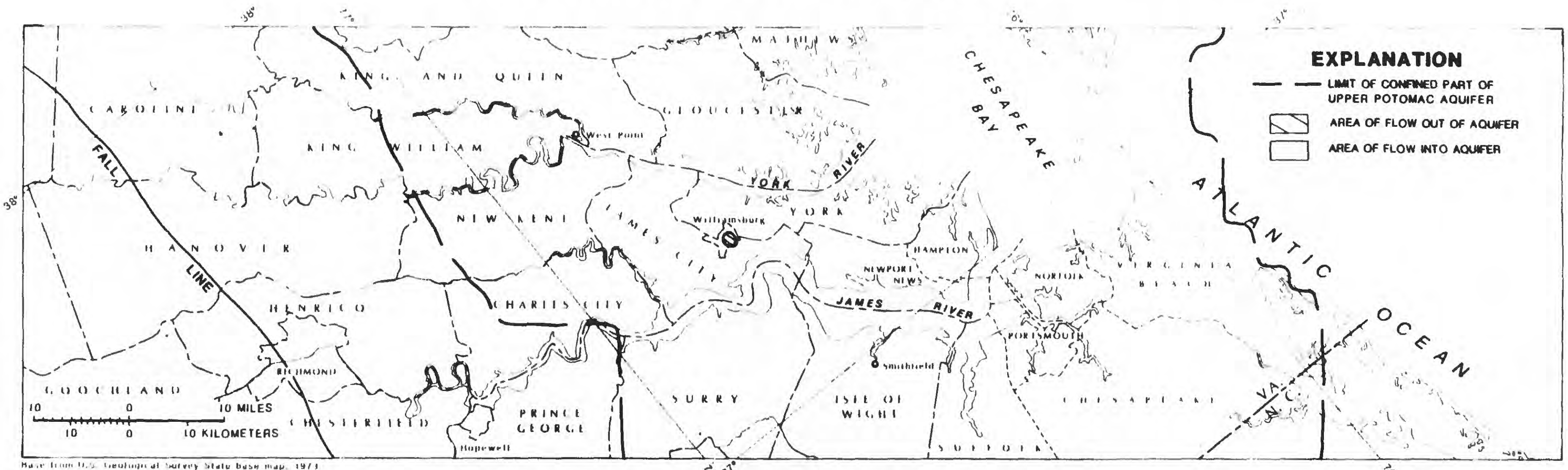


Figure 116. Direction of ground-water flow into and out of upper Potomac aquifer through overlying unit, projection II.

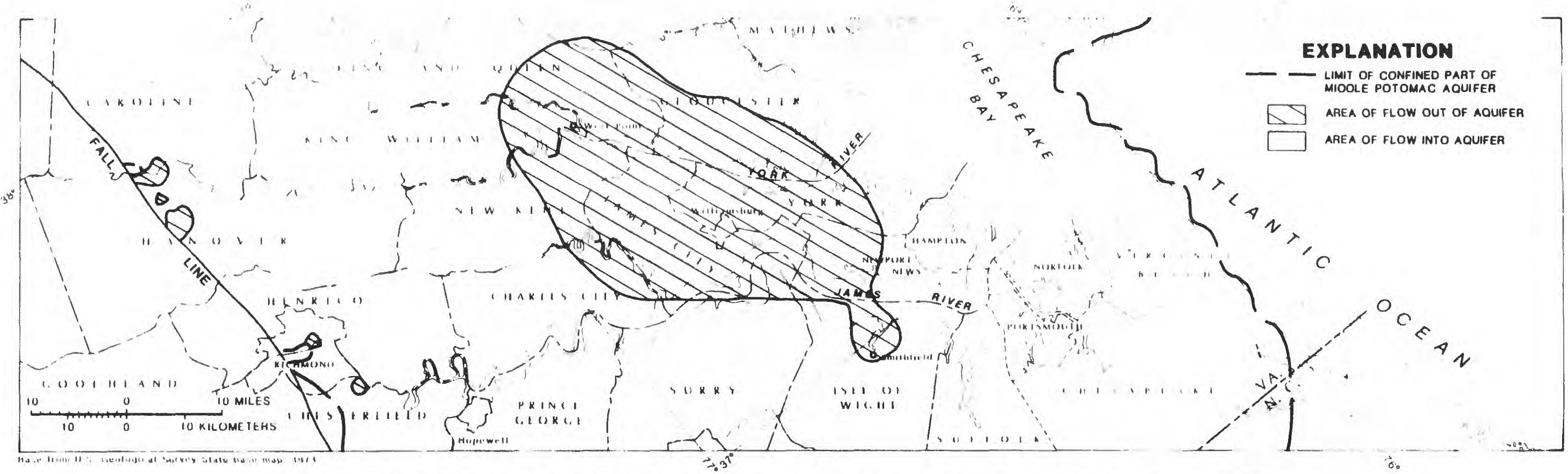


Figure 117. Direction of ground-water flow into and out of the middle Potomac aquifer through overlying confining unit, projection II.

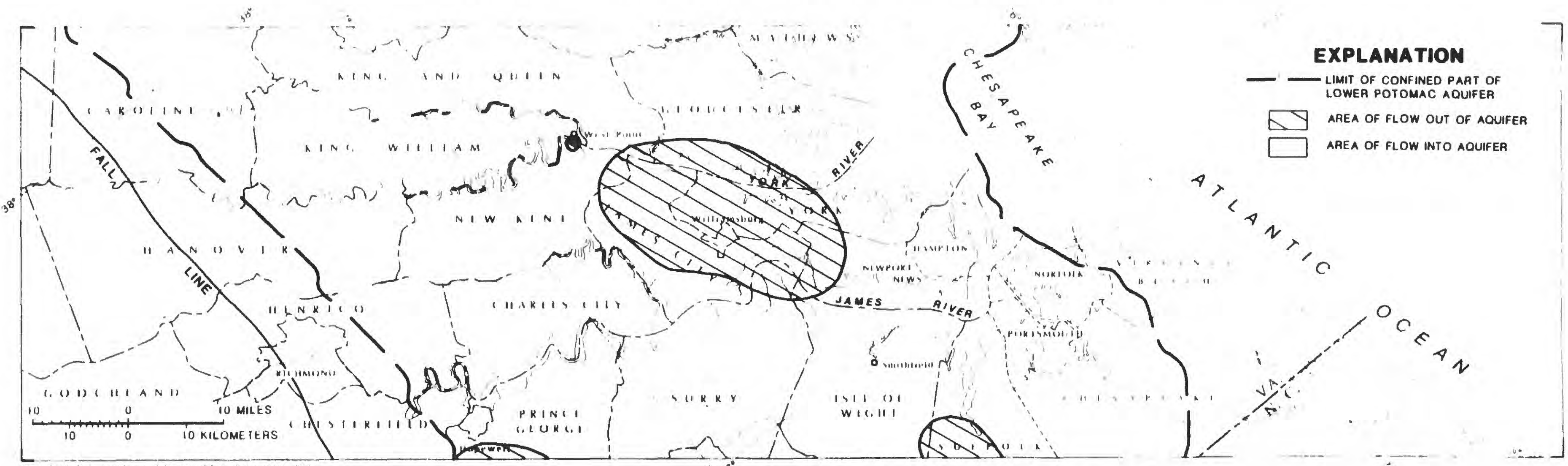


Figure 118. Direction of ground-water flow into and out of lower Potomac aquifer through overlying confining unit, projection II.

Projection III--A 12 Million-Gallons-per-Day Supply from Western James City County

Projection III withdraws an additional 12 Mgal/d from wells located in the western part of James City County and in the extreme eastern part of New Kent County. Total withdrawal from the model area was about 50 Mgal/d (table 28). Withdrawal rates for wells and source aquifers are listed in table 33. Wells are located on figure 104. Withdrawals from wells located outside the the model area were not increased from 1983 flow conditions. A water supply of this magnitude is considered by local planners to be adequate to meet the near future water needs of the immediate area (York-James Peninsula Project Advisory Committee Meeting, oral commun., 1985).

Projected water levels in the confined aquifers are shown as potentiometric surfaces in figures 119-124. The deepest water level, about 146 feet below sea level, was in the upper Potomac aquifer near the town of West Point (fig. 122). Though water levels were deepest near the town of West Point in the Potomac aquifers, major cones of depression developed in James City and New Kent Counties. Water levels remained above the top of respective aquifers. The maximum water-level decline from 1983 flow conditions and the approximate location of the maximum decline are listed for each aquifer in table 35. The maximum simulated decline, about 76 feet, was in the upper Potomac aquifer in western James City County. The areal distribution of water-level decline from 1983 flow conditions in the upper Potomac aquifer is shown in figure 125. Decline in the Yorktown-Eastover aquifer was small (less than one foot). Because withdrawal was not increased from the Yorktown-Eastover aquifer, this decline was attributed to withdrawal from wells located in the deeper confined aquifers. The small magnitude of the decline suggests that large withdrawals from the deeper confined aquifers have minimal affect on water levels in the shallow aquifers.

The model-computed water budget is listed in table 31. Changes from 1983 flow conditions in surface-water depletion, lateral-boundary flow, and withdrawal are compared in figure 94. Surface-water depletion replaced about 58 percent of the additional water withdrawn and lateral-boundary flow about 42 percent. Areas of high surface-water depletion (greater than 0.4 in/yr from prepumping-flow conditions) and areas of surface-water recharge into the ground-water flow system are shown in figure 126. Only minimal increases from 1983 flow conditions were simulated.

Flow of water into and out of aquifers through the overlying confining units are listed in table 32. Flow into all aquifers through the overlying confining units increased from 1983 flow conditions, while flow out of all aquifers, except the middle and lower Potomac aquifers, decreased. Changes from 1983 flow conditions in vertical leakage, lateral-boundary flow, and withdrawal for the middle Potomac aquifer are compared in figure 96. Lateral-boundary flow replaced about 60 percent of the additional water withdrawn and vertical leakage replaced about 40 percent. The direction of flow into and out of each aquifer through the overlying confining unit is shown in figures 127-132. The area of flow into the aquifers through the overlying confining units increased in the Yorktown-Eastover, Chickahominy-Piney Point, and Aquia aquifers, remained about the same in the upper Potomac aquifer, and decreased in the middle and lower Potomac aquifers from 1983 flow conditions.

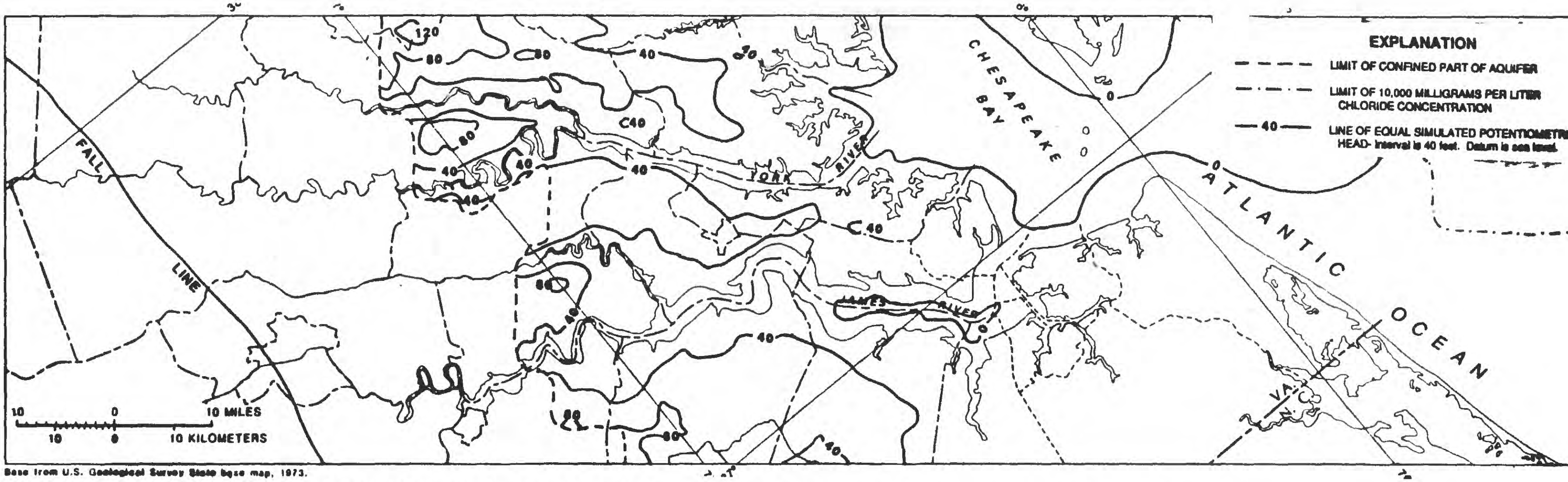


Figure 119. Potentiometric surface of Yorktown-Eastover aquifer, projection III.

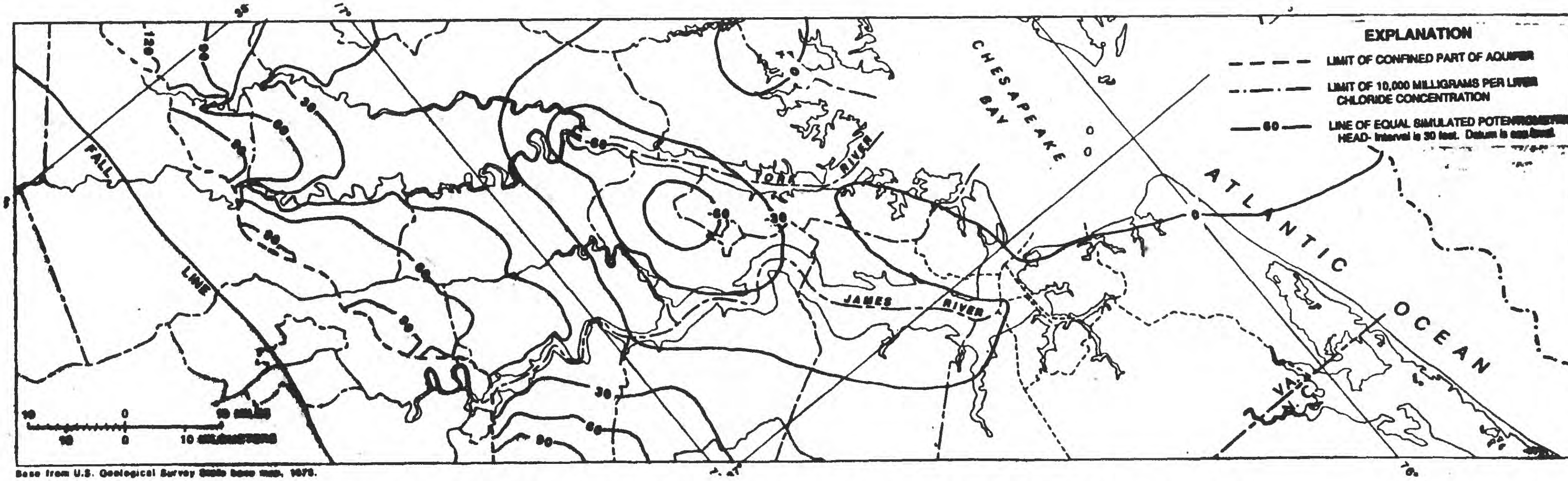


Figure 120. Potentiometric surface of Chickahominy-Piney Point aquifer, projection III.

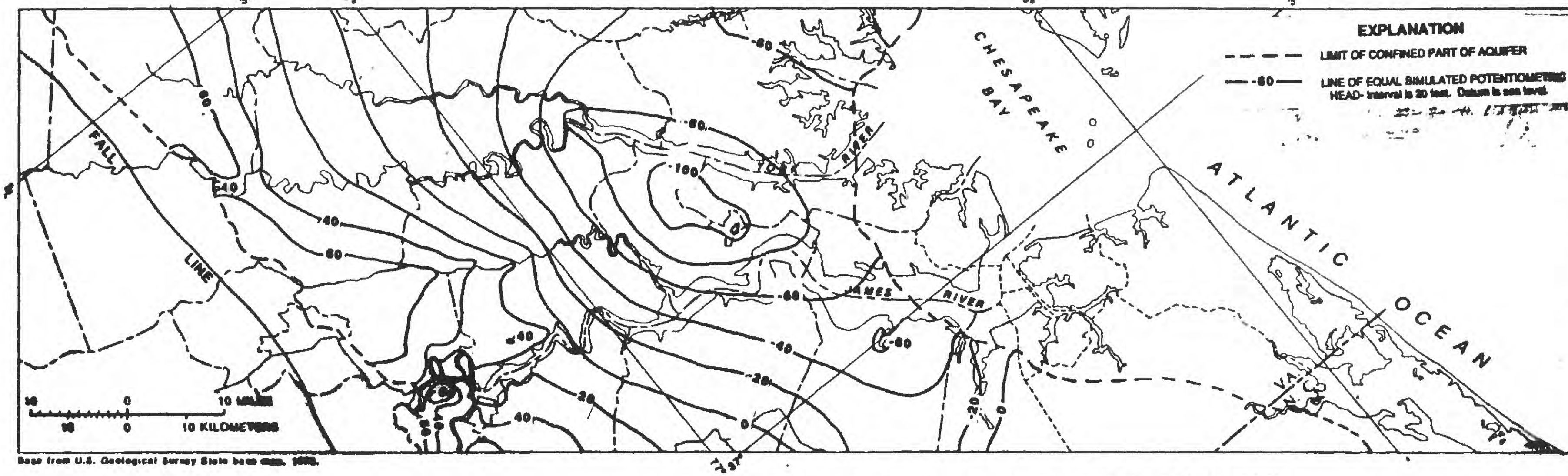


Figure 121. Potentiometric surface of Aquia aquifer, projection III.

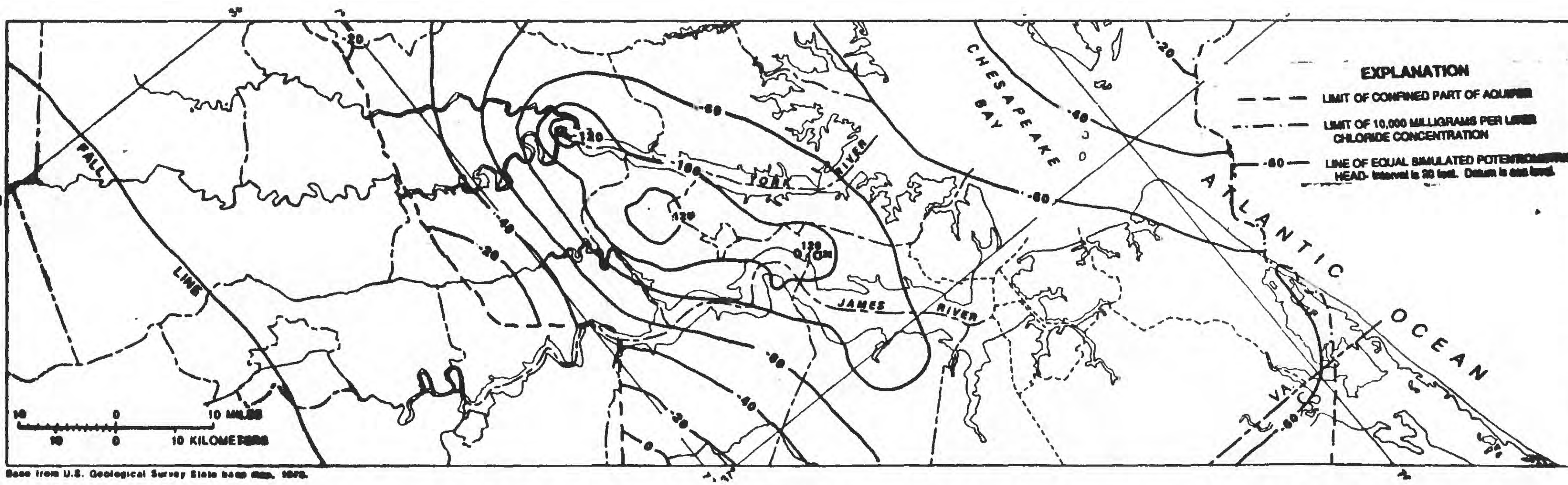


Figure 122. Potentiometric surface of upper Potomac aquifer, projection III.

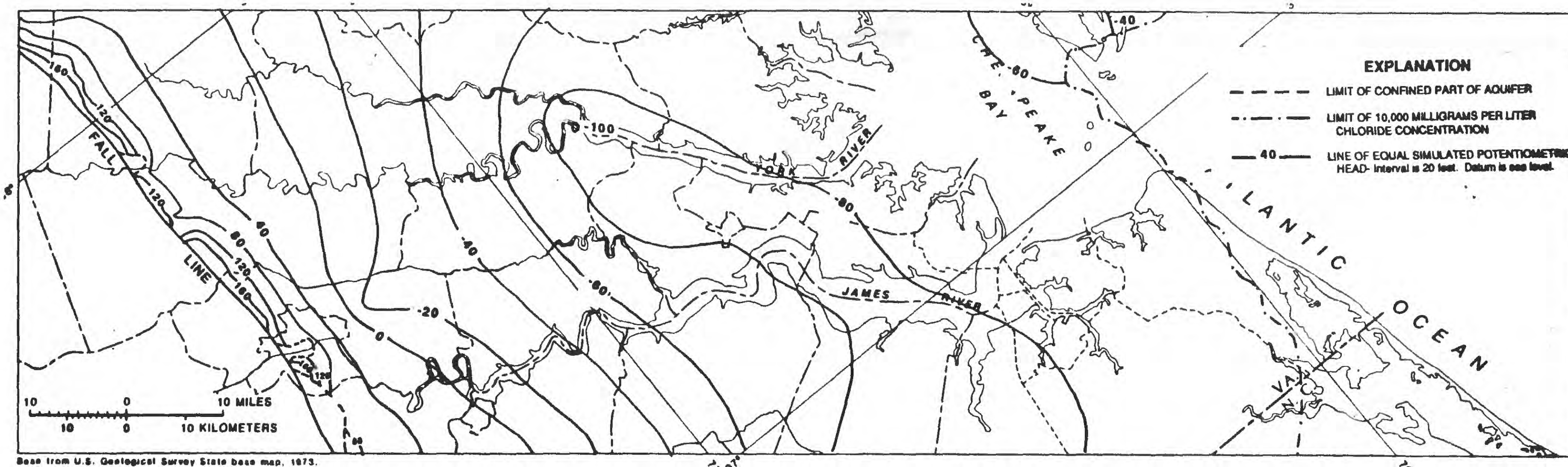


Figure 123. Potentiometric surface of middle Potomac aquifer, projection III.

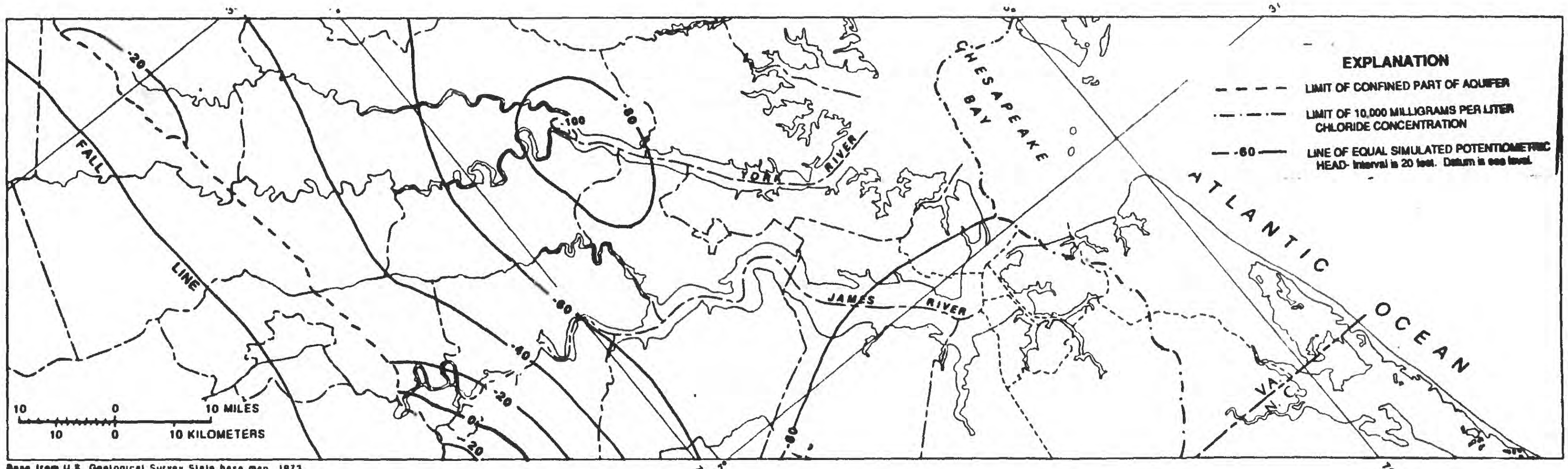


Figure 124. Potentiometric surface of lower Potomac aquifer, projection III.

Table 35.--Maximum water-level decline from 1983 flow conditions for each aquifer, projection III

Aquifer	Decline (feet)	Grid row	Grid column	Approximate areal location
Yorktown-Eastover	1.08	54	22	Central James City County
Chickahominy-Piney Point	52.26	56	22	Central James City County
Aquia	64.71	57	22	Western James City County
Upper Potomac	75.98	58	23	Western James City County
Middle Potomac	34.10	58	22	Western James City County
Lower Potomac	26.02	54	22	Central James City County

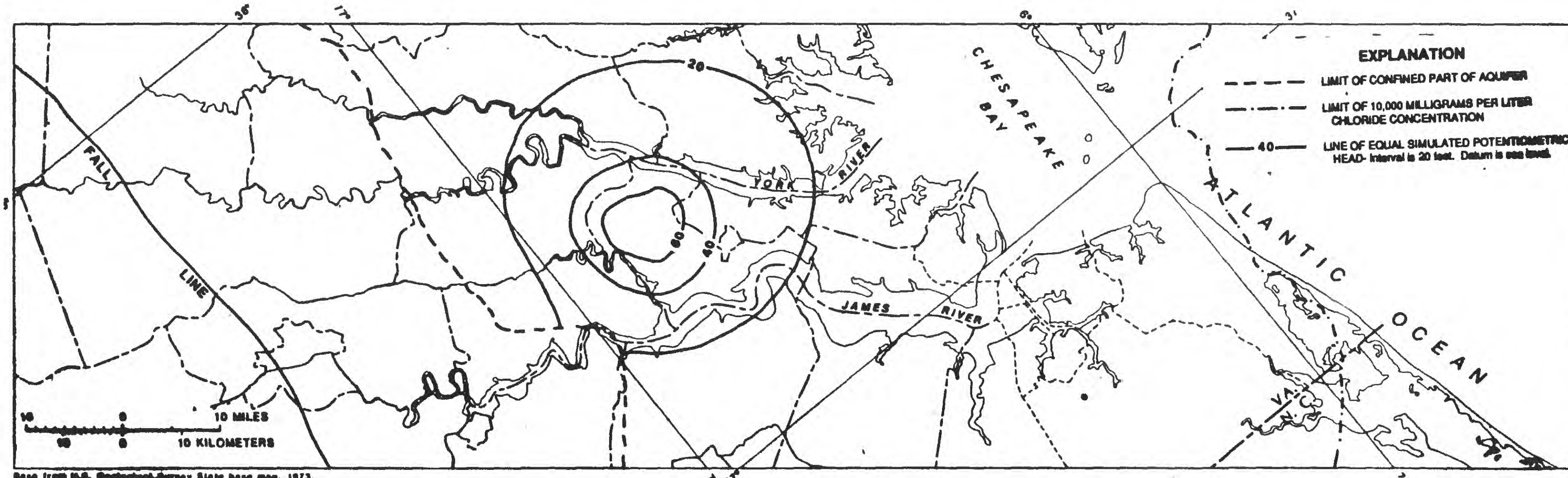
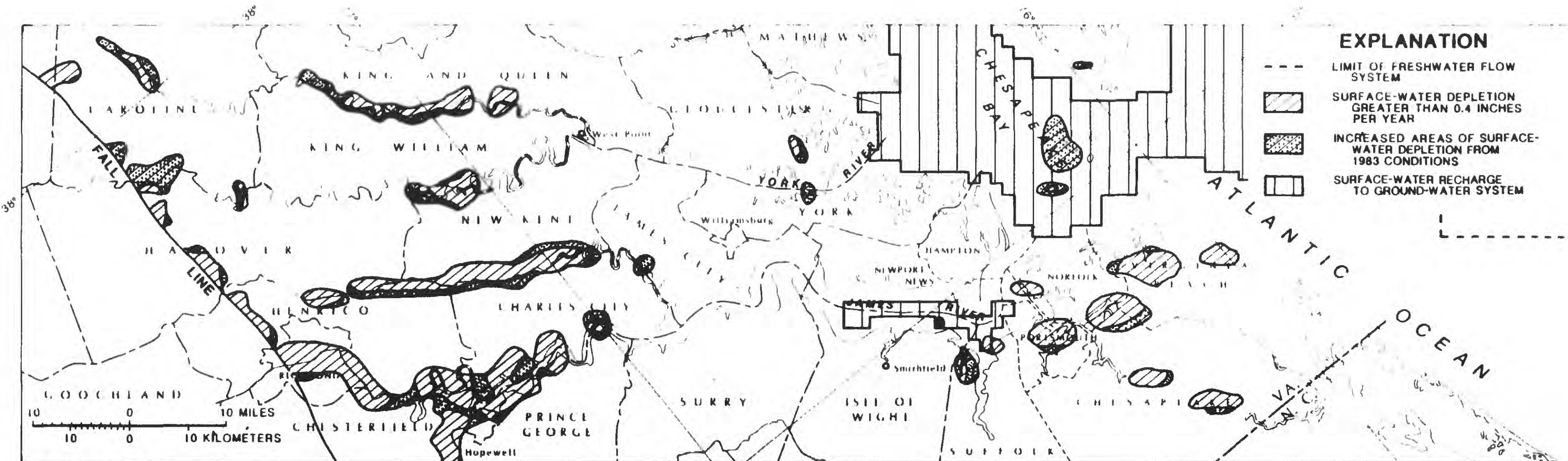


Figure 125. Water-level decline from 1983 ground-water flow conditions in upper Potomac aquifer, projection III.



Base from U.S. Geological Survey State base map, 1973

Figure 126. Areas of high surface-water depletion and surface-water recharge projection III.

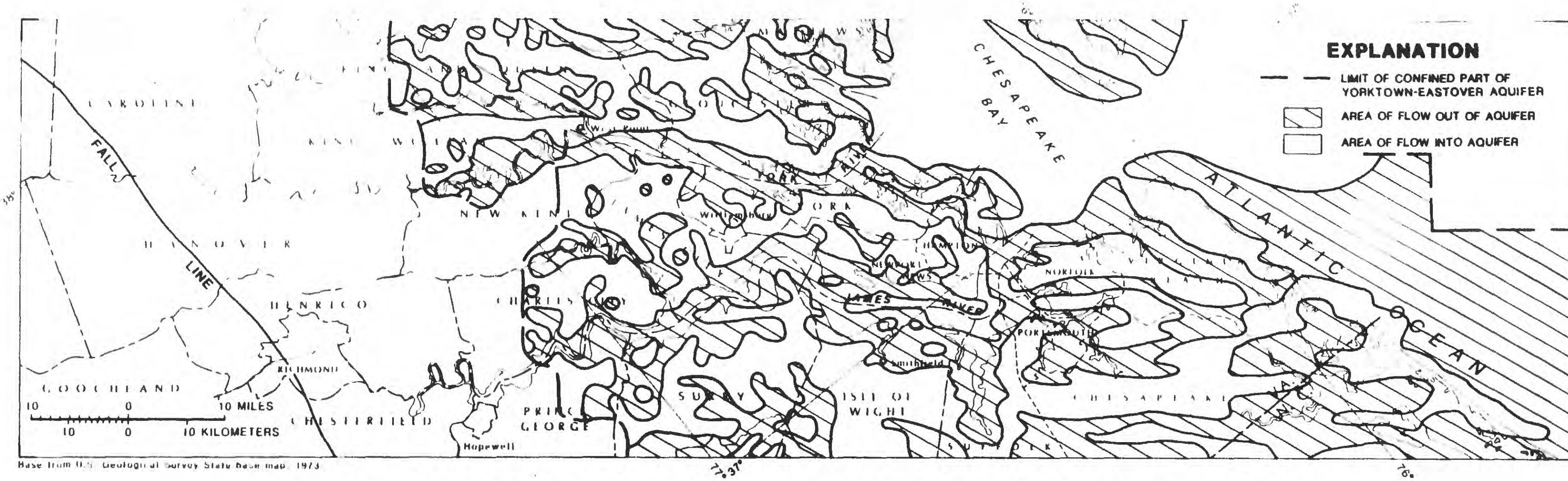


Figure 127. Direction of ground-water flow into and out of Yorktown-Eastover aquifer through overlying confining unit, projection III.

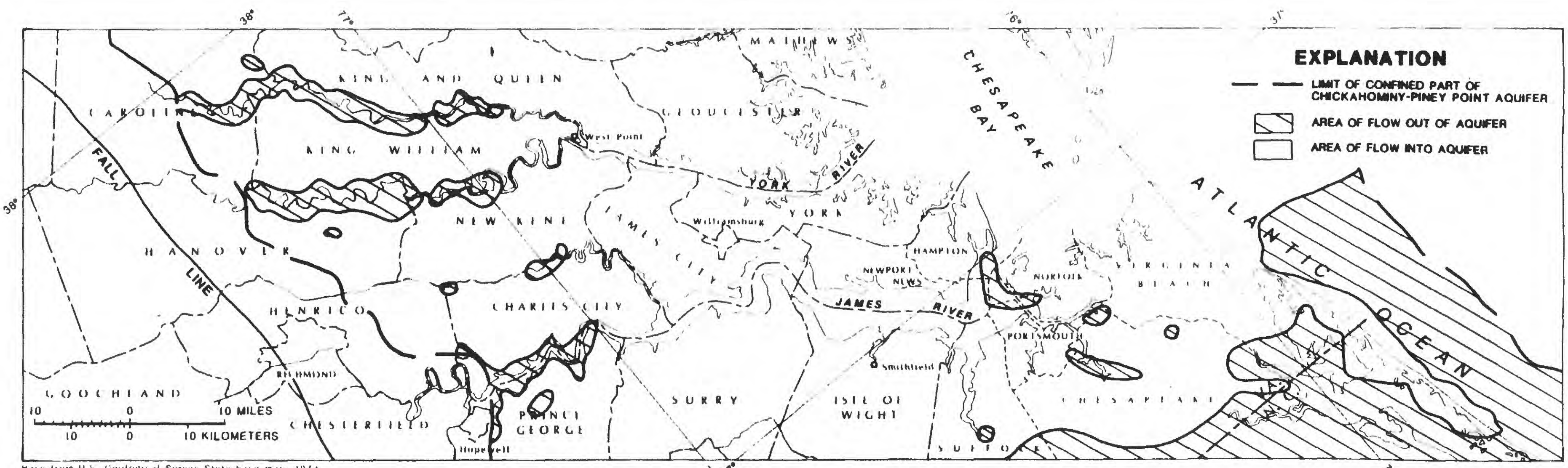


Figure 128. Direction of ground-water flow into and out of the Chickahominy-Piney Point aquifer through overlying confining unit, projection III.

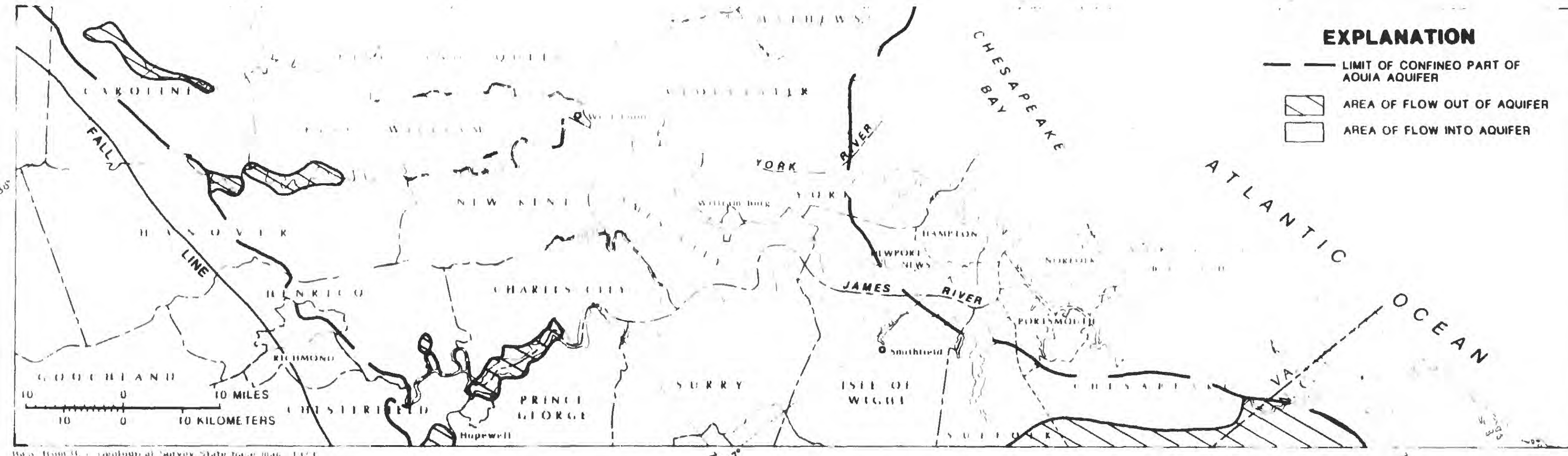


Figure 129. Direction of ground-water flow into and out of the Aquia aquifer through overlying confining unit, projection III.

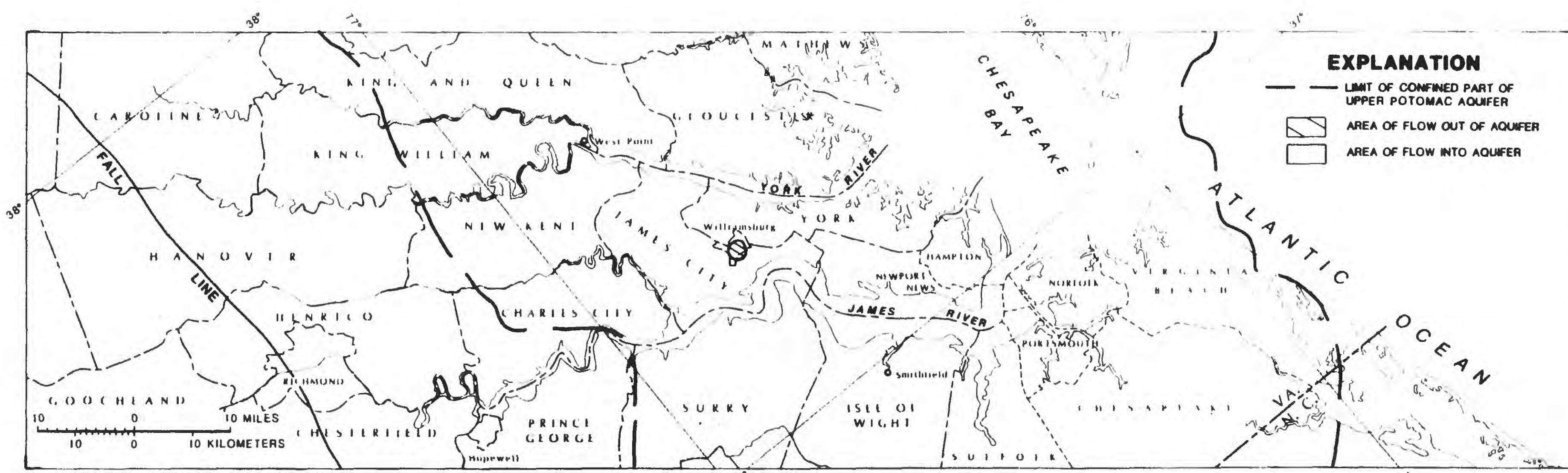


Figure 130. Direction of ground-water flow into and out of upper Potomac aquifer through overlying unit, projection III.

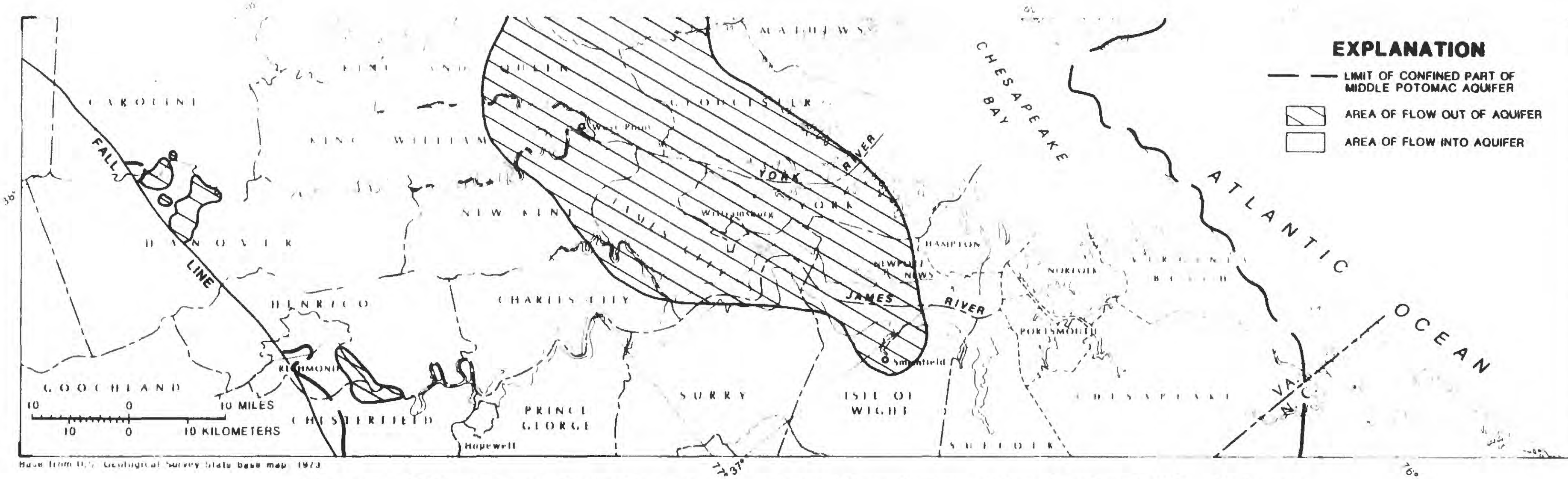


Figure 131. Direction of ground-water flow into and out of middle Potomac aquifer through overlying confining unit, projection III.

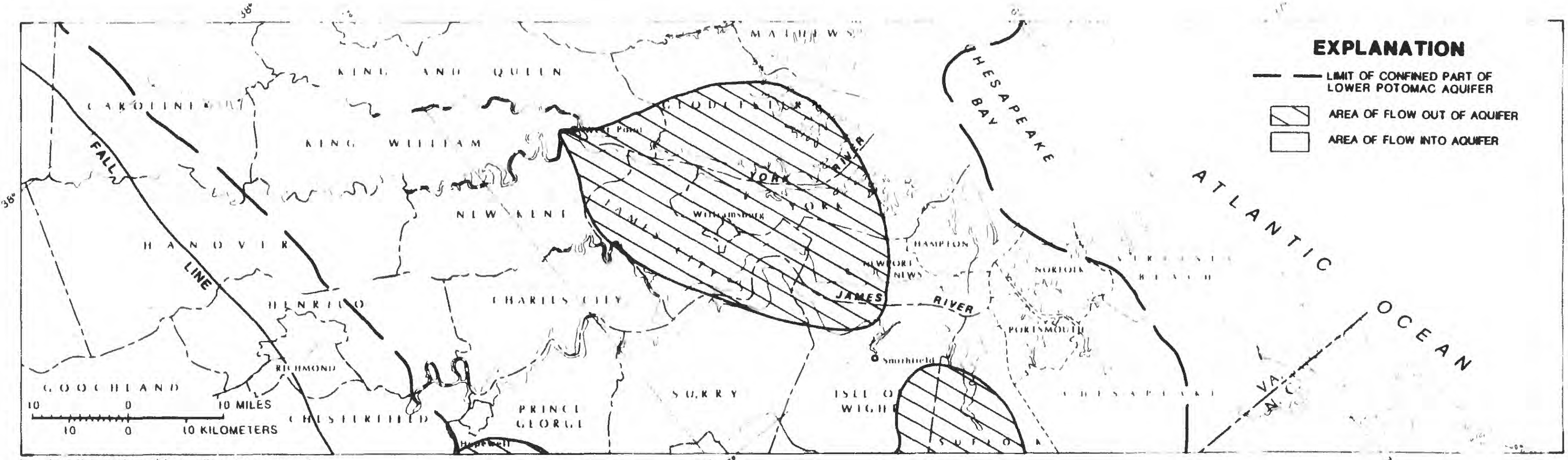


Figure 132. Direction of ground-water flow into and out of lower Potomac aquifer through overlying confining unit, projection III.

Projection IV--Supplement for Future Municipal Needs

Projection IV withdraws ground water to supplement future municipal water needs. Withdrawal was from the same wells simulated in projection II (fig. 104), except that rates for larger users were reduced (table 33). Withdrawals from wells located outside the model area were not increased from 1983 flow conditions. Total withdrawal from the model area was increased by about 25 Mgal/d and totaled about 63 Mgal/d (table 28).

Projected water levels in the confined aquifers are shown as potentiometric surfaces in figures 133-138. The deepest projected water level, about 158 feet below sea level, was in the upper Potomac aquifer near the town of West Point (fig. 136). Water levels remained above tops of respective aquifers. Major cones of depression developed in the western part of James City County and in the eastern part of New Kent County. The maximum water-level decline from 1983 flow conditions and the approximate location of the maximum decline are listed for each aquifer in table 36. The maximum simulated decline, about 93 feet, was in the upper Potomac aquifer in the western part of James City County. The areal distribution of water-level decline from 1983 flow conditions was in the upper Potomac aquifer and is shown in figure 139. Much less severe water-level decline was projected than in projection II, which suggests that if water-level decline is a concern, the resource would be better utilized as a supplemental source of water supply.

The model-computed water budget for projection IV is listed in table 31. Changes from 1983 flow conditions in surface-water depletion, lateral-boundary flow, and withdrawal are shown in figure 94. Surface-water depletion replaced about 66 percent of the additional water withdrawn and lateral-boundary flow replaced about 32 percent. Areas of high surface-water depletion (greater than 0.4 in/yr from prepumping-flow conditions) and areas of surface-water recharge into the ground-water flow system are shown on figure 140. Both areas increased from prepumping-flow conditions and were only slightly less than increases simulated by projection II.

Flow of water into and out of aquifers through the overlying confining units are listed in table 32. As in projection II, flow into the aquifers through the overlying confining units increased, and flow out of the aquifers either decreased or remained the same. Changes from 1983 flow conditions in vertical leakage, lateral-boundary flow, and withdrawal for the middle Potomac aquifer are compared in figure 96. Vertical leakage replaced about 52 percent of the additional water withdrawn and lateral boundary flow replaced about 48 percent. The direction of flow into and out of each aquifer through the overlying confining unit is shown in figures 141-146. Only minor differences exist between maps simulated in projection II.

Discussion

The use of the ground water to meet the future water needs of the York-James Peninsula requires increased yields of acceptable quality water. Therefore, most concerns about the future of this water supply are related either to decreases in aquifer yields or to deterioration of the quality of water within the aquifers. These problems are directly or indirectly caused by water-level decline. Decline of water levels below pump intake intervals

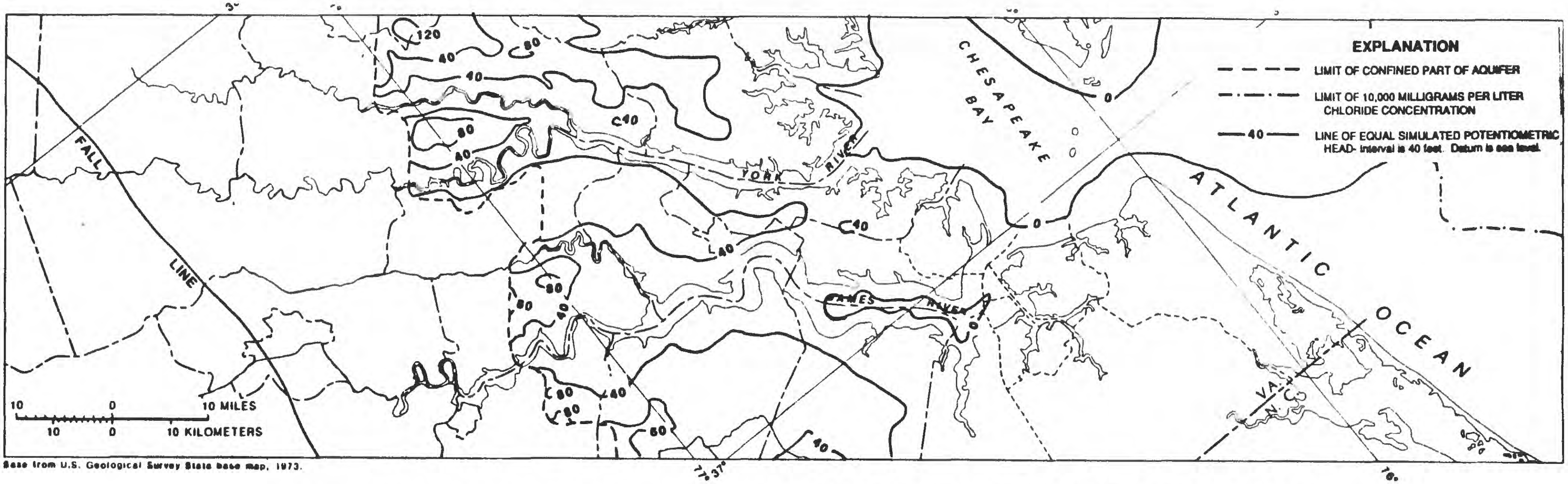


Figure 133. Potentiometric surface of Yorktown-Eastover aquifer, projection IV.

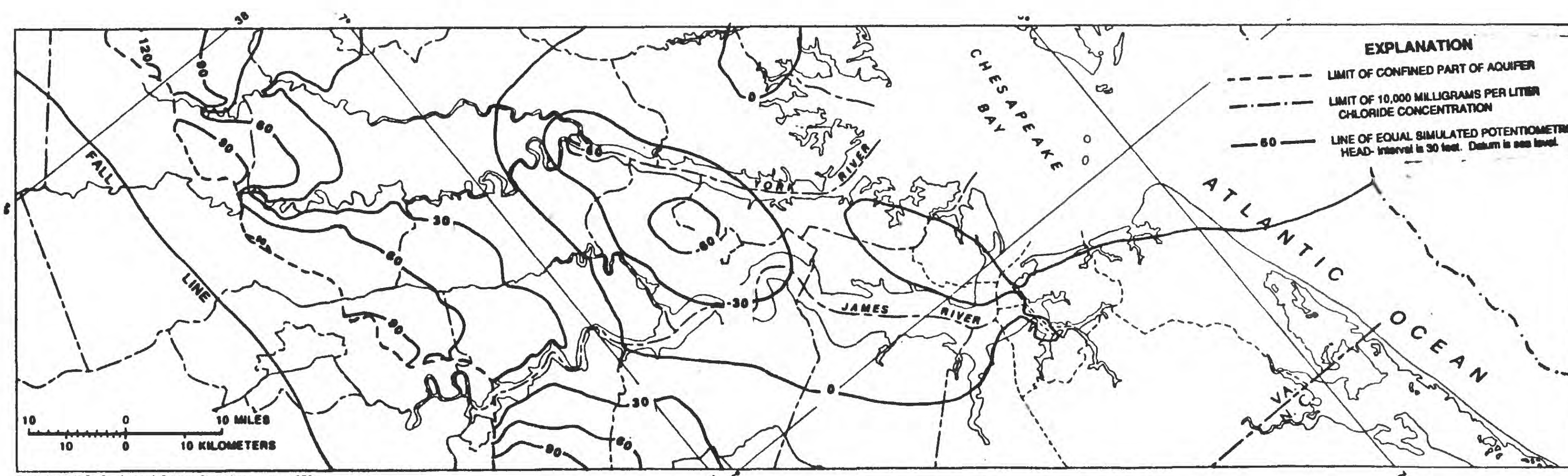


Figure 134. Potentiometric surface of Chickahominy-Piney Point aquifer, projection IV.

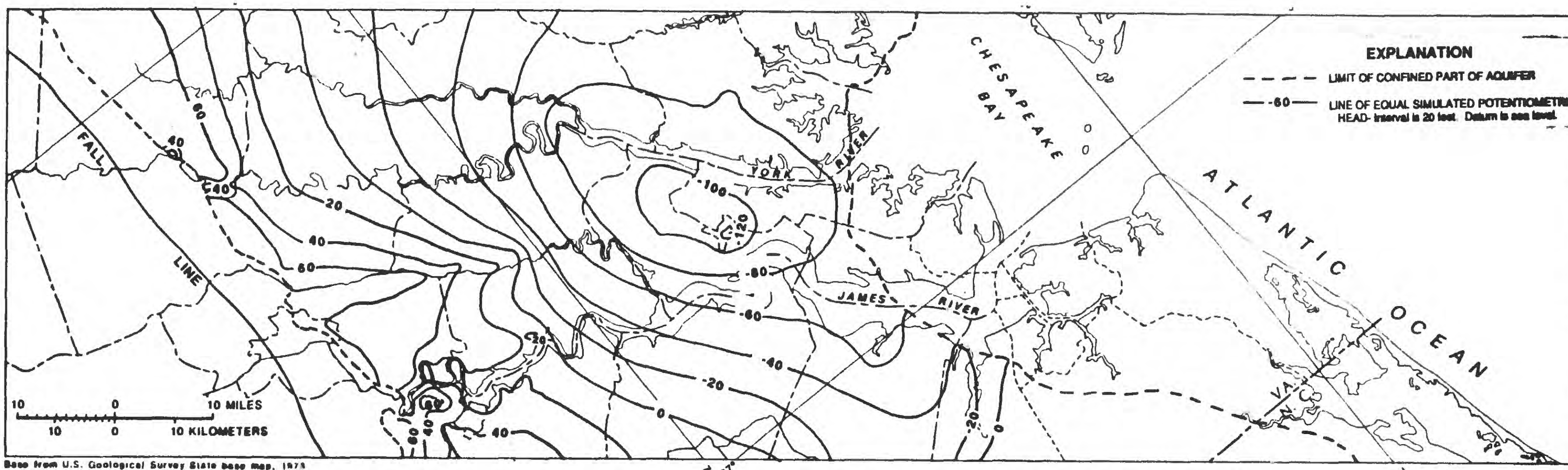


Figure 135. Potentiometric surface of Aquia aquifer, projection IV.

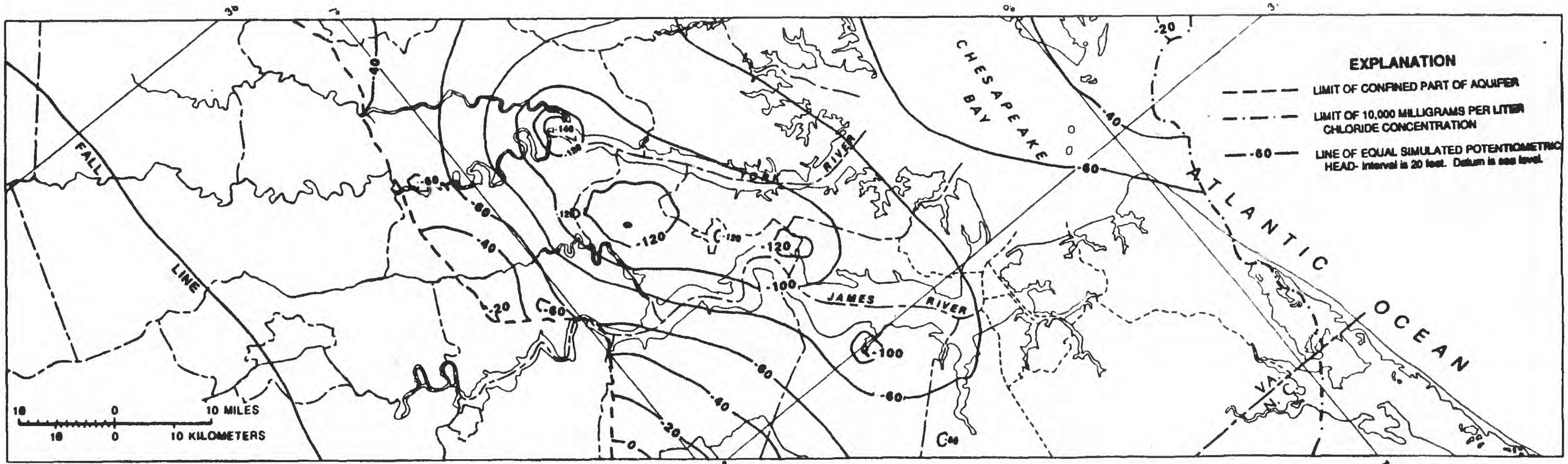


Figure 136. Potentiometric surface of upper Potomac aquifer, projection IV.

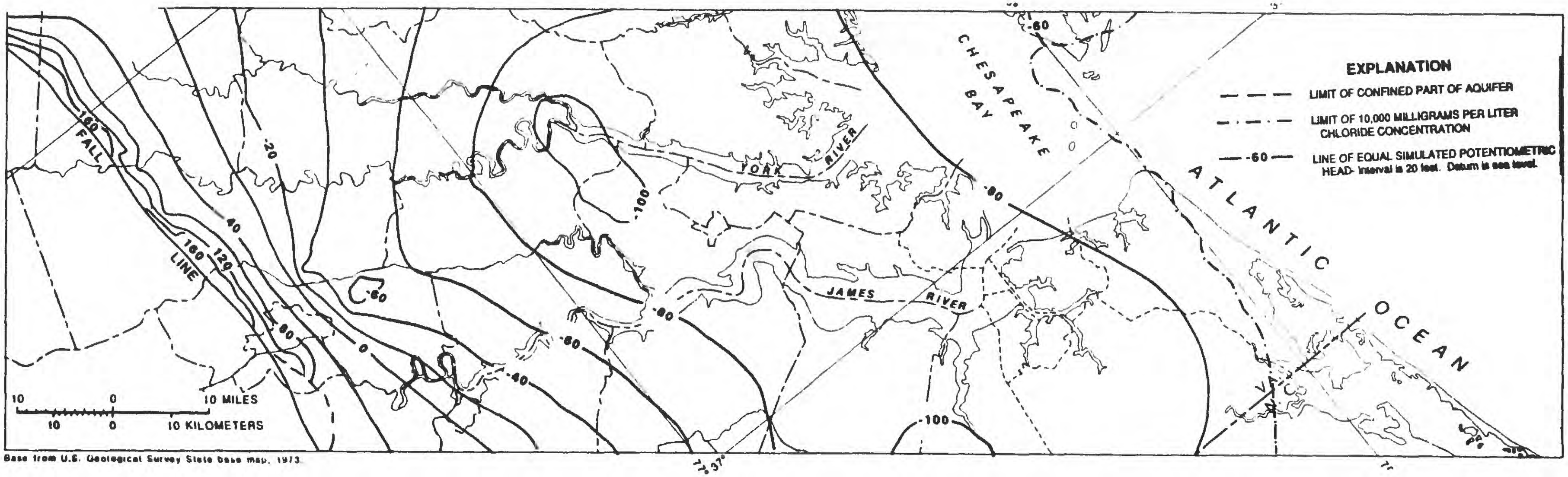


Figure 137. Potentiometric surface of middle Potomac aquifer, projection IV.

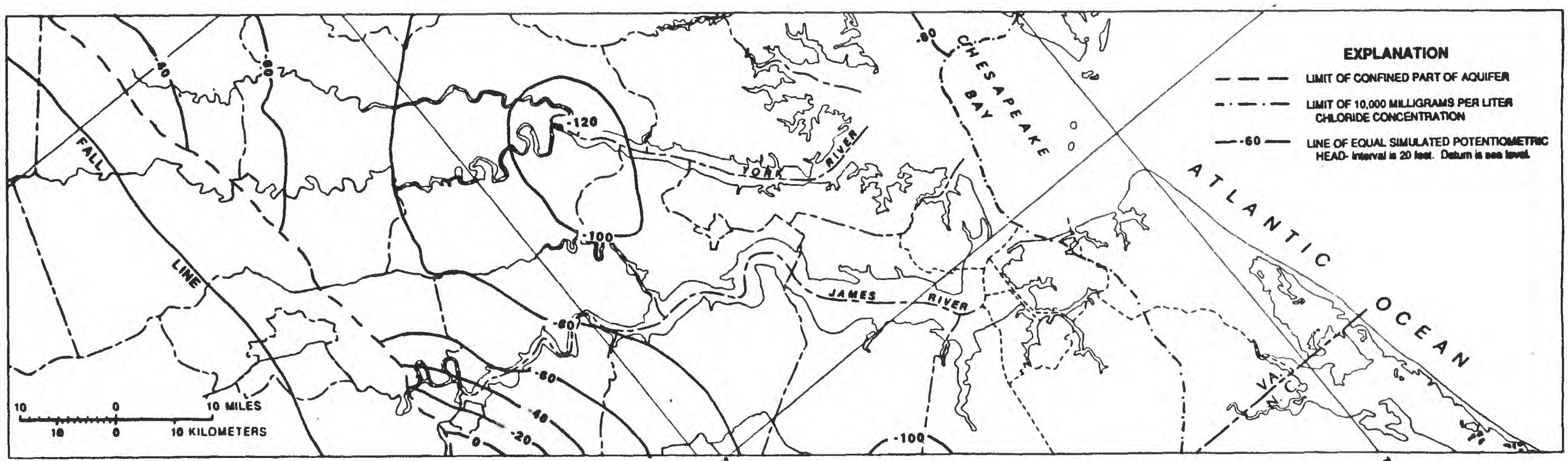


Figure 138. Potentiometric surface of lower Potomac aquifer, projection IV.

Table 36.--Maximum water-level decline from 1983 flow conditions for each aquifer, projection IV

Aquifer	Decline (feet)	Grid row	Grid column	Approximate areal location
Yorktown-Eastover	13.99	75	23	York County
Chickahominy-Piney Point	44.86	57	22	Central James City County
Aquia	62.00	58	23	Central James City County
Upper Potomac	92.88	55	21	Western James City County
Middle Potomac	57.60	29	18	Hanover County
Lower Potomac	60.86	44	9	Charles City County

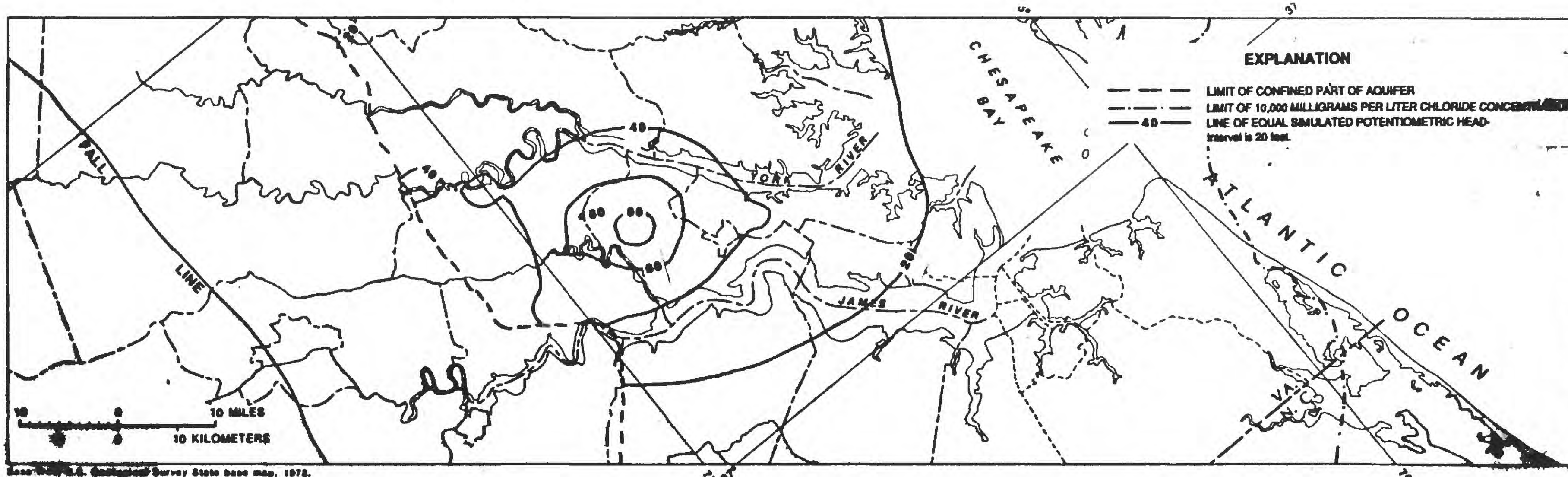


Figure 139. Water-level decline from 1983 ground-water flow conditions in upper Potomac aquifer, projection IV.

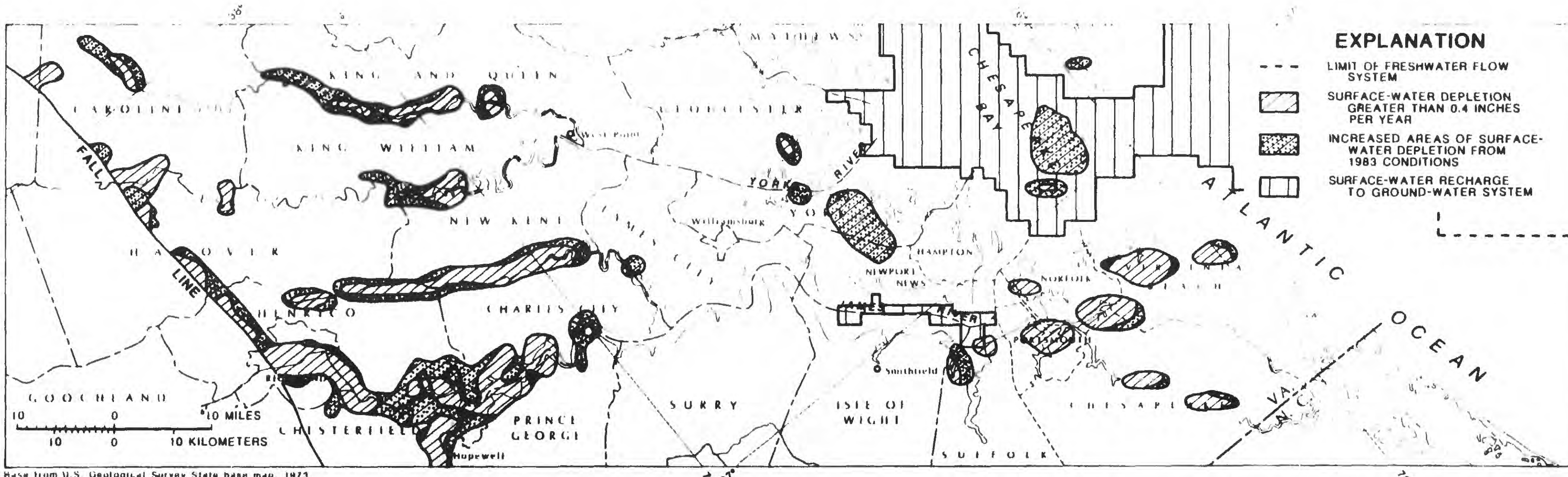


Figure 140. Areas of high surface-water depletion and surface-water recharge, projection IV.

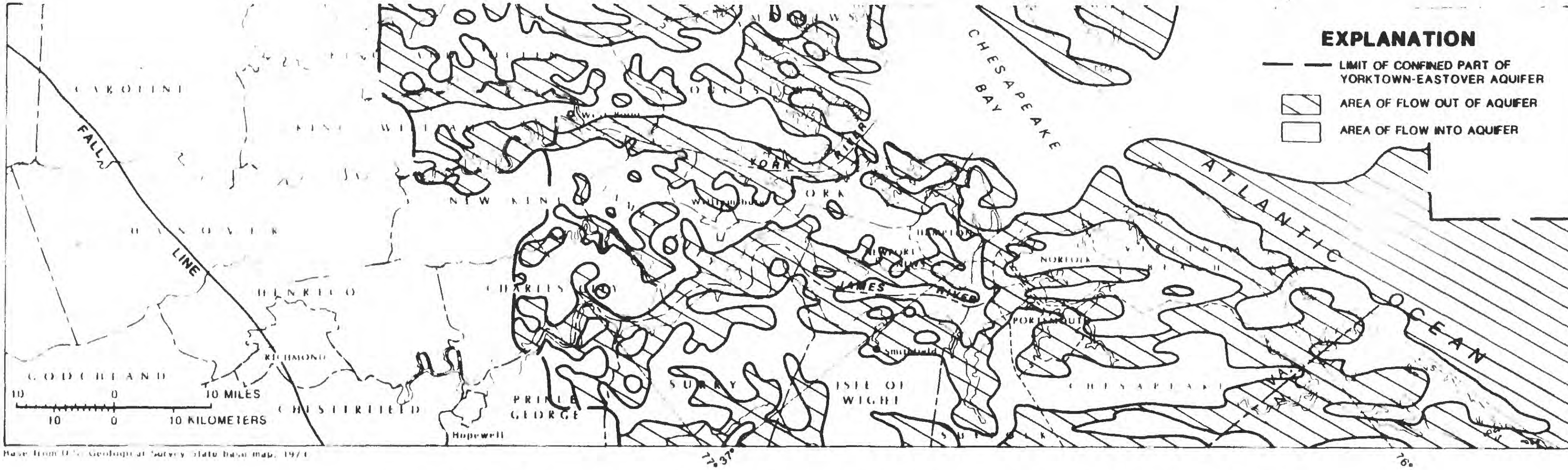


Figure 141. Direction of ground-water flow into and out of Yorktown-Eastover aquifer through overlying confining unit, projection IV.

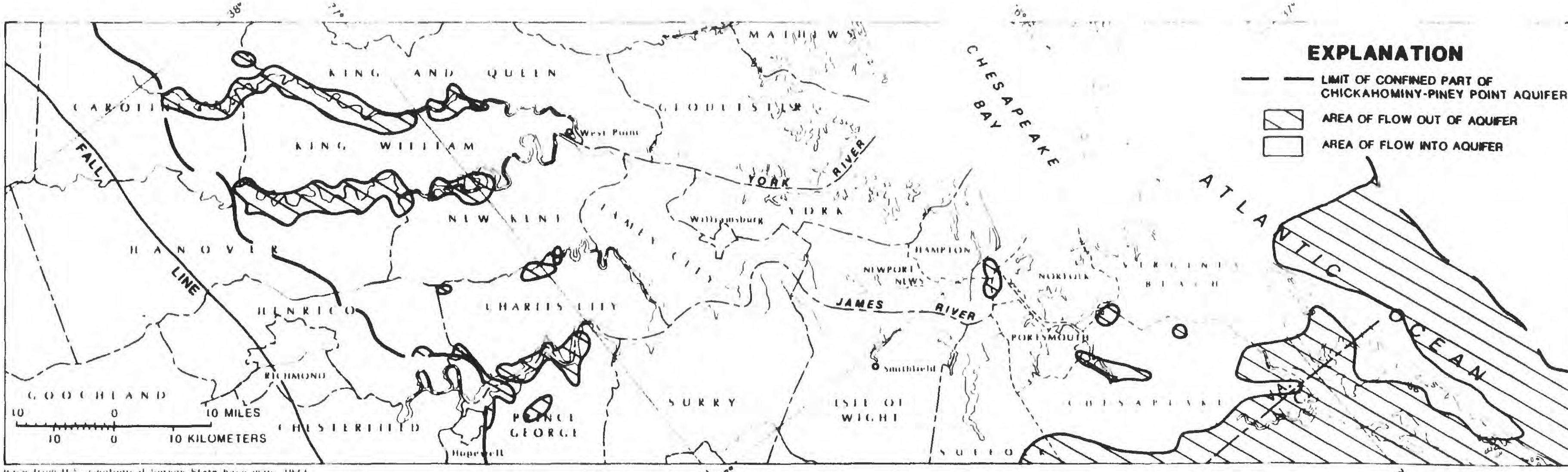


Figure 142. Direction of ground-water flow into and out of Chickahominy-Piney Point aquifer through overlying confining unit, projection IV.

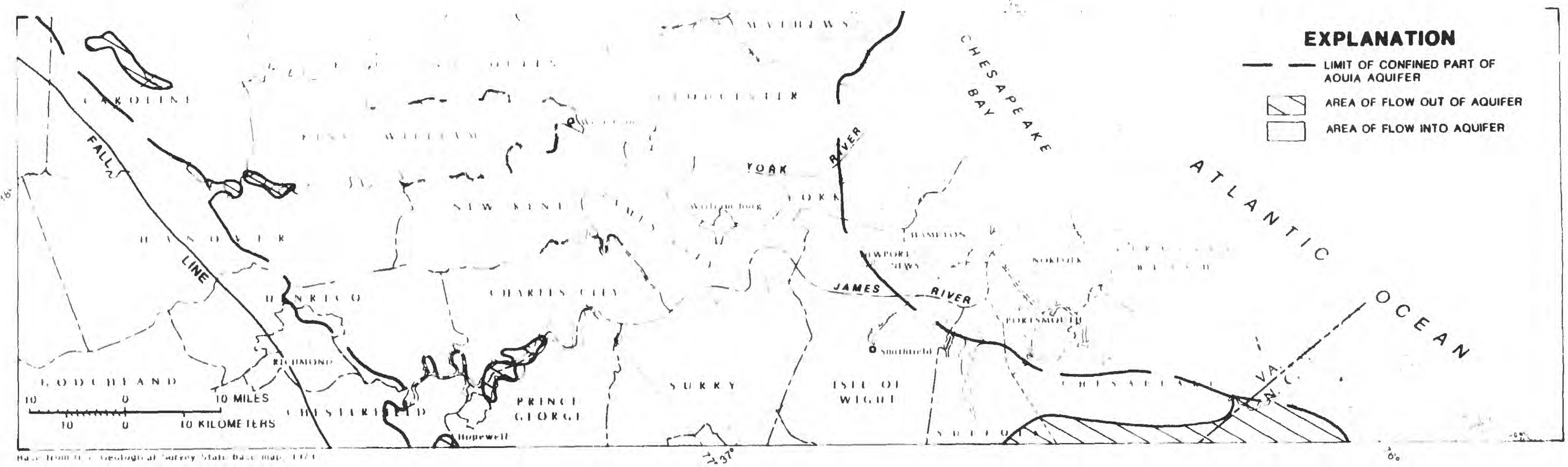


Figure 143. Direction of ground-water flow into and out of Aquia aquifer through overlying confining unit, projection IV.

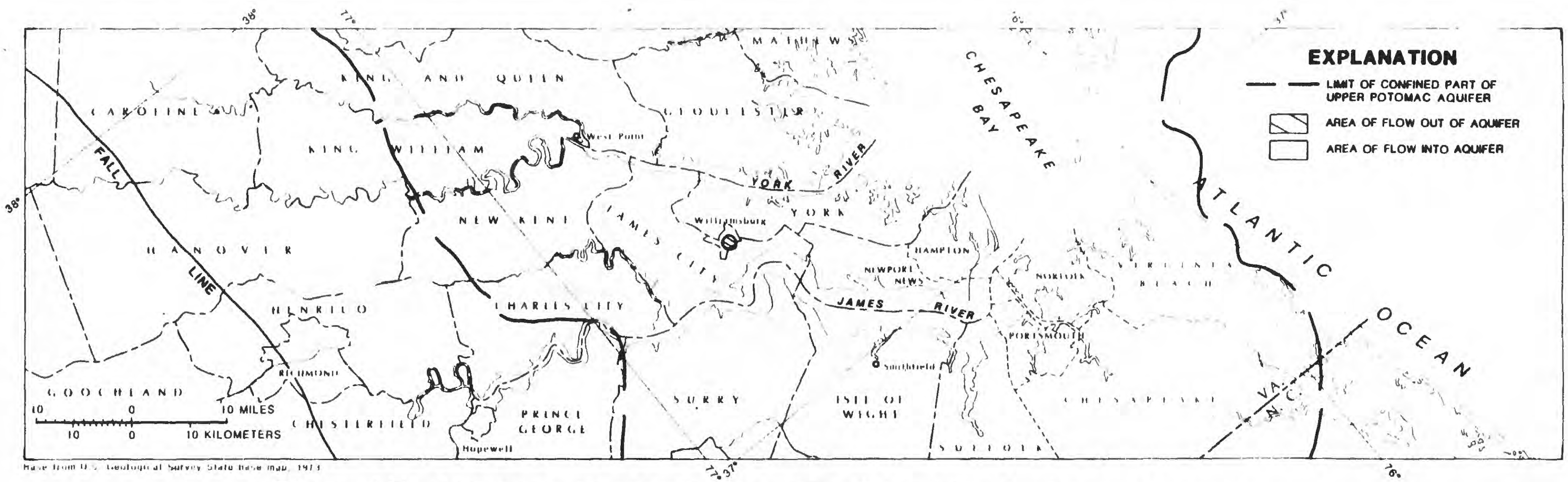


Figure 144. Direction of ground-water flow into and out of upper Potomac aquifer through overlying confining unit, projection IV.

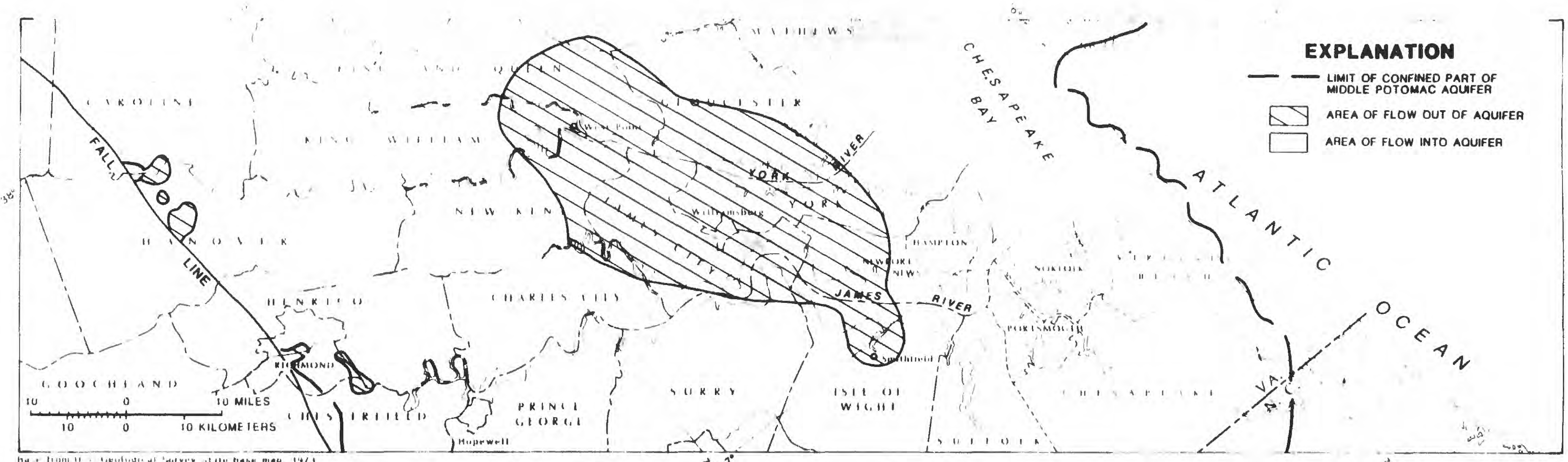


Figure 145. Direction of ground-water flow into and out of middle Potomac aquifer through overlying confining unit, projection IV.

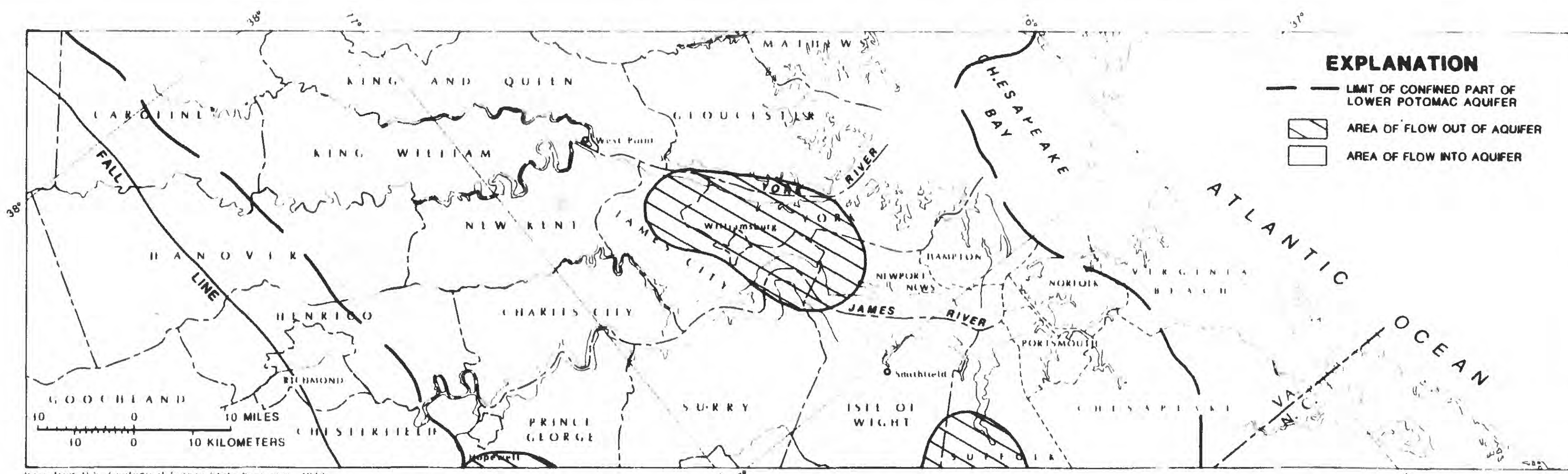


Figure 146. Direction of ground-water flow into and out of lower Potomac aquifer through overlying confining unit, projection IV.

would require that pumps be lowered in order to maintain sufficient yields and, thus, would increase energy expenditures to bring water to the user. Declines below screen intake intervals would require that wells be deepened in order to obtain water from lower horizons within the aquifer or from underlying aquifers. The cost of deepening of wells could place an enormous financial burden on existing ground-water users.

The withdrawal of ground water lowers water levels within the aquifer at the pumping center. The lowering of water levels causes water from adjacent parts of the aquifer and from adjacent aquifers to move toward the pumping center in order to replace the water withdrawn. If this replacement is with water of undesirable quality, the ground water could become unacceptable for its intended use. The model provides a method to simulate the future decline of water levels. Simulated projections provide for a comparison to determine the withdrawal scenario that would minimize future water-level declines.

Results of the projections suggest that increased ground-water withdrawal will continue to lower water levels throughout the aquifers of the York-James Peninsula. Substantial water-level declines were required to induce the recharge needed to replace the water withdrawn from the aquifers; however, water levels generally remained above the top of the respective aquifers. Because numerous users already withdraw ground water, it is far more likely that water-level declines will result in unacceptable interference among ground-water users before dewatering of aquifers becomes a concern. From a water management prospective, this means water-level declines will limit the yields from aquifers before available recharge is depleted unless existing users lower screen intakes. As the number of ground-water users grow, any future increases in withdrawal will affect more users, thus making water-level decline an even more important consideration in the management of the ground-water resource.

Results from scenarios of increased withdrawal show that the magnitude and distribution of water-level decline were dependent on the location and quantity of the water withdrawn. Water-level declines are presently a concern in (1) the Chickahominy-Piney Point aquifer near the town of West Point because water levels are approaching the top of this aquifer, (2) other confined aquifers near the town of West Point because water-level decline is already severe, and (3) the Yorktown-Eastover aquifer because the distance between water levels and the top of the aquifer is relatively small and the number of ground-water users (domestic) is already great. Projection I, which doubled withdrawal from all wells located in the Virginia Coastal Plain resulted in severe water-level declines at the established pumping centers and moderately severe decline throughout the remainder of the aquifers. Other projections, which increased withdrawal from wells located away from established pumping centers, generally resulted in less severe water-level decline in the aquifers and far less severe decline at previously established pumping centers.

Projection IV, which simulated about 21 percent less withdrawal than projection II, resulted in comparatively far less severe water-level decline and suggests that the withdrawal of ground water only as a supplement for future municipal water supply would increase the longevity of the resource. Projection III, which withdrew water from the deeper confined aquifers, had minimal effect on water levels in the Yorktown-Eastover aquifer and suggests that increased withdrawal from the deeper confined aquifers does not impact users withdrawing water from the shallow aquifers.

Results of projections show that increased withdrawal induced more recharge into the ground-water flow system to replace the water withdrawn. Contributions from individual sources of recharge were dependent on the location and quantity of the water withdrawn. Increased withdrawal from wells located outside the model area (projection I) reduced the percentage of water being replaced by lateral-boundary flow and increased the percentage being replaced by surface-water depletion. The net result would be decreased baseflow to streams.

The quality of water recharging the aquifers also is crucial to the longevity of the ground-water resource as a continued supply of fresh ground water. Each projection had a different effect on the distribution and rate of recharge induced into the ground-water flow system. Most of the surface-water recharge was from brackish sources into parts of underlying aquifers not utilized for freshwater supply. Rates of induced recharge were relatively slow. Flow directions into and out of individual aquifers indicate that this water would move downward into underlying aquifers. Water-level gradients suggest that once in these underlying aquifers water would move inland toward parts of aquifers utilized for freshwater supply. The degree and extent of contamination resulting from this inland movement of salty water and the time frame in which contamination would occur are unknown. Additional withdrawal from wells located in the Yorktown-Eastover aquifer in the eastern part of York County (projections II and IV) induced local recharge from nearby overlying brackish surface-water sources directly into the aquifer.

Increased ground-water withdrawal further affected the recharge-discharge relation between aquifers. In the eastern part of the study area, freshwater aquifers are underlain by aquifers that contain a more saline water. In some areas, projected withdrawal induced local upward flow from the underlying aquifers. The distribution and rate of upward flow were dependent on the location and quantity of water withdrawn. The decline of water levels in the confined aquifers and the movement of salty water into aquifers, either from surface sources or from underlying aquifers, needs to be minimized in order to ensure the longevity of fresh ground-water supplies.

Model Application and Limitations

Application of the model as a means to simulate the regional effects of increased withdrawal on ground-water flow conditions in the York-James Peninsula is well documented by projection results. The model was not developed to predict absolute water levels within aquifers. Model results indicate that water levels within the study area are and will be dependent on withdrawals from both inside and outside the model area. The intent of this study was not to determine future ground-water use from the Coastal Plain of Virginia, but to develop a model to provide information to aid in the understanding of ground-water flow and to address concerns about the availability of the ground water for meeting future water needs.

The model successfully simulated the regional effects of simulated scenarios of increased withdrawals on ground-water flow conditions. The large spatial and temporal scale of the model prevents hydrologic analysis of local effects and effects of small-scale withdrawals. Simulation of local effects would require spatial refinement of aquifer and confining unit characteristics and of the hydrologic stresses influencing ground-water flow (withdrawal, ground-water recharge, and lateral-boundary flow). The model did not predict effects of increased withdrawal through time. This would require temporal refinement of the hydrologic stresses influencing the flow of ground water. In order to simulate short-term effects of increased withdrawal, a more detailed definition of the storage properties of the aquifers and confining units is required.

The model does not provide a comprehensive analysis of flow in the water-table aquifer or of local flow between the ground and surface water. For the model to provide a comprehensive analysis of these flows, additional data are needed to refine the spatial and temporal variations in streambed leakance, recharge to and withdrawal from the water-table aquifer, and stage of streams.

The model is based on the assumption that the seaward limit of each aquifer is the 10,000-mg/L chloride concentration (freshwater limit). This limit was simulated as a stationary no-flow boundary condition. As declines in water level expand outward from pumping centers and intercept this limit, the validity of this assumption diminishes. Simulated water-level gradients indicate a substantial potential for lateral and vertical movement of salty water into freshwater parts of aquifers, but because of the stable positioning and no-flow condition at this boundary, the model cannot accurately simulate the movement of the saltwater/freshwater interface or the hydrologic effects associated with its movement. More accurate representation of the seaward boundary requires greater knowledge of the interaction between saltwater and freshwater in the Coastal Plain aquifers. If future data show that freshwater and saltwater act as immiscible fluids and that the movement of chloride is dominated by the flow of ground water, and only regional estimates of the position of saltwater are desired, then a sharp interface approach to simulating this boundary would be appropriate. If data indicate the two fluids are highly miscible and changes in chloride concentration need to be known, then a solute transport approach to saltwater movement would be required. Either approach requires more knowledge of present chloride distributions within aquifers and improved definition of the aquifer and confining unit properties that characterize the flow of ground water and the transport of solutes through the ground-water flow system.

SUMMARY

Ground water is an important resource of the York-James Peninsula that historically has provided a major part of the peninsula's freshwater supply. The continued withdrawal of ground water has caused a lowering of water levels throughout the multiaquifer system and has created cones of depression centered at and expanding outward from areas of concentrated ground-water use. Withdrawal is expected to increase, further lowering water levels. This is expected to result in interference among ground-water users and the possible movement of salty water into freshwater parts of aquifers. The availability of ground water for meeting future water needs has become a matter of local and regional concern. A digital flow model was used to aid in the hydrologic assessment of the ground-water resource of the York-James Peninsula.

The sediment of the York-James Peninsula forms a layered sequence of aquifers and intervening confining units. A water-table aquifer, seven confined aquifers, and intervening confining units were identified from lithologic and geophysical logs, water-level and water-quality data, and paleontologic and mineralogic analyses of core samples. Delineated aquifers from youngest to oldest are the Columbia, Yorktown-Eastover, Chickahominy-Piney Point, Aquia, and upper, middle, and lower Potomac aquifers. The Columbia aquifer is the only aquifer unconfined throughout its entire extent.

Hydrogeologic data were compiled and analyzed to characterize the hydrologic and physical properties of the aquifers and confining units. Annual ground-water withdrawal from the model area was compiled by user and aquifer. Total ground-water use, excluding domestic and irrigation, was estimated to be about 39 Mgal/d in 1983. About 87 percent (34 Mgal/d) of the 1983 use was withdrawn from the upper, middle, and lower Potomac aquifers. The upper and middle Potomac aquifers have supplied the majority of ground water withdrawn from the study area. The importance of an aquifer to local water supply varies over the study area. Ground water is withdrawn primarily from the middle and lower Potomac aquifers in the western part of the study area, from the Chickahominy-Piney Point and upper and middle Potomac aquifers in the central part, and from the Columbia and Yorktown-Eastover aquifers in the eastern part. The largest withdrawal of ground-water from the York-James Peninsula is centered near the town of West Point and was estimated to be about 15.6 Mgal/d in 1983.

Quality is an important consideration in evaluating the availability of ground water. Ground-water quality differs throughout the multiaquifer system because of contact with minerals in the sediment and mixing with resident salty water. Ground-water is characterized as a calcium-bicarbonate type water in recharge areas, changes to a sodium-bicarbonate type water downgradient from the recharge areas, and finally changes to a sodium-chloride type water approaching sites of regional discharge (Chesapeake Bay and Atlantic Ocean). Chemical constituents of greatest concern are chloride, iron, dissolved solids, fluoride, hardness, and sodium. Specific water-quality problems within individual aquifers differ. The Yorktown-Eastover aquifers contain water with high concentrations of chloride and sodium in areas fringing Chesapeake Bay and hardness in the eastern half of the peninsula. The Chickahominy-Piney Point aquifer contains water with high concentrations of chloride, sodium, dissolved solids, and fluoride in the eastern part and

hardness in the central and western part of the peninsula. The Aquia aquifer contains water with elevated concentrations of chloride, sodium, dissolved solids, and fluoride in the eastern part and hardness in the western part of the peninsula. The upper Potomac aquifer contains water with elevated concentrations of chloride, sodium, and dissolved solids in the eastern part, fluoride in the central and eastern part, and hardness in the western part of the peninsula. The middle Potomac aquifer contains water with elevated concentrations of chloride, sodium, and dissolved solids in the eastern part and hardness in the western part of the peninsula. Local areas within this aquifer contain water with elevated concentrations of fluoride and dissolved solids. The lower Potomac aquifer contains water with high concentrations of chloride, sodium, and dissolved solids in the eastern and central part and hardness in the eastern part of the peninsula. Iron is a local problem in all aquifers. The middle and lower Potomac aquifers, in the western part of the peninsula, contain water of the best quality for potable supply within the peninsula.

Aquifer transmissivity and storage coefficients and confining-unit vertical leakance were estimated by field and laboratory methods. Aquifer transmissivities and storage coefficients were determined from aquifer and specific-capacity test data. Aquifer-test data analyzed by "leaky methods" are believed to best approximate aquifer transmissivities in the peninsula. Laboratory analyses of core samples provided vertical hydraulic conductivities for confining units in the study area. Vertical hydraulic conductivities generally decreased with depth.

Maps were constructed to define areal variations in aquifer transmissivity and confining-unit vertical leakance. Transmissivity generally increases eastward (downdip) from an aquifer's western limit and then begins to decrease toward its easternmost limit. The Potomac aquifers are the most transmissive aquifers in the study area. Vertical leakance decreases eastward (downdip) from a confining unit's western limit. Higher vertical leakance values within a confining unit occur where historic and present-day river systems have eroded and replaced the original confining-unit sediment with a more permeable sediment. Deeper confining units are characterized by lower vertical leakances.

A digital flow model simulated ground-water flow prior to and throughout the history of ground-water pumpage. Success of the model was determined by comparing simulated to measured water levels. Simulated water levels were in close agreement with measured values. Maximum water-level decline from prepumped-flow conditions, about 157 feet, was in the upper Potomac aquifer near the town of West Point. Other areas of substantial decline coincided with areas of concentrated ground-water withdrawal near the town of Smithfield, in the eastern part of James City County, and in the western part of the city of Newport News. Water-level gradients indicated a change in the regional direction of ground-water flow from prepumped-flow conditions toward the major pumping centers. Aquifer water levels were well above the respective tops of aquifers, except in the Chickahominy-Piney Point aquifer near the town of West Point.

Model-computed water budgets indicate that the major source replacing water withdrawn from the the ground-water flow system was reduced flow to surface water. A combination of this reduced flow to and increased flow from surface water (surface-water depletion) replaced about 87 percent or 33 of the 38 Mgal/d of water withdrawn from the model area in the final pumping period (1981-83). Net lateral-boundary flow into the ground-water flow system across lateral-flow boundaries accounted for about 12 percent or 4 Mgal/d. The remainder was replaced by water released from aquifer storage. Increased withdrawal from wells located outside the model area reduced lateral-boundary flow into the model area. Areas of greatest surface-water depletion were along major river systems in the western part of the model area where underlying confining units were incised by ancient and present-day river systems. The majority of the surface water recharging to the ground-water flow system was from sources containing salty water (Chesapeake Bay and Atlantic Ocean), but this recharge was to parts of aquifers not used for freshwater supply. Aquifer water budgets indicate that the majority of water withdrawn from individual confined aquifers was replaced through the overlying and underlying confining units (vertical leakage). Areas of recharge into aquifers through the overlying confining unit increased from prepumped-flow conditions.

Four scenarios forecast the effects of increased withdrawal on ground-water flow conditions. Results were used to assess the availability of ground water for meeting future water needs. Each scenario had different effects on the flow of water into, through, and out of the ground-water flow system. Results suggest that increased withdrawal from the aquifers will continue to lower water levels and that this decline will limit the yields from aquifers before available recharge is depleted.

Locating projected increases in withdrawal away from established pumping centers resulted in less severe water-level declines in those areas presently experiencing the greatest declines and generally throughout the major aquifers. The withdrawal of ground water for supplemental supply would lessen the severity of future water-level declines. Withdrawal from the deeper confined aquifers had minimal effect on water levels in the Yorktown-Eastover aquifer. Water-level declines resulting from withdrawal of water from the Yorktown-Eastover aquifer in eastern York County, though relatively limited in magnitude and extent, likely would affect a substantial number of users because of the extensive use of this aquifer for domestic supply.

Projected increases in withdrawal had different effects on the distribution and rate of recharge induced to replace water withdrawn from the ground-water flow system. Most recharge was from brackish surface sources, but this recharge was to parts of aquifers not used for freshwater supply. Rates of this recharge were relatively slow. Withdrawal from the Yorktown-Eastover aquifer in eastern York County induced local recharge directly from overlying brackish surface sources. Increasing withdrawal induced upward flow of water from underlying aquifers. In some cases it is likely that this water is of a more salty quality. The distribution and rate of induced upward recharge were dependent on the location and quantity of the withdrawal. Water-level declines and the movement of salty water into the aquifers need to be minimized in order to ensure the longevity of the ground-water resource. This model provides a means for forecasting the effects of increased withdrawal that could limit future yields from the aquifers of the York-James Peninsula.

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Appendix--Selected well records and hydrogeological data.

Example

Local well number	Latitude (degrees-minutes-seconds)	Longitude (degrees-minutes-seconds)	Owner	Altitude of land surface (feet)	Altitude of bottom of logged hole (feet)	Types of logs used
51H 5	36 28 21 N	077 22 35 W	VARINA HIGH SCHOOL	140	-76 BSMT	D,E

CU1 35	CU2 15	CU3 M	CU4 M	CU6 34	CU7 M	CU8 M	CU9 M		
AQ1 M	AQ2 +43	AQ3 M	AQ4 M	AQ6 +76	AQ7 M	AQ8 M	AQ9 +140	AQ10 M	

Explanation of abbreviations and symbols

BSMT	Basement
D	Driller's log
E	Electric log
G	Geologic log
J	Gamma log

Confining unit name

CU1	Lower Potomac	CU6	Nanjemoy-Marlboro
CU2	Middle Potomac	CU7	Calvert
CU3	Upper Potomac	CU8	St. Marys
CU4	Virginia Beach	CU9	Yorktown

M	Confining unit not present in well
38	Thickness in feet of confining unit
--	No data

Aquifer name

AQ1	Lower Potomac	AQ7	Chickahominy-Piney Point
AQ2	Middle Potomac	AQ8	St. Marys-Choptank
AQ3	Upper Potomac	AQ9	Yorktown-Eastover
AQ4	Virginia Beach	AQ10	Columbia
AQ6	Aquia		

M	Aquifer not present in well
+55	Altitude of top of aquifer in feet above (+) or below (-) NGVD of 1929
--	No data

Appendix--continued

Local well number	Latitude (degrees-minutes-seconds)	Longitude (degrees-minutes-seconds)		Owner			Altitude of land surface (feet)	Altitude of bottom of logged hole (feet)	Types of logs used
51H 5	37 28 21 N	077 22 35 W		VARINA HIGH SCHOOL			140	-76	BSMT D,E
	CU1 35	CU2 15	CU3 M	CU4 M	CU6 34	CU7 M	CU8 M	CU9 M	
	AQ1 M	AQ2 +43	AQ3 M	AQ4 M	AQ6 +76	AQ7 M	AQ8 M	AQ9 +140	AQ10 M
51H 6	37 25 16 N	077 25 31 W		RICHMOND NAT. BATTLEFIELD PARK			85	-91	BSMT D,E,J
	CU1 --	CU2 24	CU3 M	CU4 M	CU6 14	CU7 M	CU8 M	CU9 M	
	AQ1 --	AQ2 -5	AQ3 M	AQ4 M	AQ6 +31	AQ7 M	AQ8 M	AQ9 +85	AQ10 M
51J 8	37 33 06 N	077 23 18 W		GLENWOOD GOLF COURSE			140	-87	BSMT D,E
	CU1 21	CU2 13	CU3 M	CU4 M	CU6 46	CU7 27	CU8 M	CU9 M	
	AQ1 -77	AQ2 -8	AQ3 M	AQ4 M	AQ6 +30	AQ7 M	AQ8 M	AQ9 +140	AQ10 M
51J 9	37 36 41 N	077 23 23 W		E. G. WADE			170	-48	BSMT D,E
	CU1 6	CU2 20	CU3 M	CU4 M	CU6 52	CU7 38	CU8 M	CU9 M	
	AQ1 M	AQ2 0	AQ3 M	AQ4 M	AQ6 +30	AQ7 M	AQ8 M	AQ9 +170	AQ10 M
51J 10	37 30 50 N	077 22 48 W		COMMONWEALTH SAND & GRAVEL CO.			155	-128	D,E
	CU1 >24	CU2 19	CU3 M	CU4 M	CU6 53	CU7 29	CU8 M	CU9 M	
	AQ1 --	AQ2 +13	AQ3 M	AQ4 M	AQ6 +52	AQ7 M	AQ8 M	AQ9 +155	AQ10 M
51K 7	37 39 22 N	077 22 34 W		SYDNOR HYDRODYNAMICS, INC.			180	-126	BSMT D,E
	CU1 20	CU2 25	CU3 M	CU4 M	CU6 50	CU7 52	CU8 M	CU9 M	
	AQ1 M	AQ2 +13	AQ3 M	AQ4 M	AQ6 +46	AQ7 M	AQ8 M	AQ9 +180	AQ10 M
51K 8	37 40 27 N	077 25 18 W		BEECHWOOD FARMS			200	+23	BSMT D,E
	CU1 17	CU2 18	CU3 M	CU4 M	CU6 35	CU7 M	CU8 M	CU9 M	
	AQ1 M	AQ2 +82	AQ3 M	AQ4 M	AQ6 M	AQ7 M	AQ8 M	AQ9 +200	AQ10 M
51K 10	37 43 51 N	077 25 08 W		L. O. SNEAD			200	-9	BSMT D,E,G,J
	CU1 17	CU2 10	CU3 M	CU4 M	CU6 48	CU7 45	CU8 M	CU9 M	
	AQ1 M	AQ2 +50	AQ3 M	AQ4 M	AQ6 +82	AQ7 M	AQ8 M	AQ9 +200	AQ10 M

Appendix--continued

52G 11	37 20 33 N	077 17 12 W		PHILIP MORRIS, INC.		20	-198	D,E	
	CU1 24	CU2 15	CU3 M	CU4 M	CU6 M	CU7 M	CU8 M	CU9 M	
	AQ1 -194	AQ2 -20	AQ3 M	AQ4 M	AQ6 M	AQ7 M	AQ8 M	AQ9 M	AQ10 +20
52H 8	37 28 59 N	077 22 03 W		HENRICO COUNTY SCHOOL BOARD		150	-135	BSMT D,E,G	
	CU1 18	CU2 8	CU3 M	CU4 M	CU6 35	CU7 19	CU8 M	CU9 M	
	AQ1 M	AQ2 +34	AQ3 M	AQ4 M	AQ6 +65	AQ7 M	AQ8 M	AQ9 +150	AQ10 M
52J 11	37 37 11 N	077 19 30 W		SYDNOR HYDRODYNAMICS, INC.		170	-240	BSMT D,E	
	CU1 --	CU2 30	CU3 M	CU4 M	CU6 73	CU7 50	CU8 M	CU9 M	
	AQ1 --	AQ2 -77	AQ3 M	AQ4 M	AQ6 -23	AQ7 +70	AQ8 M	AQ9 +170	AQ10 M
52J 12	37 31 13 N	077 16 38 W		COUNTY OF HENRICO		160	-444	D,E,G	
	CU1 30	CU2 40	CU3 M	CU4 M	CU6 81	CU7 43	CU8 M	CU9 M	
	AQ1 -328	AQ2 -106	AQ3 M	AQ4 M	AQ6 -24	AQ7 +62	AQ8 M	AQ9 +160	AQ10 M
52J 18	37 32 40 N	077 21 37 W		HECKLER VILLAGE		150	-180	D,E	
	CU1 >8	CU2 30	CU3 M	CU4 M	CU6 45	CU7 39	CU8 M	CU9 M	
	AQ1 --	AQ2 -38	AQ3 M	AQ4 M	AQ6 +25	AQ7 +86	AQ8 M	AQ9 +150	AQ10 M
52J 21	33 36 00 N	077 22 11 W		COLD HARBOR VILLAGE		160	-150	BSMT D,E	
	CU1 M	CU2 36	CU3 M	CU4 M	CU6 67	CU7 56	CU8 M	CU9 M	
	AQ1 M	AQ2 -46	AQ3 M	AQ4 M	AQ6 +11	AQ7 M	AQ8 M	AQ9 +160	AQ10 M
52J 24	37 31 29 N	077 18 21 W		COUNTY OF HENRICO		155	-301	BSMT D,E	
	CU1 37	CU2 44	CU3 M	CU4 M	CU6 50	CU7 25	CU8 M	CU9 M	
	AQ1 -245	AQ2 -55	AQ3 M	AQ4 M	AQ6 +23	AQ7 +85	AQ8 M	AQ9 +155	AQ10 M
52J 25	37 33 00 N	077 20 24 W		SHU-LU CORPORATION		160	-154	D,E	
	CU1 --	CU2 23	CU3 M	CU4 M	CU6 48	CU7 44	CU8 M	CU9 M	
	AQ1 --	AQ2 -51	AQ3 M	AQ4 M	AQ6 +2	AQ7 +66	AQ8 M	AQ9 +160	AQ10 M

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52J 27     37 31 16 N  077 20 06 W     COUNTY OF HENRICO              155      -193        D,E

           CU1  26    CU2  44    CU3  M     CU4  M     CU6  23    CU7  38    CU8  M     CU9  M
           AQ1 -181   AQ2 -13    AQ3  M     AQ4  M     AQ6 +59    AQ7  M     AQ8  M     AQ9 +155   AQ10  M

52J 30     37 30 34 N  077 19 20 W     BYRD INTERNATIONAL AIRPORT     160      -88         D,E

           CU1  --    CU2  35    CU3  M     CU4  M     CU6  47    CU7  26    CU8  M     CU9  M
           AQ1  --    AQ2 -58    AQ3  M     AQ4  M     AQ6 +30    AQ7 +88    AQ8  M     AQ9 +160   AQ10  M

52J 31     37 34 31 N  077 19 18 W     F. D. THARPS                    70      -236        D,E

           CU1  --    CU2  28    CU3  M     CU4  M     CU6  44    CU7  13    CU8  M     CU9  M
           AQ1  --    AQ2 -84    AQ3  M     AQ4  M     AQ6 -28    AQ7 +45    AQ8  M     AQ9 +70    AQ10  M

52J 32     38 37 24 N  077 19 18 W     SYDNOR HYDRODYNAMICS, INC.     160      -140        D,E

           CU1  --    CU2  21    CU3  M     CU4  M     CU6  64    CU7  43    CU8  M     CU9  M
           AQ1  --    AQ2 -30    AQ3  M     AQ4  M     AQ6 +6     AQ7 +82    AQ8  M     AQ9 +160   AQ10  M

52J 33     37 36 06 N  077 20 49 W     SYDNOR HYDRODYNAMICS, INC.     170      -252   BSMT D,E

           CU1  23    CU2  12    CU3  M     CU4  M     CU6  46    CU7  49    CU8  M     CU9  M
           AQ1  M     AQ2 -48    AQ3  M     AQ4  M     AQ6 -7     AQ7 +66    AQ8  M     AQ9 +170   AQ10  M

52K  6     37 39 15 N  077 21 46 W     SYDNOR HYDRODYNAMICS, INC.     180      -190        D,E

           CU1  --    CU2  22    CU3  M     CU4  M     CU6  31    CU7  42    CU8  M     CU9  M
           AQ1  --    AQ2 -6     AQ3  M     AQ4  M     AQ6 +29    AQ7 +72    AQ8  M     AQ9 +180   AQ10  M

52K  9     37 42 28 N  077 22 01 W     E. S. ROBERTSON                170      -90         D,E

           CU1  --    CU2  21    CU3  M     CU4  M     CU6  15    CU7  32    CU8  M     CU9  M
           AQ1  --    AQ2 +5     AQ3  M     AQ4  M     AQ6 +38    AQ7 +70    AQ8  M     AQ9 +170   AQ10  M

52K 10     37 37 31 N  077 17 49 W     CONTINENTAL TELEPHONE, INC.    190      -177        D,E,G

           CU1  --    CU2  52    CU3  M     CU4  M     CU6  66    CU7  47    CU8  M     CU9  M
           AQ1  --    AQ2 -144   AQ3  M     AQ4  M     AQ6 -46    AQ7 +68    AQ8  M     AQ9 +190   AQ10  M
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52K 11	37 41 10 N	077 21 15 W		COLONIAL FORREST SUBDIV.		185	-145	D,E	
	CU1 --	CU2 35	CU3 M	CU4 M	CU6 70	CU7 49	CU8 M	CU9 M	
	AQ1 --	AQ2 -70	AQ3 M	AQ4 M	AQ6 -1	AQ7 +91	AQ8 M	AQ9 +185	AQ10 M
52L 2	37 47 51 N	077 19 55 W		KIWANIS CLUB OF RICHMOND		190	-130	D,E,G	
	CU1 --	CU2 26	CU3 M	CU4 M	CU6 62	CU7 44	CU8 M	CU9 M	
	AQ1 --	AQ2 -62	AQ3 M	AQ4 M	AQ6 -2	AQ7 +72	AQ8 M	AQ9 +190	AQ10 M
52L 4	37 46 05 N	077 16 43 W		C. W. ENGEL		60	-210	D,E	
	CU1 --	CU2 60	CU3 M	CU4 M	CU6 62	CU7 M	CU8 M	CU9 M	
	AQ1 --	AQ2 -112	AQ3 M	AQ4 M	AQ6 -30	AQ7 M	AQ8 M	AQ9 M	AQ10 +60
52M 2	37 54 02 N	077 19 05 W		D. C. BURRUSS		105	-157	D,E	
	CU1 --	CU2 74	CU3 M	CU4 M	CU6 61	CU7 17	CU8 M	CU9 M	
	AQ1 --	AQ2 -103	AQ3 M	AQ4 M	AQ6 -1	AQ7 +76	AQ8 M	AQ9 M	AQ10 +105
52N 14	38 01 06 N	077 21 22 W		USGS		145	-7	E,G,J	
	CU1 --	CU2 >20	CU3 M	CU4 M	CU6 50	CU7 M	CU8 M	CU9 M	
	AQ1 --	AQ2 --	AQ3 M	AQ4 M	AQ6 +75	AQ7 M	AQ8 M	AQ9 +145	AQ10 M
52N 16	38 03 23 N	077 20 47 W		TOWN OF BOWLING GREEN		205	-314	D,E	
	CU1 57	CU2 54	CU3 M	CU4 M	CU6 21	CU7 34	CU8 M	CU9 M	
	AQ1 -266	AQ2 -43	AQ3 M	AQ4 M	AQ6 +78	AQ7 +111	AQ8 M	AQ9 +205	AQ10 M
53G 13	37 21 05 N	077 11 36 W		CHARLES CITY COUNTY		75	-250	D,E	
	CU1 --	CU2 20	CU3 17	CU4 M	CU6 44	CU7 9	CU8 M	CU9 M	
	AQ1 --	AQ2 -127	AQ3 M	AQ4 M	AQ6 -39	AQ7 +35	AQ8 M	AQ9 +75	AQ10 M
53J 7	37 30 58 N	077 13 59 W		BRADLEY ACRES		130	-510	BSMT D,E,G	
	CU1 8	CU2 8	CU3 M	CU4 M	CU6 46	CU7 42	CU8 M	CU9 M	
	AQ1 -360	AQ2 -98	AQ3 M	AQ4 M	AQ6 -38	AQ7 +44	AQ8 M	AQ9 +130	AQ10 M

53K 17	37 43 42 N 077 08 39 W	C&N CORPORATION	160	-240	D,E				
	CU1 --	CU2 18	CU3 18	CU4 M	CU6 54	CU7 68	CU8 10	CU9 M	
	AQ1 --	AQ2 -198	AQ3 M	AQ4 M	AQ6 -86	AQ7 +22	AQ8 M	AQ9 +160	AQ10 M
53K 18	37 38 15 N 077 07 50 W	D. FLEET	30	-338	D,E				
	CU1 --	CU2 44	CU3 34	CU4 M	CU6 58	CU7 20	CU8 M	CU9 M	
	AQ1 --	AQ2 -240	AQ3 M	AQ4 M	AQ6 -92	AQ7 -5	AQ8 M	AQ9 M	AQ10 +30
53L 2	37 45 40 N 077 09 21 W	L. A. LIPSCOMB	140	-290	D,E				
	CU1 --	CU2 46	CU3 12	CU4 M	CU6 64	CU7 74	CU8 16	CU9 M	
	AQ1 --	AQ2 -244	AQ3 M	AQ4 M	AQ6 -108	AQ7 +4	AQ8 M	AQ9 +140	AQ10 M
54G 10	37 19 56 N 077 05 52 W	VASWCB	35	-545	BSMT E,G,J				
	CU1 12	CU2 26	CU3 M	CU4 M	CU6 42	CU7 17	CU8 M	CU9 M	
	AQ1 -455	AQ2 -174	AQ3 M	AQ4 M	AQ6 -95	AQ7 -22	AQ8 M	AQ9 M	AQ10 +35
54H 4	37 29 51 N 077 07 19 W	WOODHAVEN SHORES, INC.	110	-390	D,E				
	CU1 --	CU2 14	CU3 15	CU4 M	CU6 44	CU7 53	CU8 M	CU9 M	
	AQ1 --	AQ2 -204	AQ3 -146	AQ4 M	AQ6 -100	AQ7 +22	AQ8 M	AQ9 +110	AQ10 M
54H 11	37 29 58 N 077 02 36 W	VIRGINIA DEPT. OF HIGHWAYS	65	-338	D,E,J				
	CU1 --	CU2 28	CU3 10	CU4 M	CU6 42	CU7 33	CU8 M	CU9 M	
	AQ1 --	AQ2 -255	AQ3 -211	AQ4 M	AQ6 -129	AQ7 -14	AQ8 M	AQ9 +65	AQ10 M
54J 4	37 32 07 N 077 06 52 W	KENWOOD FARMS, INC.	160	-343	D,E,J				
	CU1 --	CU2 24	CU3 18	CU4 M	CU6 45	CU7 60	CU8 M	CU9 M	
	AQ1 --	AQ2 -207	AQ3 -142	AQ4 M	AQ6 -101	AQ7 +16	AQ8 M	AQ9 +160	AQ10 M
55E 1	37 02 45 N 076 56 06 W	TOWN OF DENDRON	110	-400	D,E,G				
	CU1 --	CU2 55	CU3 32	CU4 M	CU6 21	CU7 40	CU8 20	CU9 27	
	AQ1 --	AQ2 -323	AQ3 -192	AQ4 M	AQ6 -96	AQ7 -66	AQ8 M	AQ9 +45	AQ10 +110

55E 3	37 04 51 N	076 54 18 W	SURRY COUNTY	90	-390	D,E,G			
	CU1 --	CU2 46	CU3 23	CU4 M	CU6 29	CU7 32	CU8 26	CU9 20	
	AQ1 --	AQ2 -356	AQ3 -198	AQ4 M	AQ6 -121	AQ7 -68	AQ8 M	AQ9 +44	AQ10 +90
55F 20	37 13 21 N	076 57 06 W	TOWN OF CLAREMONT	90	-313	D,E			
	CU1 --	CU2 28	CU3 11	CU4 M	CU6 33	CU7 34	CU8 M	CU9 10	
	AQ1 --	AQ2 -217	AQ3 -189	AQ4 M	AQ6 -113	AQ7 -58	AQ8 M	AQ9 +80	AQ10 M
55G 4	37 18 45 N	076 56 13 W	CHARLES CITY COUNTY	35	-303	D,E			
	CU1 --	CU2 30	CU3 22	CU4 M	CU6 44	CU7 44	CU8 M	CU9 M	
	AQ1 --	AQ2 -269	AQ3 -209	AQ4 M	AQ6 -153	AQ7 -58	AQ8 M	AQ9 M	AQ10 +35
55H 1	37 24 28 N	076 56 15 W	CITY OF NEWPORT NEWS	10	-768	D,E,J			
	CU1 22	CU2 20	CU3 12	CU4 M	CU6 44	CU7 42	CU8 M	CU9 M	
	AQ1 -650	AQ2 -304	AQ3 -242	AQ4 M	AQ6 -168	AQ7 -60	AQ8 M	AQ9 M	AQ10 +10
55H 6	37 23 59 N	076 54 04 W	SOUTHERN PROPERTIES, INC.	95	-183	D,E			
	CU1 --	CU2 --	CU3 --	CU4 --	CU6 >30	CU7 49	CU8 10	CU9 14	
	AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 -71	AQ8 M	AQ9 +81	AQ10 M
55L 2	37 49 32 N	076 56 42 W	SYDNOR HYDRODYNAMICS, INC.	170	-130	D,E			
	CU1 --	CU2 --	CU3 --	CU4 --	CU6 >8	CU7 85	CU8 65	CU9 15	
	AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 -59	AQ8 M	AQ9 +155	AQ10 M
56F 16	37 14 34 N	076 48 15 W	SYDNOR HYDRODYNAMICS, INC.	30	-465	D,E,G			
	CU1 --	CU2 60	CU3 16	CU4 M	CU6 53	CU7 40	CU8 18	CU9 M	
	AQ1 --	AQ2 -368	AQ3 -254	AQ4 M	AQ6 -211	AQ7 -94	AQ8 M	AQ9 M	AQ10 +30
56F 42	37 08 32 N	076 50 27 W	SYDNOR HYDRODYNAMICS, INC.	110	-375	D,E,G			
	CU1 --	CU2 28	CU3 12	CU4 M	CU6 33	CU7 38	CU8 22	CU9 24	
	AQ1 --	AQ2 -308	AQ3 -226	AQ4 M	AQ6 -156	AQ7 -82	AQ8 M	AQ9 +56	AQ10 +110

56G 5	37 19 10 N 076 45 43 W			JAMES CITY CO. AUTHORITY		90	-307	D,E	
	CU1 --	CU2 --	CU3 >39	CU4 M	CU6 46	CU7 50	CU8 40	CU9 24	
	AQ1 --	AQ2 --	AQ3 --	AQ4 M	AQ6 -226	AQ7 -106	AQ8 M	AQ9 +53	AQ10 +90
56G 6	37 19 05 N 076 47 12 W			JAMES CITY SERVICE AUTHORITY		120	-306	D,E,G,J	
	CU1 --	CU2 --	CU3 19	CU4 M	CU6 62	CU7 60	CU8 M	CU9 23	
	AQ1 --	AQ2 --	AQ3 -279	AQ4 M	AQ6 -232	AQ7 -104	AQ8 M	AQ9 +56	AQ10 +120
56G 9	37 21 49 N 076 46 12 W			JAMES CITY SCHOOL BOARD		105	-195	D,E	
	CU1 --	CU2 --	CU3 --	CUBS --	CU6 >24	CU7 57	CU8 M	CU9 24	
	AQ1 --	AQ2 --	AQ3 --	AQBS --	AQ6 --	AQ7 -109	AQ8 M	AQ9 +57	AQ10 +105
56G 52	37 16 24 N 076 46 20 W			POWHATAN ENTERPRISES, INC.		90	-218	D,E	
	CU1 --	CU2 --	CU3 --	CU4 M	CU6 59	CU7 40	CU8 68	CU9 15	
	AQ1 --	AQ2 --	AQ3 --	AQ4 M	AQ6 -203	AQ7 -94	AQ8 M	AQ9 +55	AQ10 +90
56H 25-30	37 25 06 N 076 51 17 W			JAMES CITY CO. RES. STA.(RS-1)		100	-905	D,E,G,J	
	CU1 28	CU2 64	CU3 11	CU4 M	CU6 52	CU7 54	CU8 10	CU9 16	
	AQ1 -736	AQ2 -350	AQ3 -263	AQ4 M	AQ6 -186	AQ7 -64	AQ8 M	AQ9 +64	AQ10 +100
56J 5	37 32 46 N 076 48 30 W			CHESAPEAKE CORPORATION		25	-1252 BSMT	D,E,J	
	CU1 34	CU2 72	CU3 38	CU4 10	CU6 82	CU7 40	CU8 16	CU9 5	
	AQ1 -885	AQ2 -503	AQ3 -343	AQ4 -295	AQ6 -251	AQ7 -85	AQ8 M	AQ9 +2	AQ10 +25
56J 11	37 31 26 N 076 45 41 W			CHESAPEAKE CORPORATION		15	-1255 BSMT	D,E,G	
	CU1 32	CU2 50	CU3 81	CU4 21	CU6 86	CU7 50	CU8 20	CU9 6	
	AQ1 -931	AQ2 -557	AQ3 -434	AQ4 -330	AQ6 -279	AQ7 -119	AQ8 M	AQ9 -5	AQ10 +15
57D 3	36 59 27 N 076 37 58 W			SMITHFIELD PACKING COMPANY		30	-570	E	
	CU1 --	CU2 32	CU3 22	CU4 M	CU6 47	CU7 50	CU8 26	CU9 18	
	AQ1 --	AQ2 -503	AQ3 -310	AQ4 M	AQ6 -279	AQ7 -200	AQ8 M	AQ9 -28	AQ10 +30

57D 20	36 52 32 N 076 40 56 W	CITY OF VIRGINIA BEACH			50	-910	D,E		
	CU1 >10	CU2 30	CU3 30	CU4 M	CU6 45	CU7 30	CU8 M	CU9 43	
	AQ1 --	AQ2 -412	AQ3 -290	AQ4 M	AQ6 -238	AQ7 -140	AQ8 M	AQ9 -25	AQ10 +50
57E 10	37 02 36 N 076 42 59 W	VASWCB			85	-615	D,E		
	CU1 --	CU2 24	CU3 11	CU4 M	CU6 40	CU7 55	CU8 15	CU9 25	
	AQ1 --	AQ2 -405	AQ3 -272	AQ4 M	AQ6 -215	AQ7 -145	AQ8 M	AQ9 +14	AQ10 +85
57F 2	37 14 21 N 076 38 28 W	WILLIAMSBURG COUNTRY CLUB			80	-513	D,E		
	CU1 --	CU2 24	CU3 20	CU4 M	CU6 68	CU7 80	CU8 56	CU9 24	
	AQ1 --	AQ2 -476	AQ3 -380	AQ4 M	AQ6 -320	AQ7 -214	AQ8 M	AQ9 +16	AQ10 +80
57F 3	37 09 16 N 076 40 19 W	VEPCO			25	-390	D,E		
	CU1 --	CU2 --	CU3 31	CU4 M	CU6 66	CU7 52	CU8 48	CU9 14	
	AQ1 --	AQ2 --	AQ3 -353	AQ4 M	AQ6 -294	AQ7 -187	AQ8 M	AQ9 -9	AQ10 +25
57F 7	37 13 43 N 076 40 08 W	BUSCH PROPERTIES, INC.			55	-455	D,E,G,J		
	CU1 --	CU2 16	CU3 23	CU4 M	CU6 77	CU7 68	CU8 58	CU9 21	
	AQ1 --	AQ2 -453	AQ3 -361	AQ4 M	AQ6 -301	AQ7 -195	AQ8 M	AQ9 -5	AQ10 +55
57F 26	37 09 51 N 076 41 57 W	VEPCO			35	-385	D,E		
	CU1 --	CU2 --	CU3 24	CU4 M	CU6 62	CU7 70	CU8 47	CU9 12	
	AQ1 --	AQ2 --	AQ3 -357	AQ4 M	AQ6 -285	AQ7 -167	AQ8 M	AQ9 -19	AQ10 +35
57G 1	37 17 49 N 076 44 18 W	EASTERN STATE HOSPITAL			90	-494	D,E,J		
	CU1 --	CU2 46	CU3 10	CU4 M	CU6 74	CU7 52	CU8 48	CU9 27	
	AQ1 --	AQ2 -403	AQ3 -318	AQ4 M	AQ6 -266	AQ7 -144	AQ8 M	AQ9 +38	AQ10 +90
57G 21	37 15 39 N 076 40 06 W	SYDNOR HYDRODYNAMICS, INC.			80	-420	D,E		
	CU1 --	CU2 --	CU3 6	CU4 M	CU6 90	CU7 72	CU8 70	CU9 30	
	AQ1 --	AQ2 --	AQ3 -356	AQ4 M	AQ6 -316	AQ7 -192	AQ8 M	AQ9 +16	AQ10 +80

57G 22	37 19 34 N	076 44 14 W	SYDNOR HYDRODYNAMICS, INC.				100	-325	D,E,G	
	CU1 --	CU2 --	CU3 >35	CU4 M	CU6 62	CU7 66	CU8 20	CU9 21		
	AQ1 --	AQ2 --	AQ3 --	AQ4 M	AQ6 -250	AQ7 -136	AQ8 M	AQ9 +44	AQ10 +100	
57G 25	37 16 05 N	076 42 03 W	COLONIAL WILLIAMSBURG				70	-428	D,E	
	CU1 --	CU2 >28	CU3 18	CU4 M	CU6 66	CU7 60	CU8 36	CU9 22		
	AQ1 --	AQ2 --	AQ3 -334	AQ4 M	AQ6 -288	AQ7 -176	AQ8 M	AQ9 +24	AQ10 +70	
57G 30	37 15 56 N	076 41 51 W	COLONIAL WILLIAMSBURG				55	-445	D,E	
	CU1 --	CU2 >49	CU3 8	CU4 M	CU6 71	CU7 66	CU8 30	CU9 15		
	AQ1 --	AQ2 --	AQ3 -315	AQ4 M	AQ6 -295	AQ7 -181	AQ8 M	AQ9 +20	AQ10 +55	
57G 66	37 18 59 N	076 42 02 W	WALLER MILL PARK				70	-428	D,E	
	CU1 --	CU2 --	CU3 33	CU4 M	CU6 75	CU7 82	CU8 35	CU9 12		
	AQ1 --	AQ2 --	AQ3 -345	AQ4 M	AQ6 -282	AQ7 -164	AQ8 M	AQ9 +38	AQ10 +70	
57H 6	37 23 10 N	076 41 14 W	TIDEWATER WATER COMPANY				50	-503	D,E	
	CU1 --	CU2 22	CU3 20	CU4 M	CU6 74	CU7 68	CU8 30	CU9 24		
	AQ1 --	AQ2 -436	AQ3 -362	AQ4 M	AQ6 -296	AQ7 -168	AQ8 M	AQ9 +6	AQ10 +50	
57J 3	37 30 08 N	076 42 58 W	CHESAPEAKE CORPORATION				50	-1000	D,E	
	CU1 36	CU2 44	CU3 36	CU4 M	CU6 90	CU7 56	CU8 32	CU9 15		
	AQ1 -963	AQ2 -533	AQ3 -369	AQ4 M	AQ6 -297	AQ7 -137	AQ8 M	AQ9 +11	AQ10 +50	
58C 7	36 48 38 N	076 37 09 W	CITY OF NORFOLK				40	-899	D,E,G	
	CU1 --	CU2 12	CU3 41	CU4 M	CU6 53	CU7 36	CU8 M	CU9 24		
	AQ1 --	AQ2 -493	AQ3 -357	AQ4 M	AQ6 -291	AQ7 -182	AQ8 M	AQ9 -46	AQ10 +40	
58C 8	36 52 18 N	076 31 30 W	G. A. NIMMO				20	-558	E	
	CU1 --	CU2 38	CU3 21	CU4 M	CU6 63	CU7 52	CU8 26	CU9 14		
	AQ1 --	AQ2 -508	AQ3 -403	AQ4 M	AQ6 -364	AQ7 -252	AQ8 M	AQ9 -40	AQ10 +20	

58C 10	36 46 05 N	076 32 24 W	CITY OF SUFFOLK	25	-599	D,E,J			
	CU1 --	CU2 18	CU3 120	CU4 M	CU6 26	CU7 50	CU8 12	CU9 30	
	AQ1 --	AQ2 -551	AQ3 -429	AQ4 M	AQ6 -325	AQ7 -249	AQ8 M	AQ9 -35	AQ10 +25
58C 51	36 49 04 N	076 33 05 W	CITY OF NORFOLK	5	-993	D,E			
	CU1 --	CU2 14	CU3 64	CU4 M	CU6 50	CU7 46	CU8 12	CU9 34	
	AQ1 --	AQ2 -533	AQ3 -411	AQ4 M	AQ6 -334	AQ7 -241	AQ8 M	AQ9 -49	AQ10 +5
58D 6	36 59 39 N	076 33 30 W	RESCUE WATER COMPANY	20	-528	E			
	CU1 --	CU2 --	CU3 16	CU4 M	CU6 54	CU7 46	CU8 25	CU9 42	
	AQ1 --	AQ2 --	AQ3 -361	AQ4 M	AQ6 -322	AQ7 -191	AQ8 M	AQ9 -46	AQ10 +20
58D 9	36 57 27 N	076 31 39 W	VIRGINIA TIDEWATER PROPERTIES, INC.	15	-539	D,E			
	CU1 --	CU2 30	CU3 9	CU4 M	CU6 66	CU7 49	CU8 31	CU9 --	
	AQ1 --	AQ2 -501	AQ3 -384	AQ4 M	AQ6 M	AQ7 -233	AQ8 M	AQ9 --	AQ10 +15
58E 2	37 00 31 N	076 36 12 W	V. H. MONETTE CO.	25	-475	E			
	CU1 --	CU2 >10	CU3 30	CU4 M	CU6 50	CU7 44	CU8 42	CU9 33	
	AQ1 --	AQ2 --	AQ3 -358	AQ4 M	AQ6 -273	AQ7 -186	AQ8 M	AQ9 -19	AQ10 +25
58F 3	37 11 20 N	076 36 54 W	DOW BADISCHE, INC.	20	-1540	D,E,G,J			
	CU1 46	CU2 10	CU3 30	CU4 M	CU6 56	CU7 77	CU8 49	CU9 30	
	AQ1 -1124	AQ2 -498	AQ3 -398	AQ4 M	AQ6 -348	AQ7 -234	AQ8 M	AQ9 -42	AQ10 +20
58F 18	37 14 15 N	076 35 39 W	U.S. NAVY	40	-470	D,E			
	CU1 --	CU2 --	CU3 16	CU4 M	CU6 80	CU7 74	CU8 93	CU9 M	
	AQ1 --	AQ2 --	AQ3 -422	AQ4 M	AQ6 -340	AQ7 -230	AQ8 M	AQ9 +40	AQ10 M
58F 38	37 12 50 N	076 36 52 W	M. B. HITCHENS	40	-362	D,E			
	CU1 --	CU2 --	CU3 >10	CU4 M	CU6 52	CU7 82	CU8 96	CU9 M	
	AQ1 --	AQ2 --	AQ3 --	AQ4 M	AQ6 -320	AQ7 -234	AQ8 M	AQ9 +40	AQ10 M

58F 48 37 13 49 N 076 32 57 W YORK COUNTY PUBLIC WORKS 80 -100 D,E,J

CU1 -- CU2 -- CU3 -- CU4 -- CU6 -- CU7 -- CU8 >48 CU9 24
AQ1 -- AQ2 -- AQ3 -- AQ4 -- AQ6 -- AQ7 -- AQ8 -- AQ9 +2 AQ10 +80

58F 50-55 38 12 08 N 076 34 11 W NEWPORT NEWS RES. STA. (RS-2) 50 -1425 D,E,G,J

CU1 28 CU2 23 CU3 8 CU4 M CU6 70 CU7 84 CU8 55 CU9 20
AQ1 -1136 AQ2 -552 AQ3 -428 AQ4 M AQ6 -378 AQ7 -274 AQ8 M AQ9 -40 AQ10 +50

58F 57 37 09 40 N 076 34 50 W CITY OF NEWPORT NEWS 20 -474 D,E

CU1 -- CU2 -- CU3 -- CU4 -- CU6 >74 CU7 94 CU8 74 CU9 22
AQ1 -- AQ2 -- AQ3 -- AQ4 -- AQ6 -- AQ7 -330 AQ8 M AQ9 -18 AQ10 +20

58H 4 37 23 31 N 076 31 26 W VASWCB 75 -1793 BSMT D,E,G,J

CU1 18 CU2 52 CU3 21 CU4 M CU6 92 CU7 78 CU8 87 CU9 35
AQ1 -1179 AQ2 -756 AQ3 -600 AQ4 M AQ6 -539 AQ7 -323 AQ8 M AQ9 -44 AQ10 +75

58J 11 37 33 52 N 076 37 28 W RAPPAHANOCK COMMUNITY COLLEGE 110 -590 D,E

CU1 -- CU2 54 CU3 10 CU4 M CU6 97 CU7 55 CU8 78 CU9 22
AQ1 -- AQ2 -- AQ3 -384 AQ4 M AQ6 -350 AQ7 -174 AQ8 M AQ9 +26 AQ10 +110

59C 2 36 48 08 N 076 23 15 W VIRGINIA DIVISION OF FORESTRY 20 -633 E,G

CU1 -- CU2 -- CU3 50 CU4 M CU6 86 CU7 86 CU8 53 CU9 32
AQ1 -- AQ2 -- AQ3 -582 AQ4 M AQ6 M AQ7 -362 AQ8 M AQ9 -30 AQ10 +20

59C 13 36 52 18 N 076 27 47 W TIDEWATER WATER COMPANY 15 -640 D,E,J

CU1 -- CU2 >13 CU3 30 CU4 M CU6 66 CU7 60 CU8 58 CU9 36
AQ1 -- AQ2 -- AQ3 -492 AQ4 M AQ6 M AQ7 -314 AQ8 M AQ9 -42 AQ10 +15

59C 28 36 47 02 N 076 24 55 W CITY OF CHESAPEAKE 20 -980 D,E,J

CU1 -- CU2 20 CU3 73 CU4 M CU6 33 CU7 72 CU8 44 CU9 32
AQ1 -- AQ2 -800 AQ3 -518 AQ4 M AQ6 M AQ7 -341 AQ8 M AQ9 -67 AQ10 +20

59D 1	36 52 55 N	076 23 11 W	TIDEWATER WATER COMPANY			15	-573	D,E	
	CU1 --	CU2 --	CU3 42	CU4 M	CU6 55	CU7 98	CU8 54	CU9 29	
	AQ1 --	AQ2 --	AQ3 -507	AQ4 M	AQ6 M	AQ7 -363	AQ8 M	AQ9 -41	AQ10 +15
59D 20	36 58 40 N	076 25 50 W	CITY OF NEWPORT NEWS			20	-890	D,E	
	CU1 --	CU2 24	CU3 62	CU4 M	CU6 78	CU7 95	CU8 72	CU9 30	
	AQ1 --	AQ2 -780	AQ3 -592	AQ4 M	AQ6 M	AQ7 -387	AQ8 M	AQ9 -40	AQ10 +20
59E 5	37 05 38 N	076 22 43 W	NASA RESEARCH CENTER			10	-2053 BSMT	D,E,J	
	CU1 78	CU2 34	CU3 67	CU4 M	CU6 84	CU7 130	CU8 80	CU9 30	
	AQ1 -1364	AQ2 -858	AQ3 -737	AQ4 M	AQ6 M	AQ7 -440	AQ8 M	AQ9 -80	AQ10 +10
59E 6	37 05 31 N	076 24 54 W	U.S. ARMY			15	-985	D,E,J	
	CU1 --	CU2 34	CU3 92	CU4 M	CU6 60	CU7 134	CU8 84	CU9 20	
	AQ1 --	AQ2 -779	AQ3 -671	AQ4 M	AQ6 M	AQ7 -409	AQ8 M	AQ9 -75	AQ10 +15
59F 5	37 12 21	076 26 26 W	YORK COUNTY PARK			10	-220	D,E	
	CU1 --	CU2 --	CU3 --	CU4 --	CU6 --	CU7 --	CU8 95	CU9 38	
	AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 --	AQ8 --	AQ9 -40	AQ10 +10
60B 1	36 38 11 N	076 22 22 W	CANAL BANK MOTOR LODGE			15	-723	D,E	
	CU1 --	CU2 --	CU3 100	CU4 8	CU6 16	CU7 87	CU8 M	CU9 33	
	AQ1 --	AQ2 --	AQ3 -717	AQ4 -443	AQ6 -415	AQ7 -387	AQ8 M	AQ9 -73	AQ10 +15
60B 2	36 41 49 N	076 20 19 W	J. LENSEY			15	-807	D,E	
	CU1 --	CU2 --	CU3 144	CU4 20	CU6 18	CU7 94	CU8 47	CU9 44	
	AQ1 --	AQ2 --	AQ3 -734	AQ4 -459	AQ6 -433	AQ7 -406	AQ8 M	AQ9 -82	AQ10 +15
60B 3	36 38 36 N	076 20 17 W	VASWCB			15	-965	E,J	
	CU1 --	CU2 56	CU3 176	CU4 18	CU6 26	CU7 106	CU8 54	CU9 --	
	AQ1 --	AQ2 -951	AQ3 -808	AQ4 -471	AQ6 -434	AQ7 -471	AQ8 M	AQ9 --	AQ10 +15

60C 6	36 48 53 N	076 17 09 W	LONE STAR CEMENT CORPORATION		10	-790	D,E,G		
	CU1 --	CU2 --	CU3 14	CU4 M	CU6 122	CU7 140	CU8 72	CU9 38	
	AQ1 --	AQ2 --	AQ3 -700	AQ4 M	AQ6 -680	AQ7 -482	AQ8 M	AQ9 -53	AQ10 +10
60C 7	36 51 15 N	076 19 17 W	CITY OF PORTSMOUTH		10	-1444	D,E,G,J		
	CU1 36	CU2 20	CU3 46	CU4 M	CU6 95	CU7 118	CU8 48	CU9 27	
	AQ1 -1306	AQ2 -875	AQ3 -646	AQ4 M	AQ6 M	AQ7 -422	AQ8 M	AQ9 -61	AQ10 +10
60C 25	36 51 31 N	076 18 29 W	CAMPBELL SOUP COMPANY		10	-890	D,E,J		
	CU1 --	CU2 >30	CU3 25	CU4 M	CU6 94	CU7 130	CU8 55	CU9 25	
	AQ1 --	AQ2 --	AQ3 -648	AQ4 M	AQ6 -592	AQ7 -435	AQ8 M	AQ9 -44	AQ10 +10
60C 40	36 47 02 N	076 21 56 W	CITY OF CHESAPEAKE		20	-940	D,E,G,J		
	CU1 --	CU2 22	CU3 30	CU4 M	CU6 80	CU7 92	CU8 42	CU9 16	
	AQ1 --	AQ2 -845	AQ3 -604	AQ4 M	AQ6 M	AQ7 -376	AQ8 M	AQ9 -78	AQ10 +20
60E 8	37 00 43 N	076 22 03 W	DIXIE HOSPITAL		15	-383	D,E		
	CU1 --	CU2 --	CU3 --	CUBS --	CU6 --	CU7 --	CU8 >168	CU9 25	
	AQ1 --	AQ2 --	AQ3 --	AQBS --	AQ6 --	AQ7 --	AQ8 --	AQ9 -65	AQ10 +15
61A 2	36 34 48 N	076 12 12 W	CITY OF CHESAPEAKE		10	-690	D,E,G		
	CU1 --	CU2 --	CU3 --	CU4 --	CU6 36	CU7 70	CU8 113	CU9 25	
	AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 M	AQ7 -536	AQ8 M	AQ9 -100	AQ10 +10
61B 2	36 42 27 N	076 07 47 W	VASWCB		20	-1180	E,J		
	CU1 --	CU2 --	CU3 182	CU4 40	CU6 M	CU7 138	CU8 126	CU9 25	
	AQ1 --	AQ2 --	AQ3 -1022	AQ4 -720	AQ6 M	AQ7 -603	AQ8 M	AQ9 -75	AQ10 +20
61C 1	36 52 21 N	076 12 15 W	USGS		15	-2457	E,G,J		
	CU1 60	CU2 35	CU3 58	CU4 M	CU6 M	CU7 170	CU8 100	CU9 30	
	AQ1 -1580	AQ2 -1015	AQ3 -700	AQ4 M	AQ6 M	AQ7 -565	AQ8 M	AQ9 -75	AQ10 +15

61D	5	36 54 25 N	076 10 50 W	CITY OF VIRGINIA BEACH			25	-1593	E,G,J	
		CU1 --	CU2 62	CU3 19	CU4 M	CU6 37	CU7 190	CU8 M	CU9 46	
		AQ1 --	AQ2 -1024	AQ3 -781	AQ4 M	AQ6 M	AQ7 -625	AQ8 M	AQ9 -75	AQ10 +25
62C	2	36 47 15 N	076 03 08 W	VASWCB			20	-378	E,G,J	
		CU1 --	CU2 --	CU3 --	CU4 --	CU6 --	CU7 --	CU8 102	CU9 52	
		AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 --	AQ8 --	AQ9 -92	AQ10 +20
62C	4	36 47 11 N	076 06 00 W	VASWCB			13	-385	E,G,J	
		CU1 --	CU2 --	CU3 --	CU4 --	CU6 --	CU7 --	CU8 >126	CU9 54	
		AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 --	AQ8 --	AQ9 -95	AQ10 +13
62C	5	36 45 04 N	076 03 13 W	VASWCB			20	-380	D,E,G	
		CU1 --	CU2 --	CU3 --	CU4 --	CU6 --	CU7 --	CU8 >92	CU9 40	
		AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 --	AQ8 --	AQ9 -88	AQ10 +20
62D	2	36 57 59 N	076 06 47 W	CHES. BAY BRIDGE TUNNEL AUTH.			3	-1502	D,J	
		CU1 --	CU2 --	CU3 --	CU4 --	CU6 --	CU7 --	CU8 --	CU9 --	
		AQ1 --	AQ2 --	AQ3 --	AQ4 ---	AQ6 --	AQ7 --	AQ8 --	AQ9 --	AQ10 --
63C	1	36 52 00 N	075 58 51 W	BUSH DEVELOPMENT CORPORATION			20	-1567	D,E,J	
		CU1 --	CU2 40	CU3 105	CU4 M	CU6 60	CU7 190	CU8 140	CU9 42	
		AQ1 --	AQ2 -1404	AQ3 -1091	AQ4 M	AQ6 M	AQ7 -770	AQ8 M	AQ9 -142	AQ10 +20
63F	1	37 11 59 N	075 57 32 W	NORTHAMPTON SCHOOL BOARD			30	-461	D,E,G,J	
		CU1 --	CU2 --	CU3 --	CU4 --	CU6 --	CU7 --	CU8 >93	CU9 30	
		AQ1 --	AQ2 --	AQ3 --	AQ4 --	AQ6 --	AQ7 --	AQ8 --	AQ9 -110	AQ10 +30