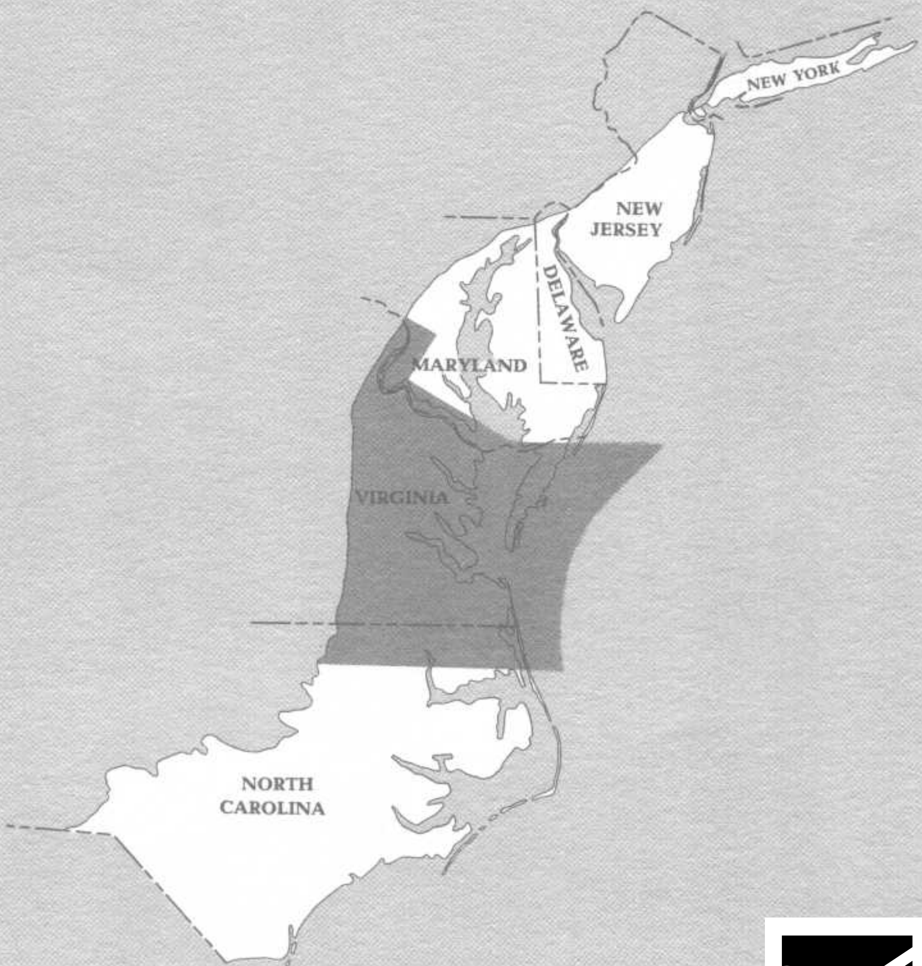
CONCEPTUALIZATION AND ANALYSIS OF GROUND-WATER FLOW SYSTEM IN THE COASTAL PLAIN OF VIRGINIA AND ADJACENT PARTS OF MARYLAND AND NORTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS



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

Ground-Water Recharge

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

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

where

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

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

Streambed Leakance

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

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

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

where

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

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

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

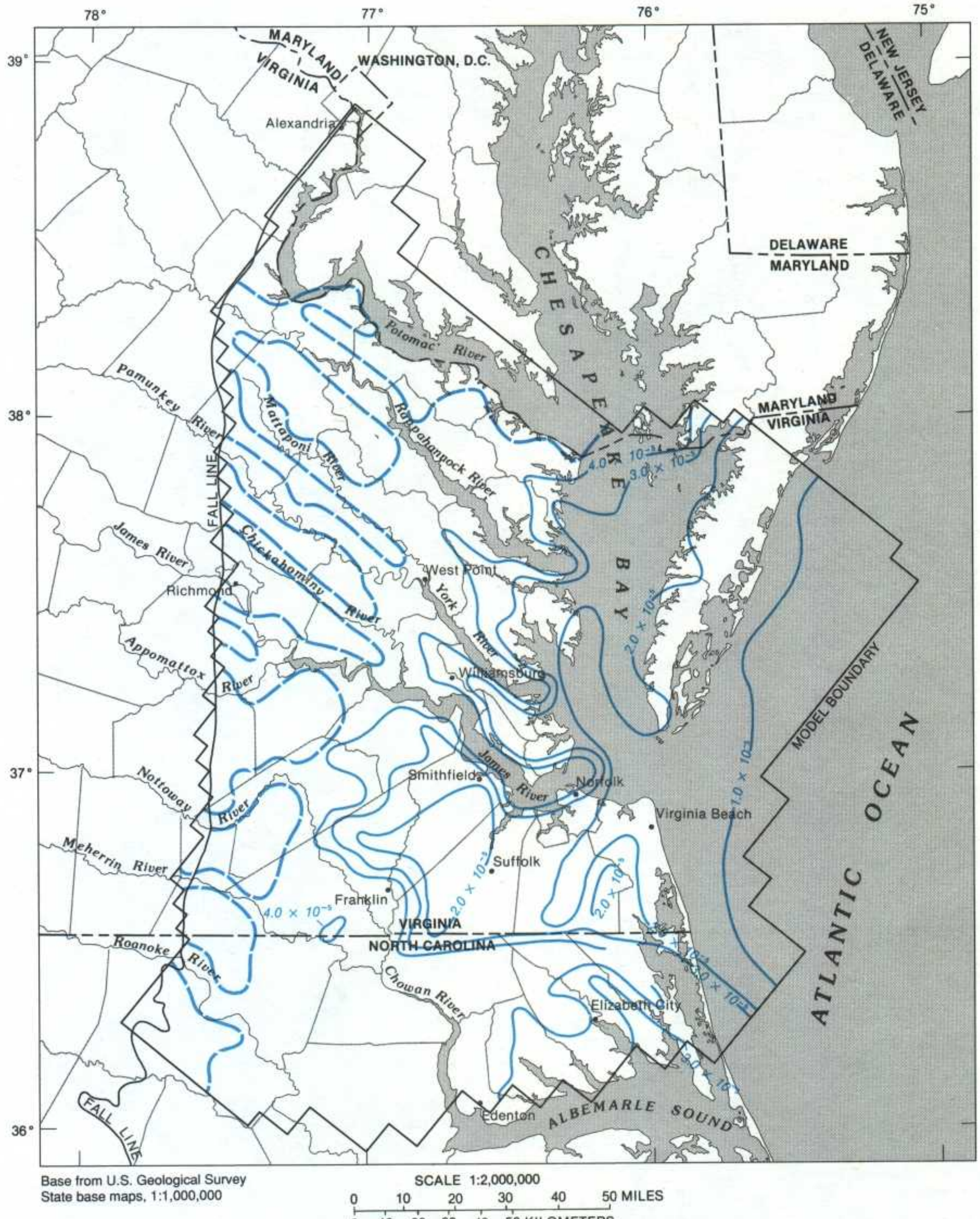
where

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

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

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

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

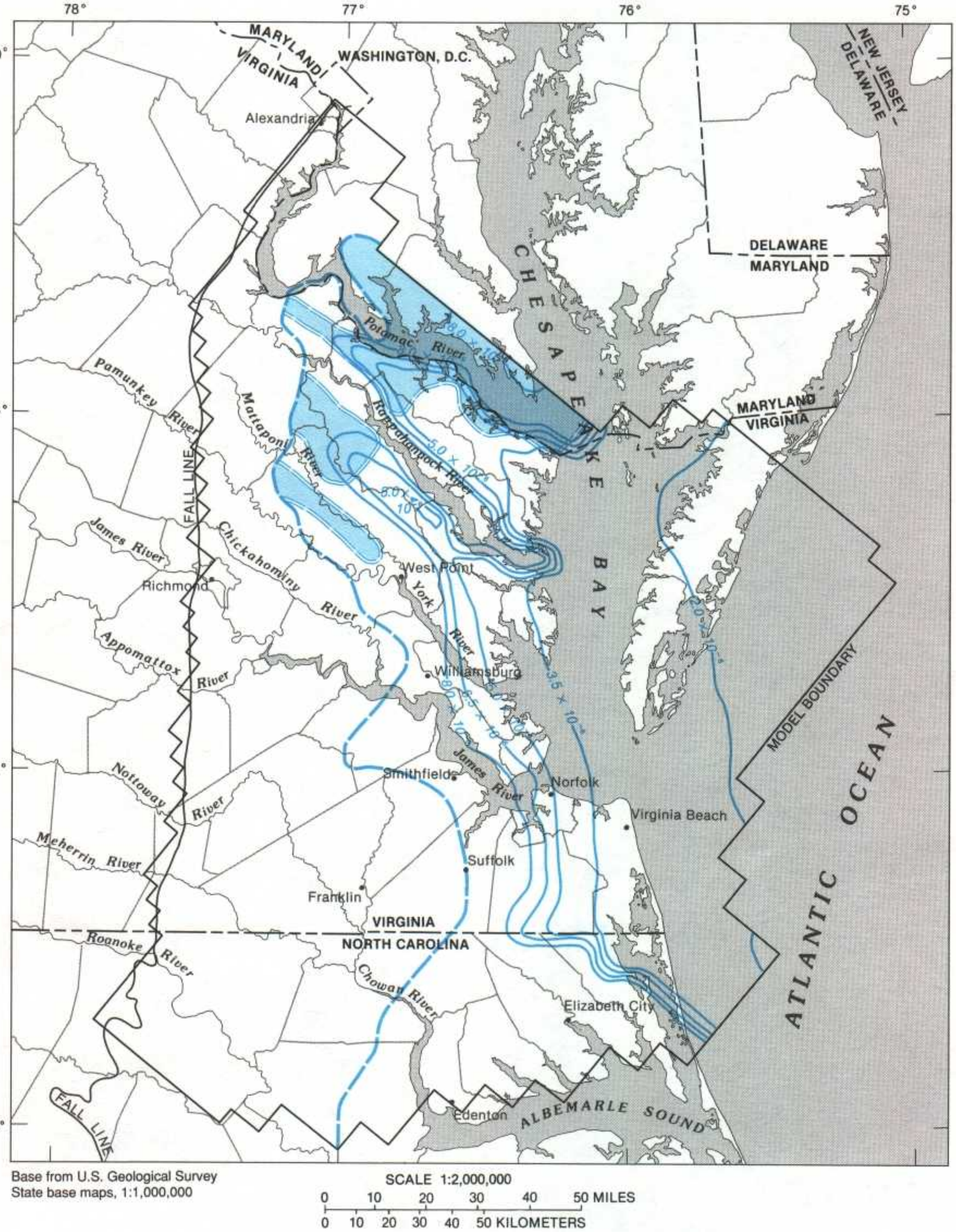


EXPLANATION

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

APPROXIMATE LIMIT OF YORKTOWN CONFINING UNIT

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



EXPLANATION

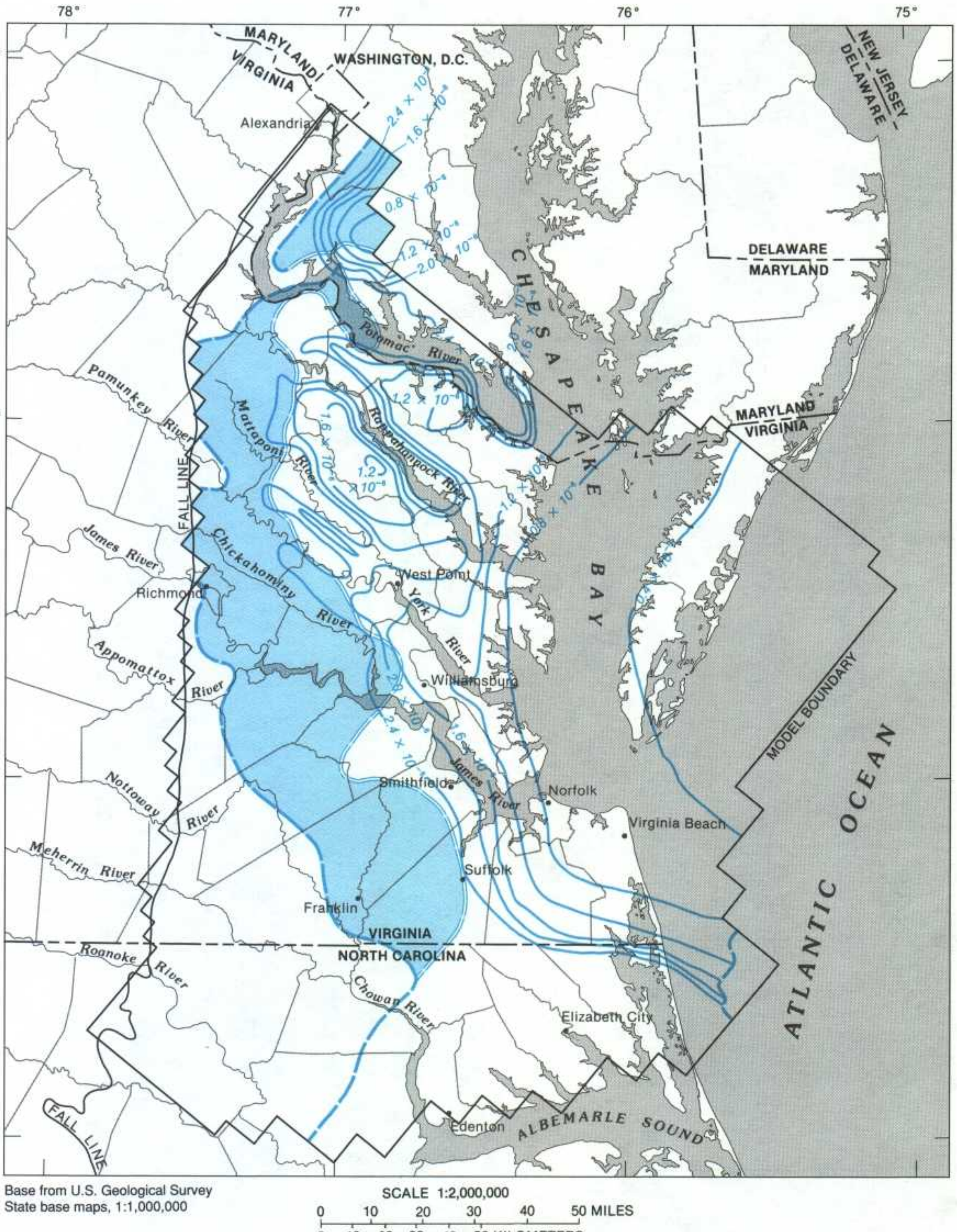
-8.0×10^{-5} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 1.5×10^{-6} day^{-1}

APPROXIMATE LIMIT OF ST. MARYS CONFINING UNIT

APPROXIMATE LIMIT OF YORKTOWN CONFINING UNIT

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

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



EXPLANATION

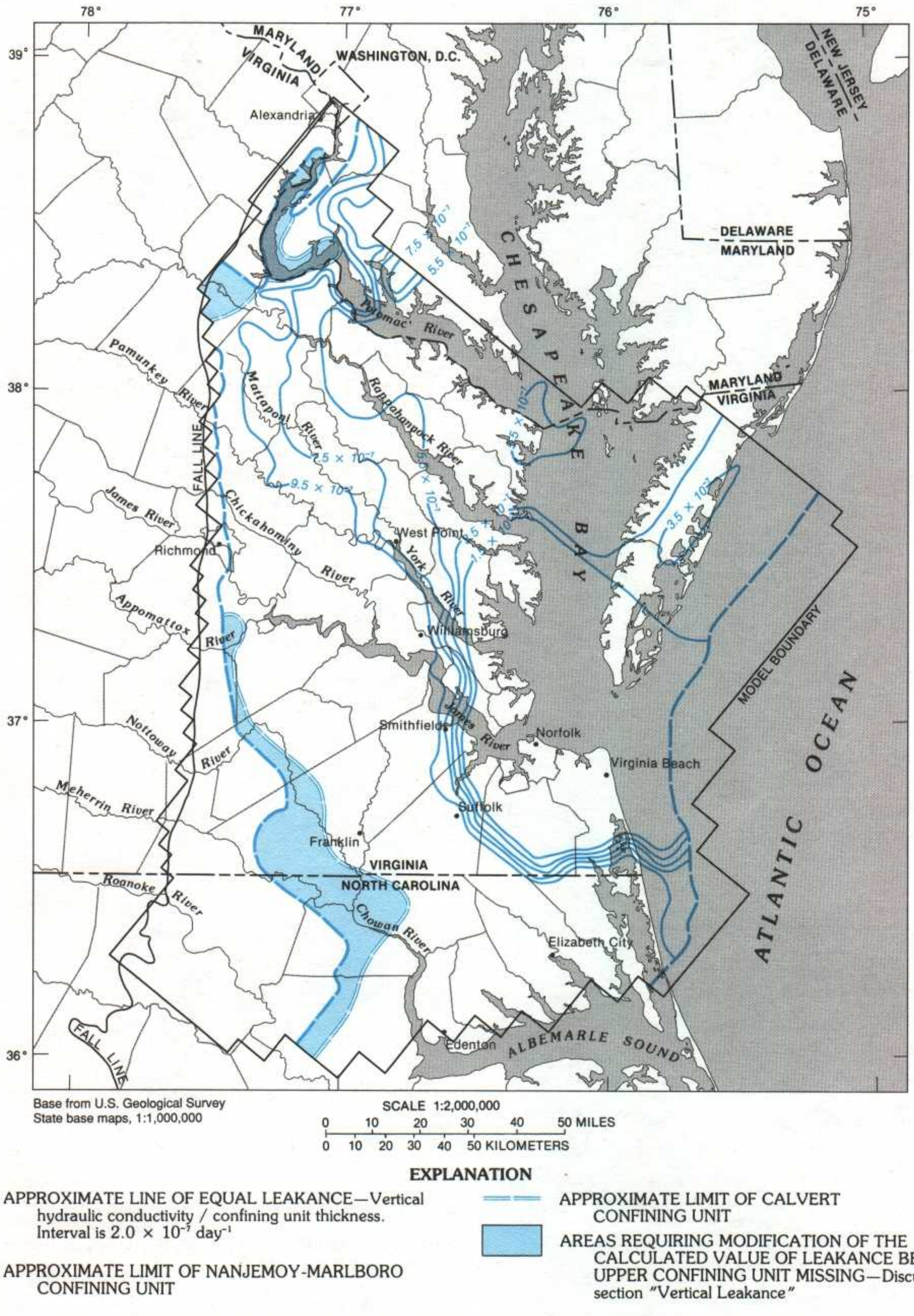
2.4×10^{-6} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity/confining unit thickness. Interval is 0.4×10^{-6} day^{-1}

APPROXIMATE LIMIT OF CALVERT CONFINING UNIT

APPROXIMATE LIMIT OF ST. MARYS CONFINING UNIT

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

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



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

SCALE 1:2,000,000

0 10 20 30 40 50 MILES

0 10 20 30 40 50 KILOMETERS

EXPLANATION

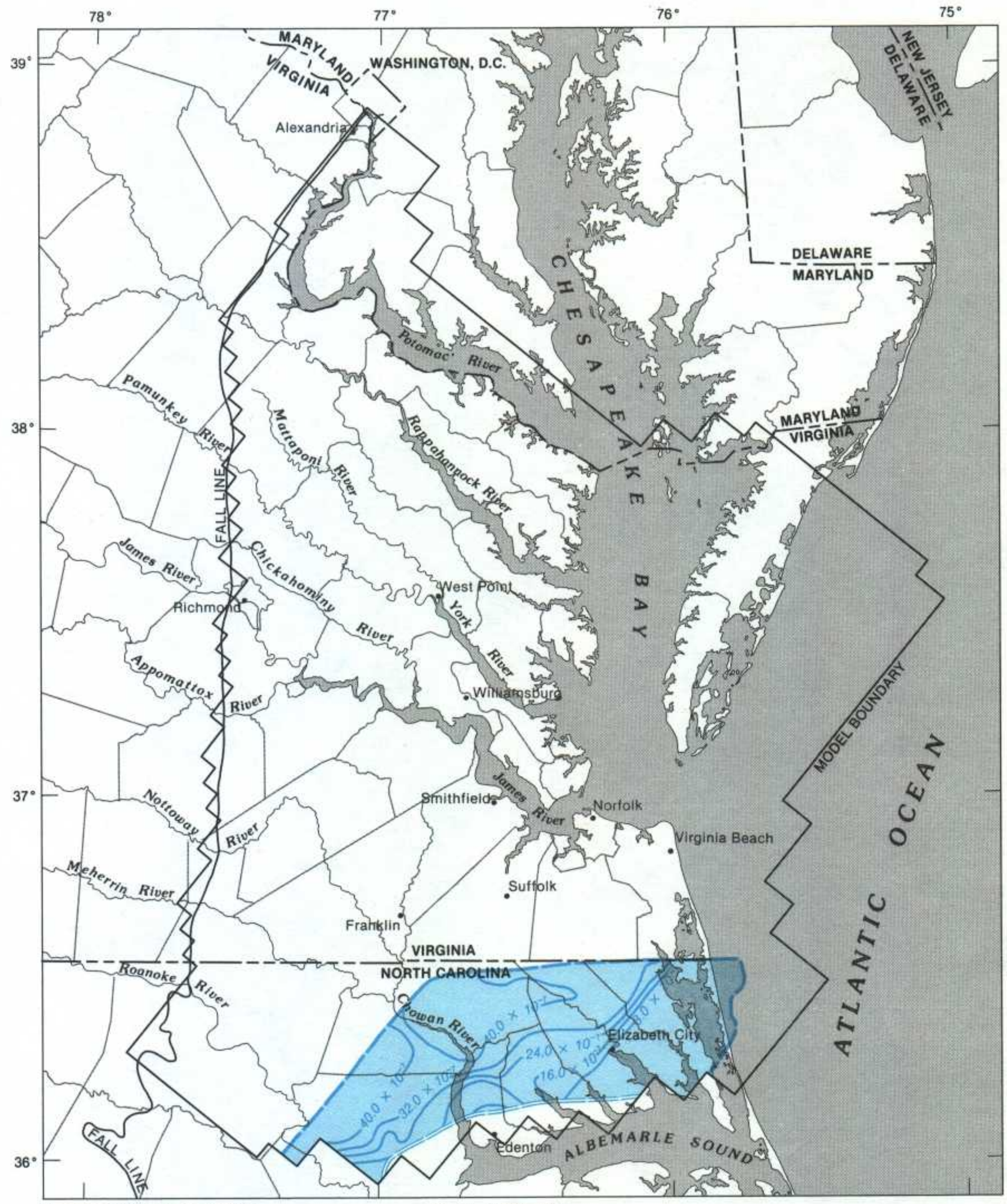
-3.5×10^{-7} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 2.0×10^{-7} day^{-1}

APPROXIMATE LIMIT OF NANJEMOY-MARLBORO CONFINING UNIT

APPROXIMATE LIMIT OF CALVERT CONFINING UNIT

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

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



EXPLANATION

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

APPROXIMATE LIMIT OF CONFINING UNIT 4

APPROXIMATE LIMIT OF CONFINING UNIT 5

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

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

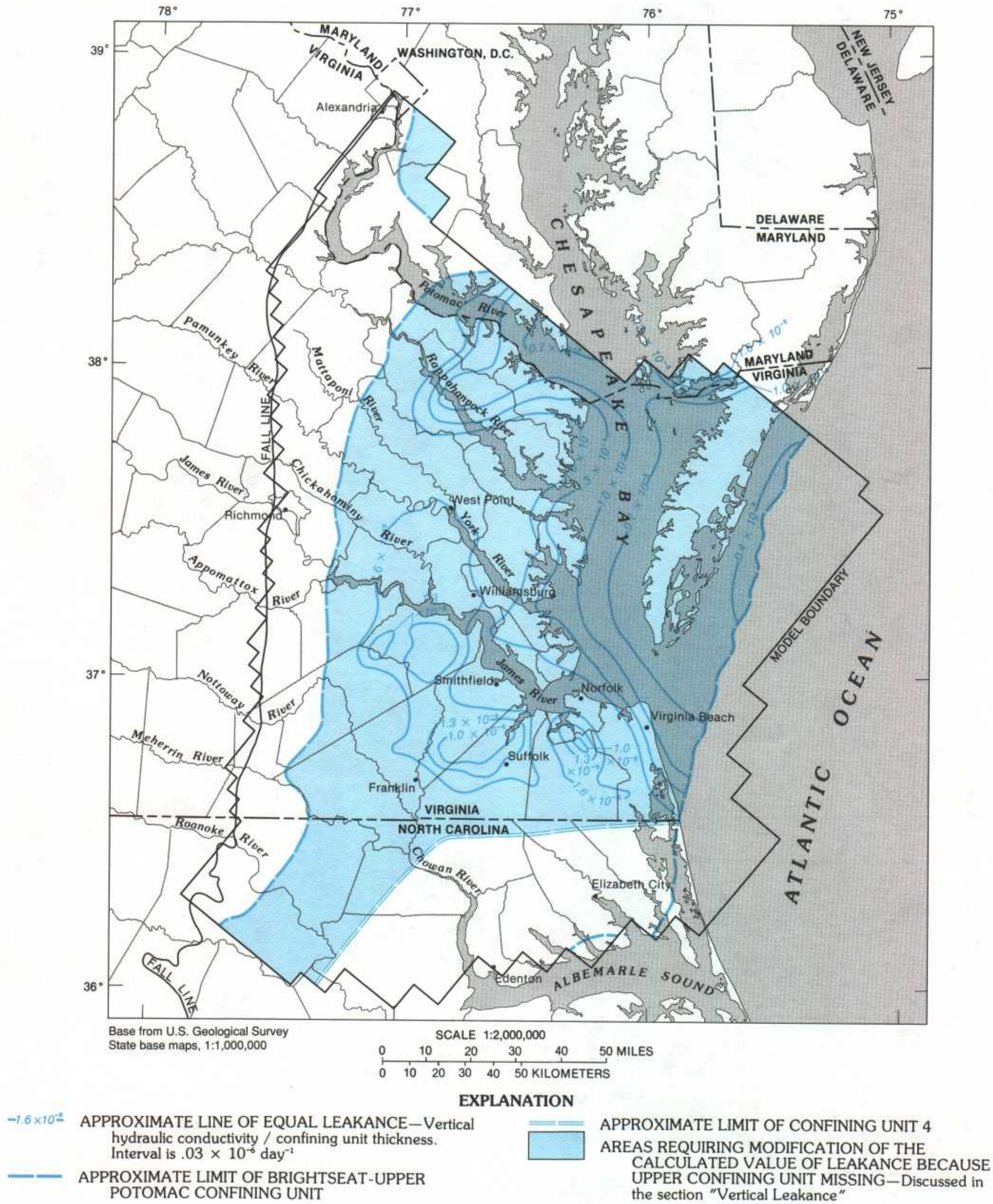
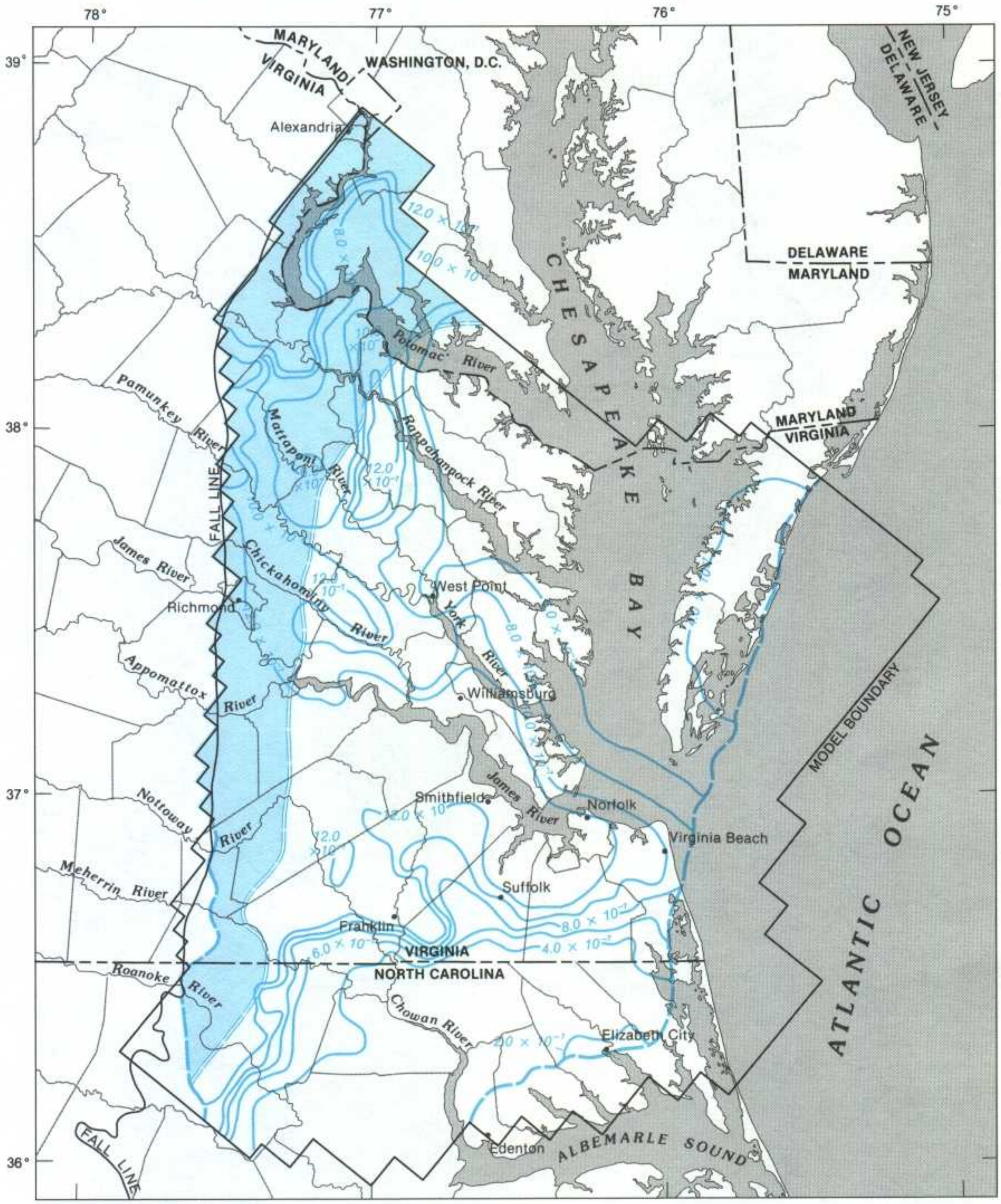


FIGURE 28.—Vertical leakance of the Brightseat-upper Potomac confining unit used in model simulations.



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

SCALE 1:2,000,000

0 10 20 30 40 50 MILES

0 10 20 30 40 50 KILOMETERS

EXPLANATION

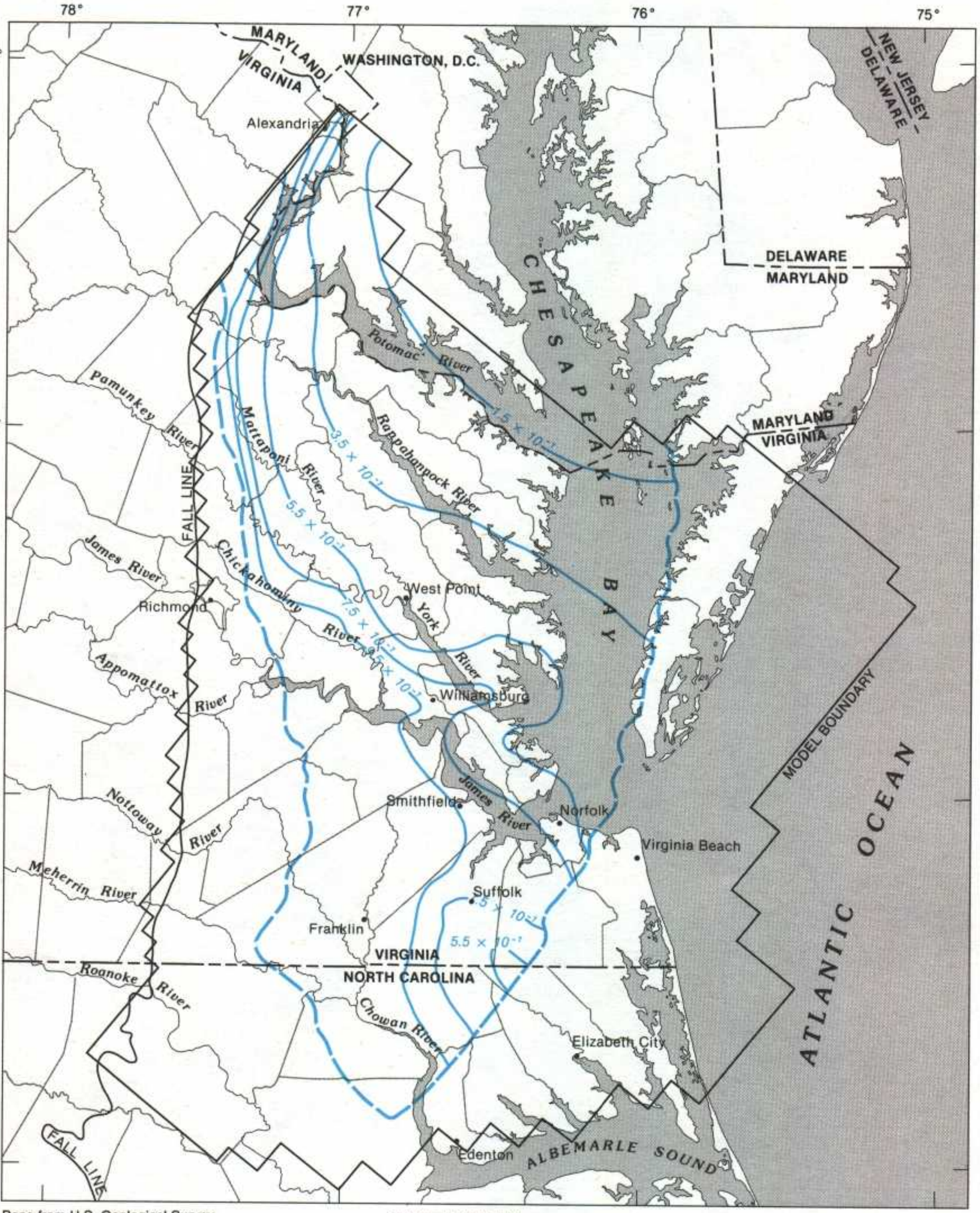
-8.0×10^{-7} APPROXIMATE LINE OF EQUAL LEAKANCE—Vertical hydraulic conductivity / confining unit thickness. Interval is 2.0×10^{-7} day^{-1}

APPROXIMATE LIMIT OF MIDDLE POTOMAC CONFINING UNIT

APPROXIMATE LIMIT OF THE BRIGHTSEAT-UPPER POTOMAC AQUIFER

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

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



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

SCALE 1:2,000,000

0 10 20 30 40 50 MILES

0 10 20 30 40 50 KILOMETERS

EXPLANATION

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

APPROXIMATE LIMIT OF LOWER POTOMAC CONFINING UNIT

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

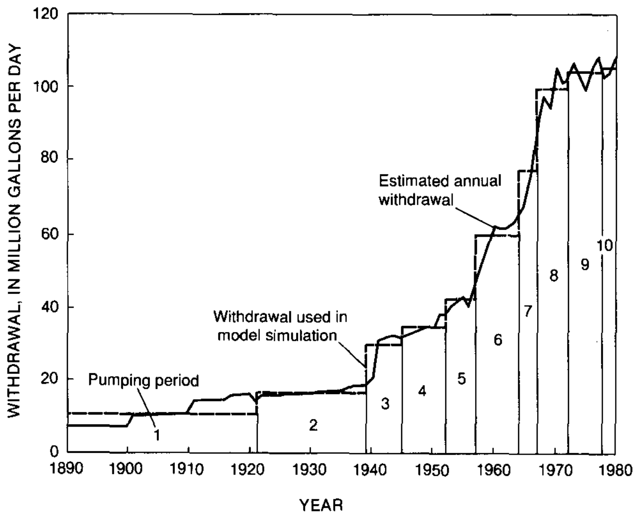


FIGURE 31.—Estimated annual withdrawal and average withdrawal calculated for simulated pumping periods.

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

Time Discretization and Ground-Water Withdrawal

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

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

Lateral Boundary Flow

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

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

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

STRATEGY OF CALIBRATION

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

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

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

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

Prepumping Conditions

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

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

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

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

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