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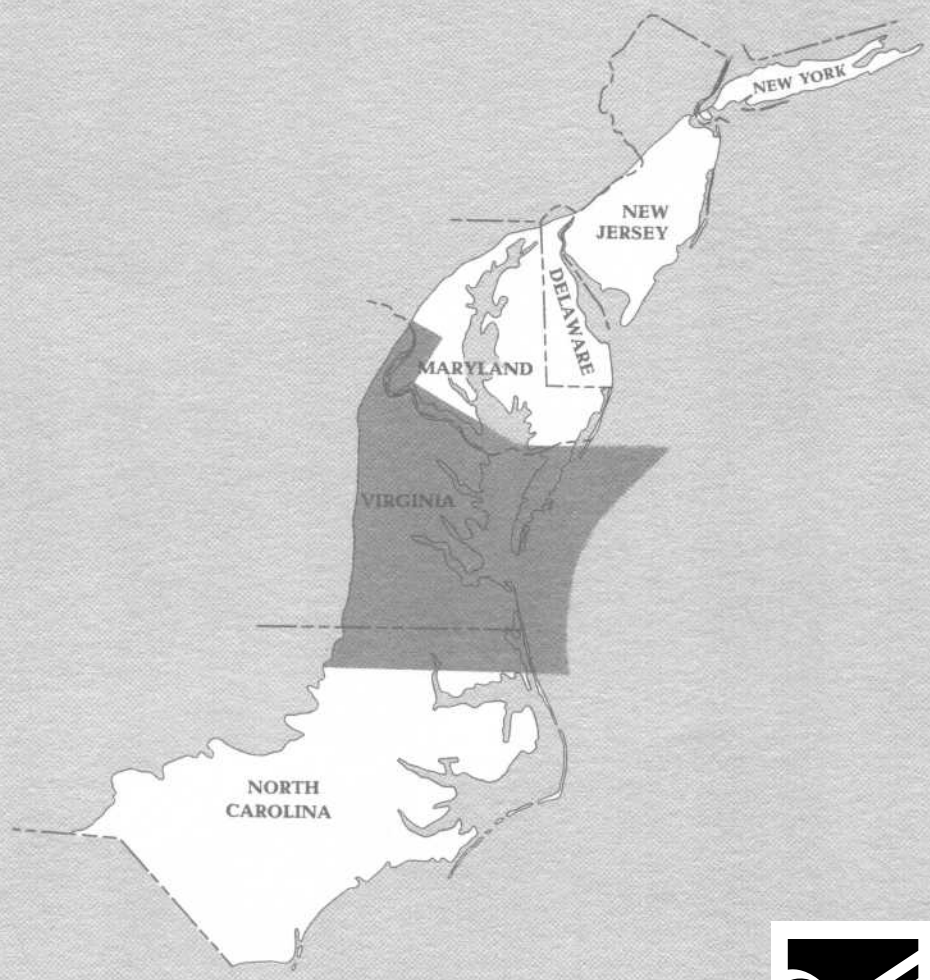
CONCEPTUALIZATION AND ANALYSIS OF GROUND-WATER FLOW SYSTEM IN THE COASTAL PLAIN OF VIRGINIA AND ADJACENT PARTS OF MARYLAND AND NORTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1404—F

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

STRATEGY OF CALIBRATION

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

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

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

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

PREPUMPING CONDITIONS

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

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

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

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

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

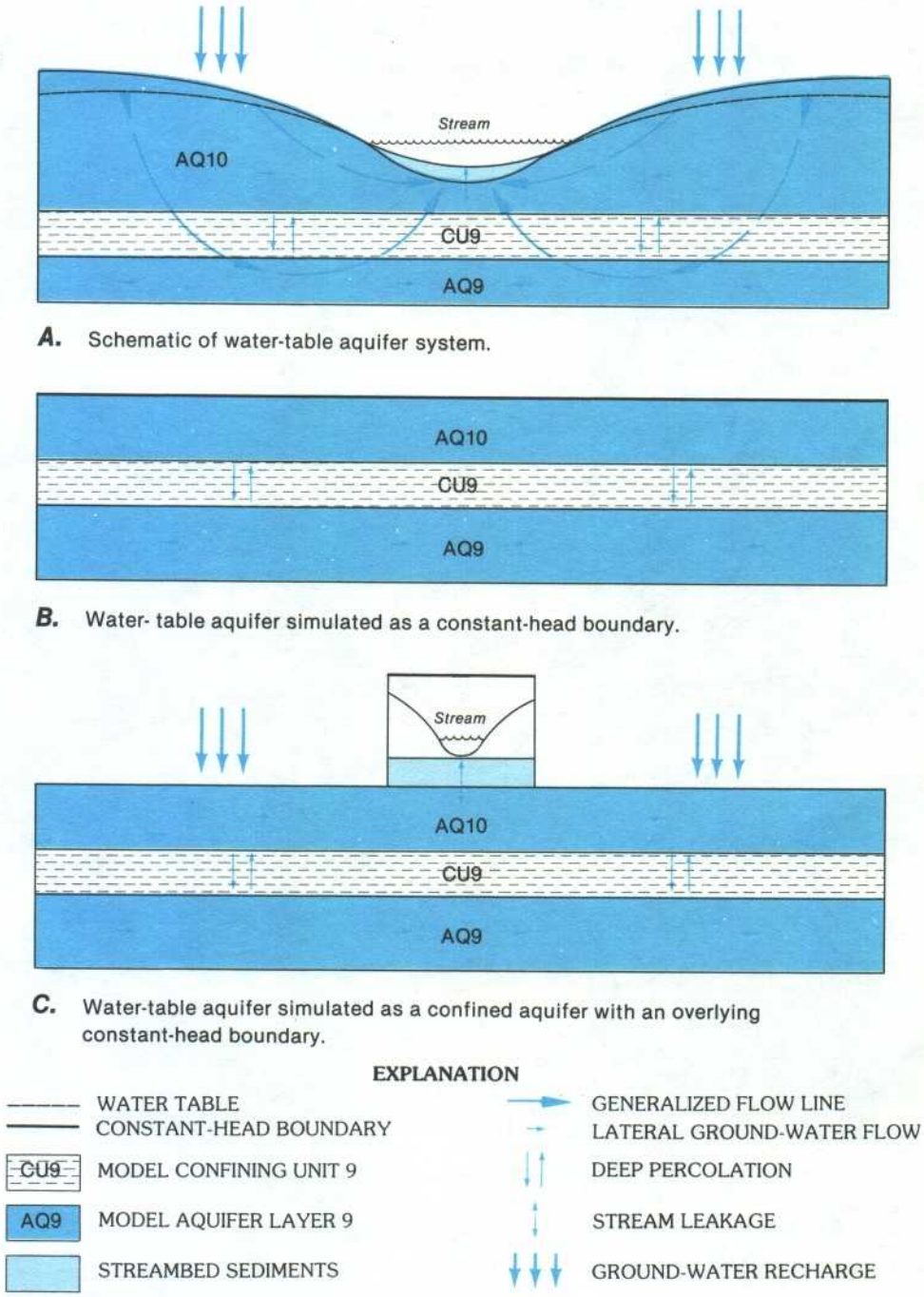
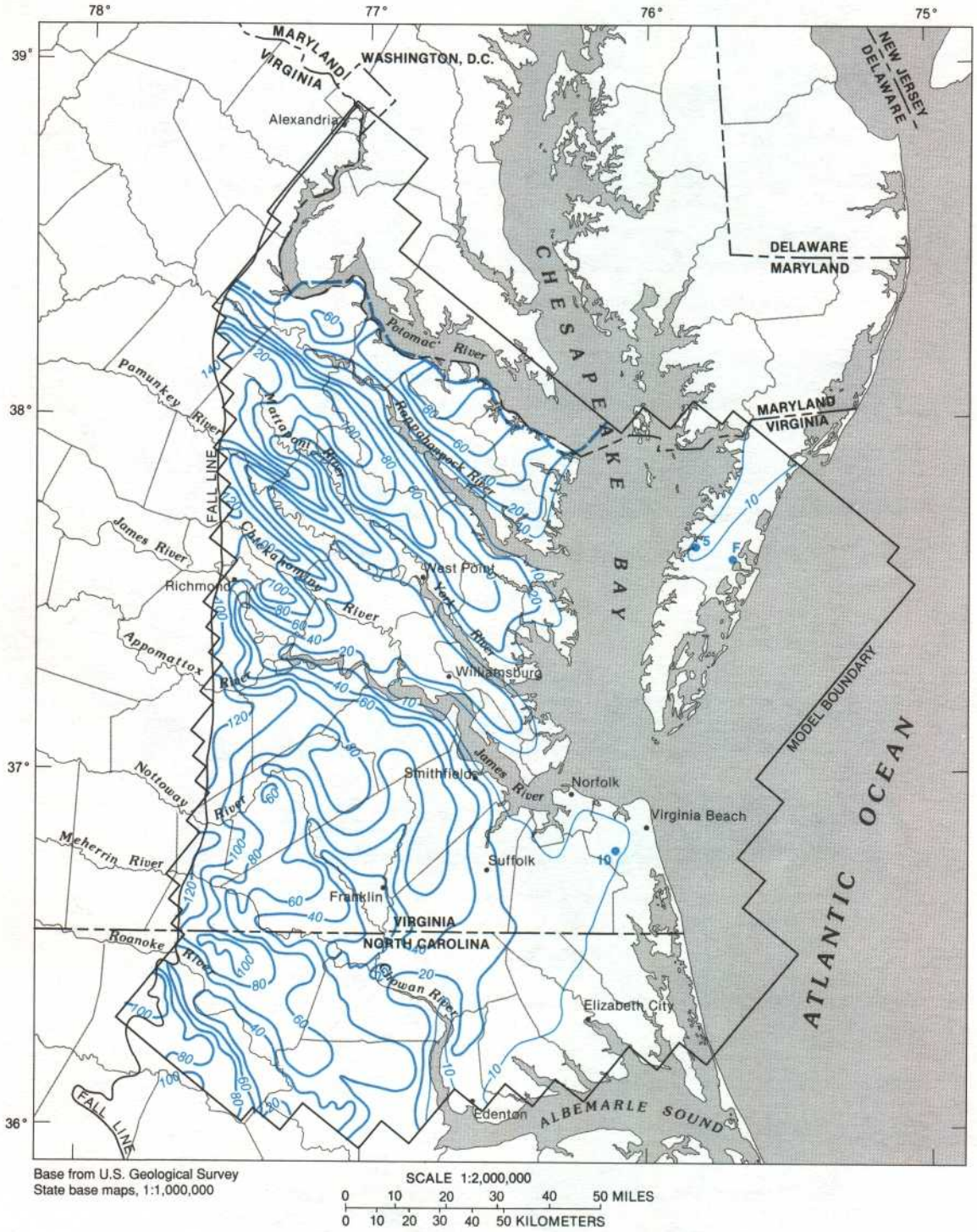


FIGURE 32.—Model conceptualizations of the water-table aquifer.

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

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



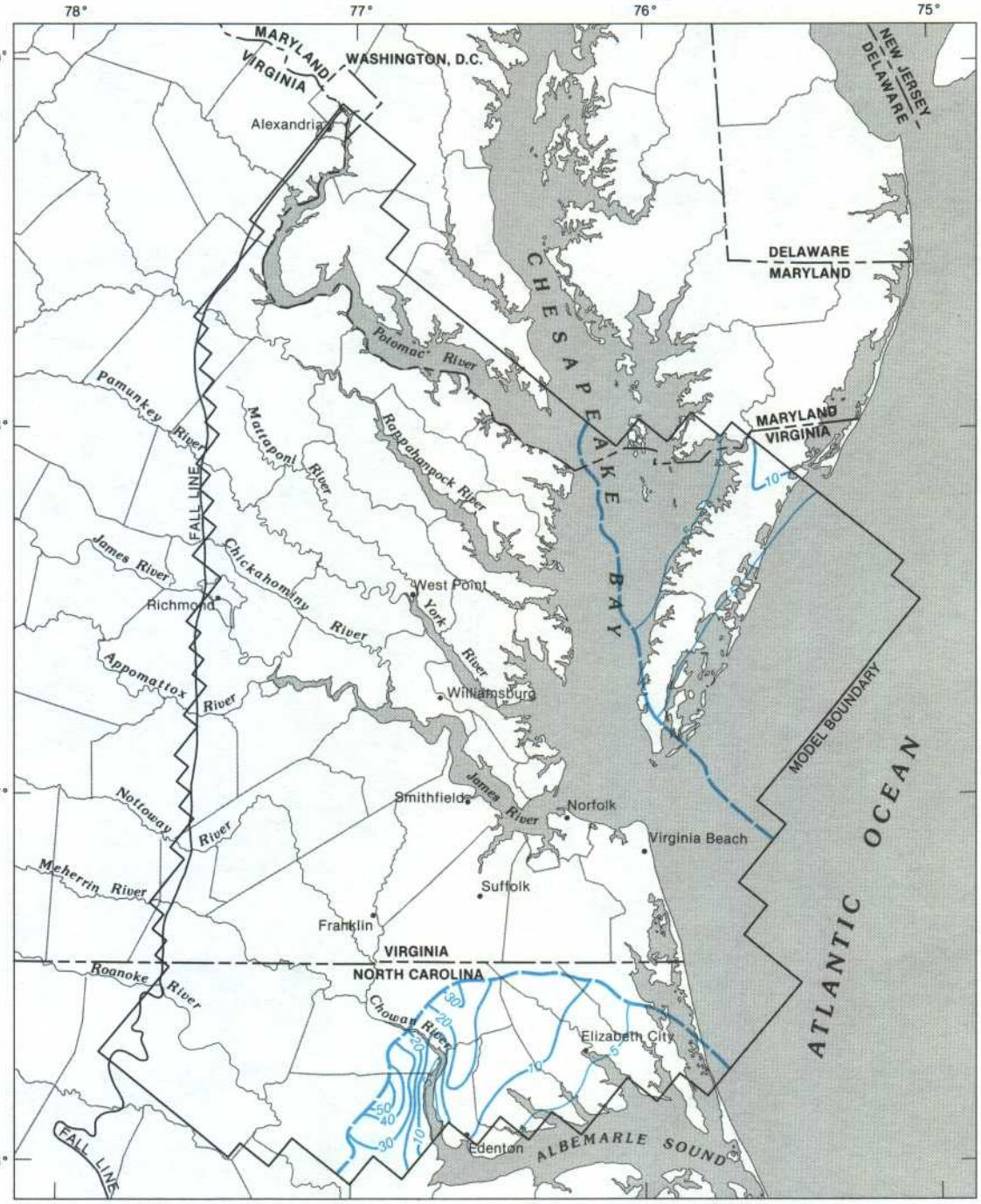
EXPLANATION

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

—— APPROXIMATE LIMIT OF YORKTOWN-EASTOVER AQUIFER

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

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

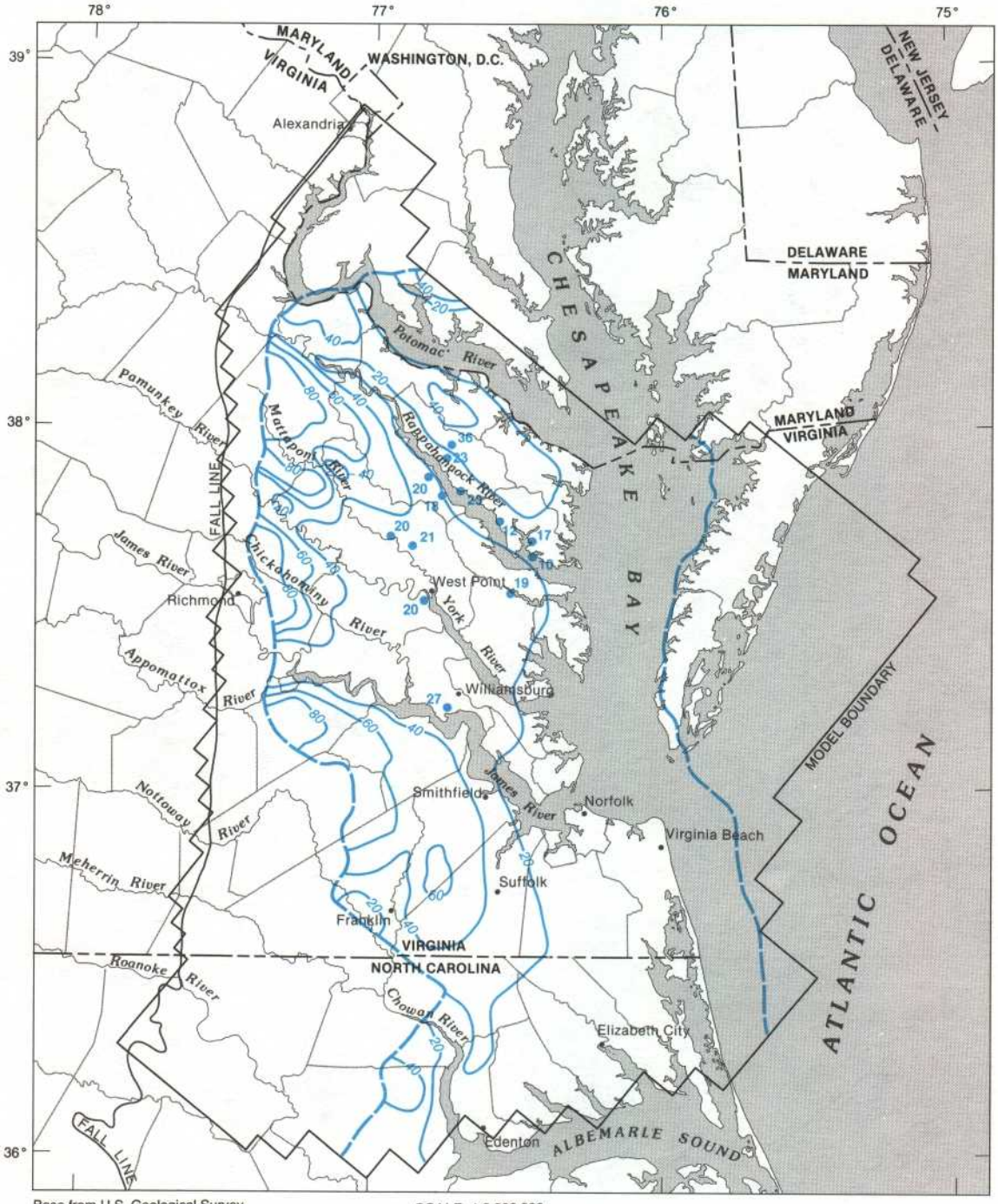


EXPLANATION

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

— — APPROXIMATE LIMIT OF ST. MARYS-CHOPTANK AQUIFER

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



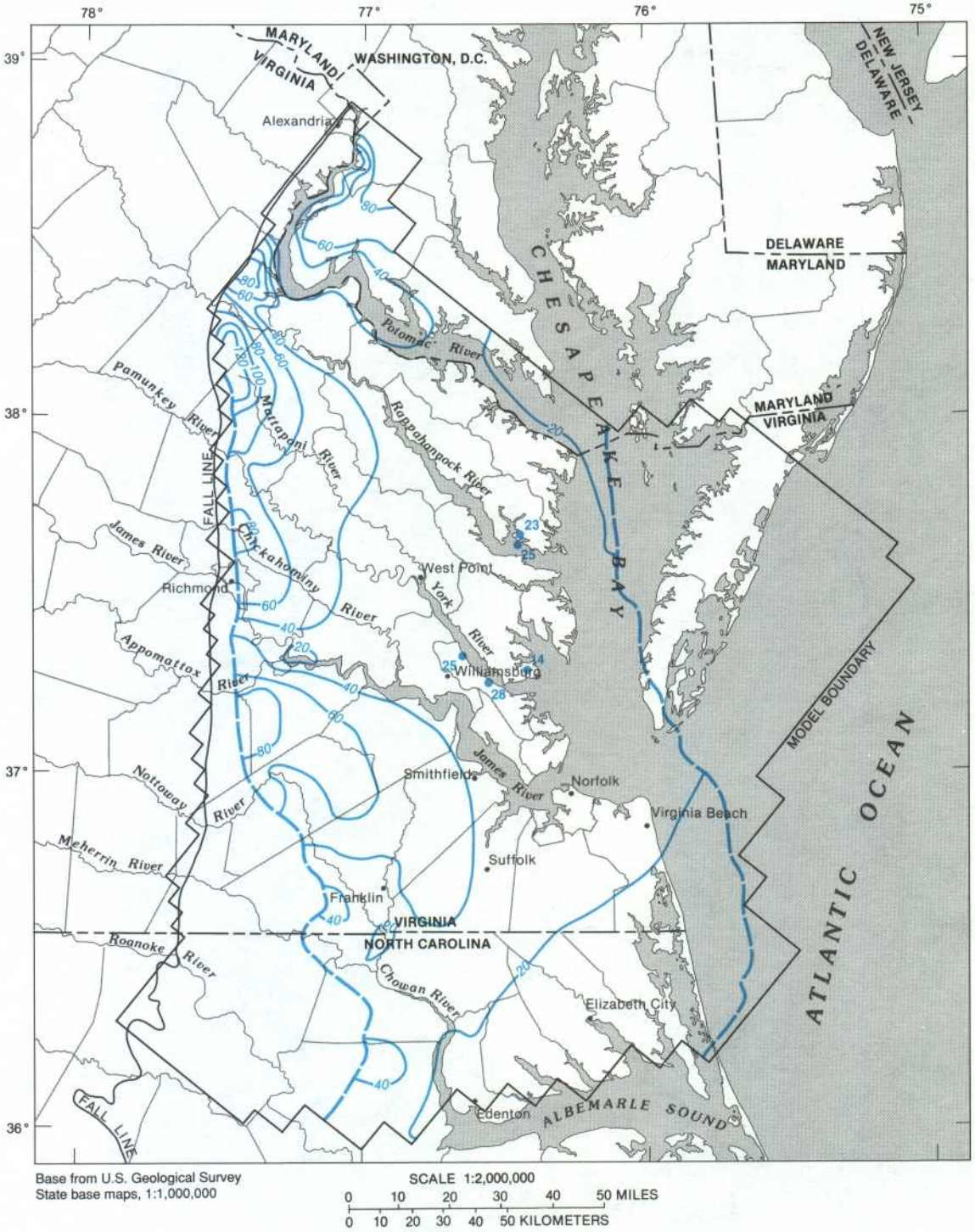
EXPLANATION

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

—— APPROXIMATE LIMIT OF CHICKAHOMINY-PINEY POINT AQUIFER

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

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



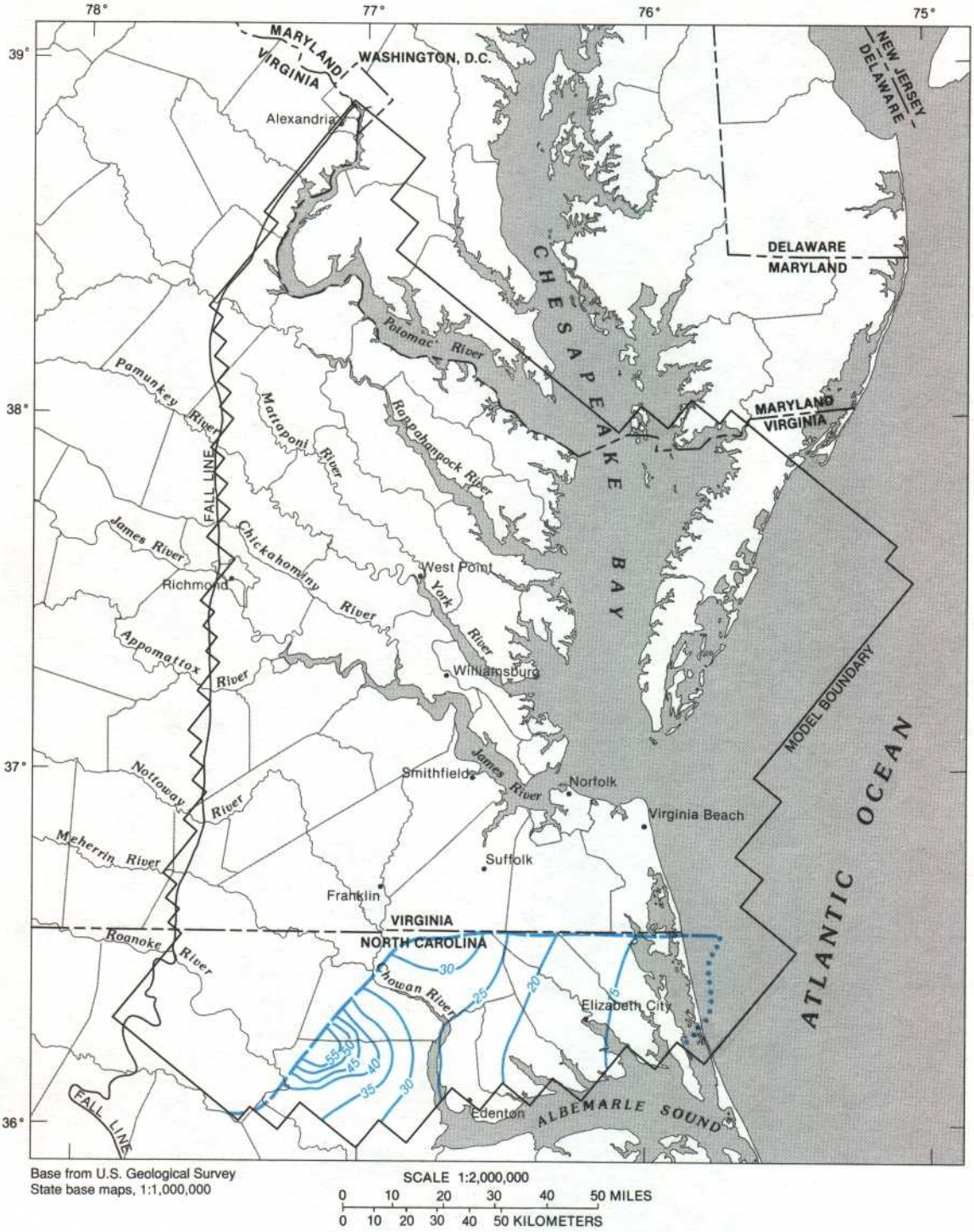
EXPLANATION

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

—— APPROXIMATE LIMIT OF AQUIA AQUIFER

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

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



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

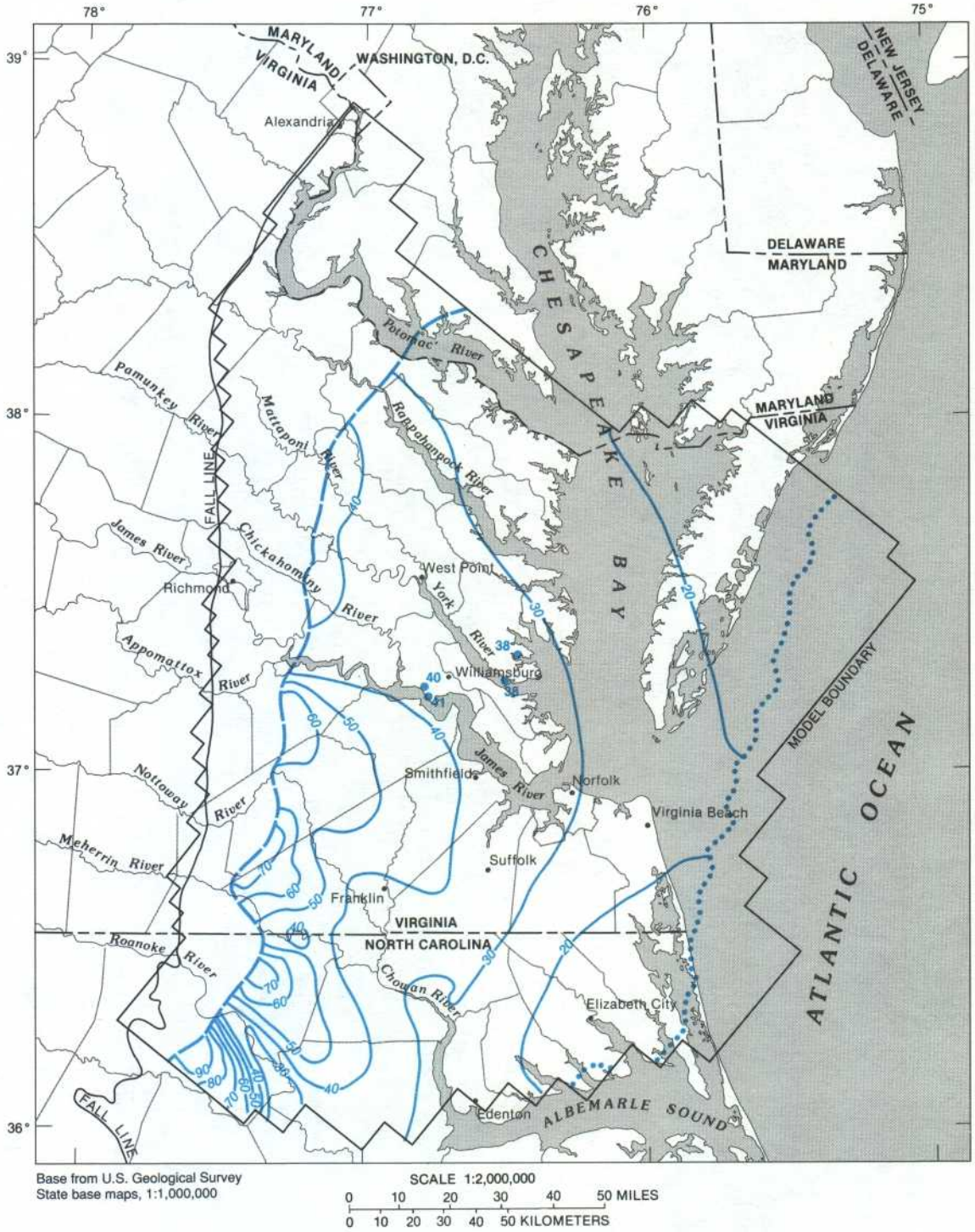
EXPLANATION

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

APPROXIMATE LIMIT OF AQUIFER 4

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

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



EXPLANATION

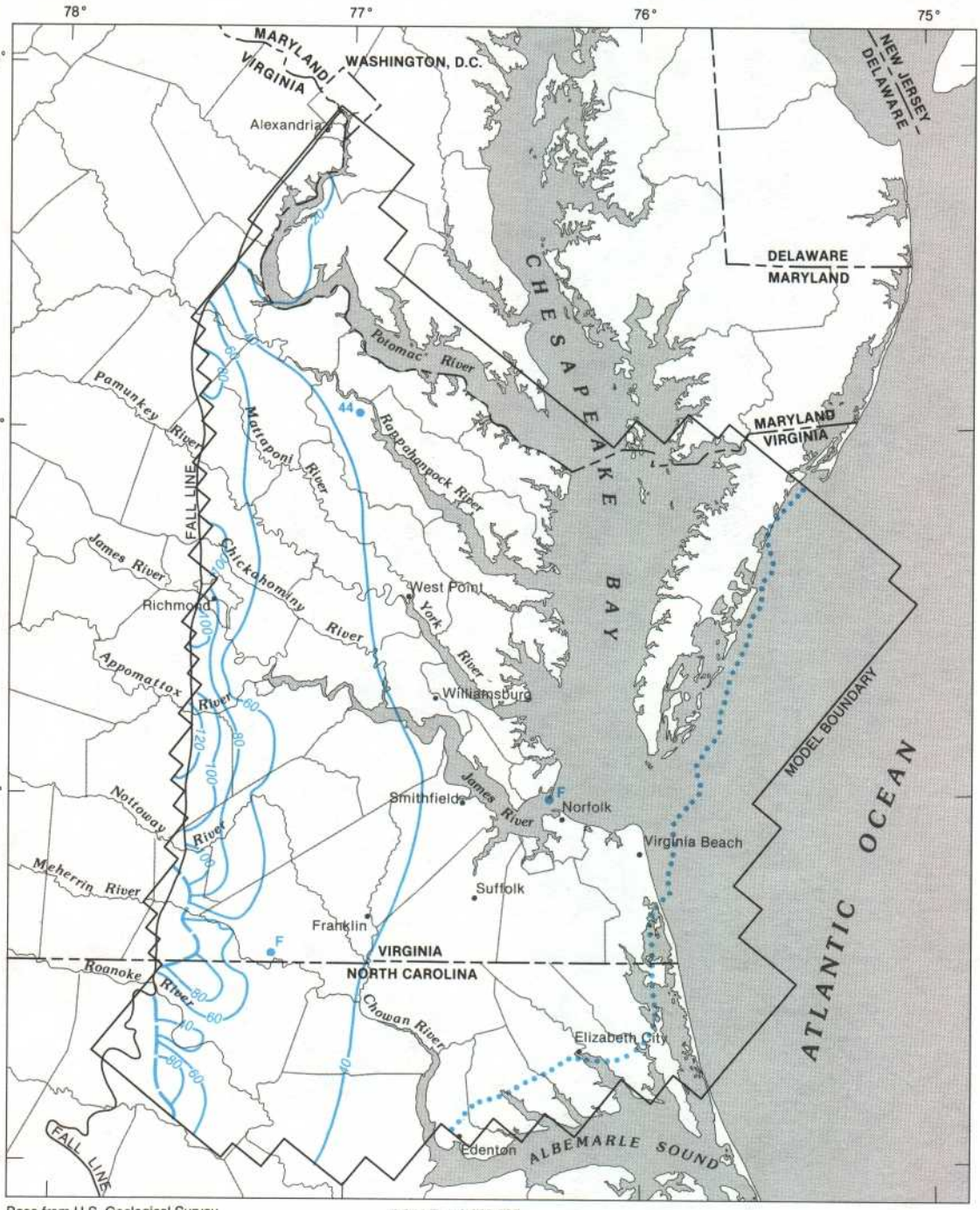
—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 10 feet. Datum is sea level

APPROXIMATE LIMIT OF BRIGHTSEAT-UPPER POTOMAC AQUIFER

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

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

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



EXPLANATION

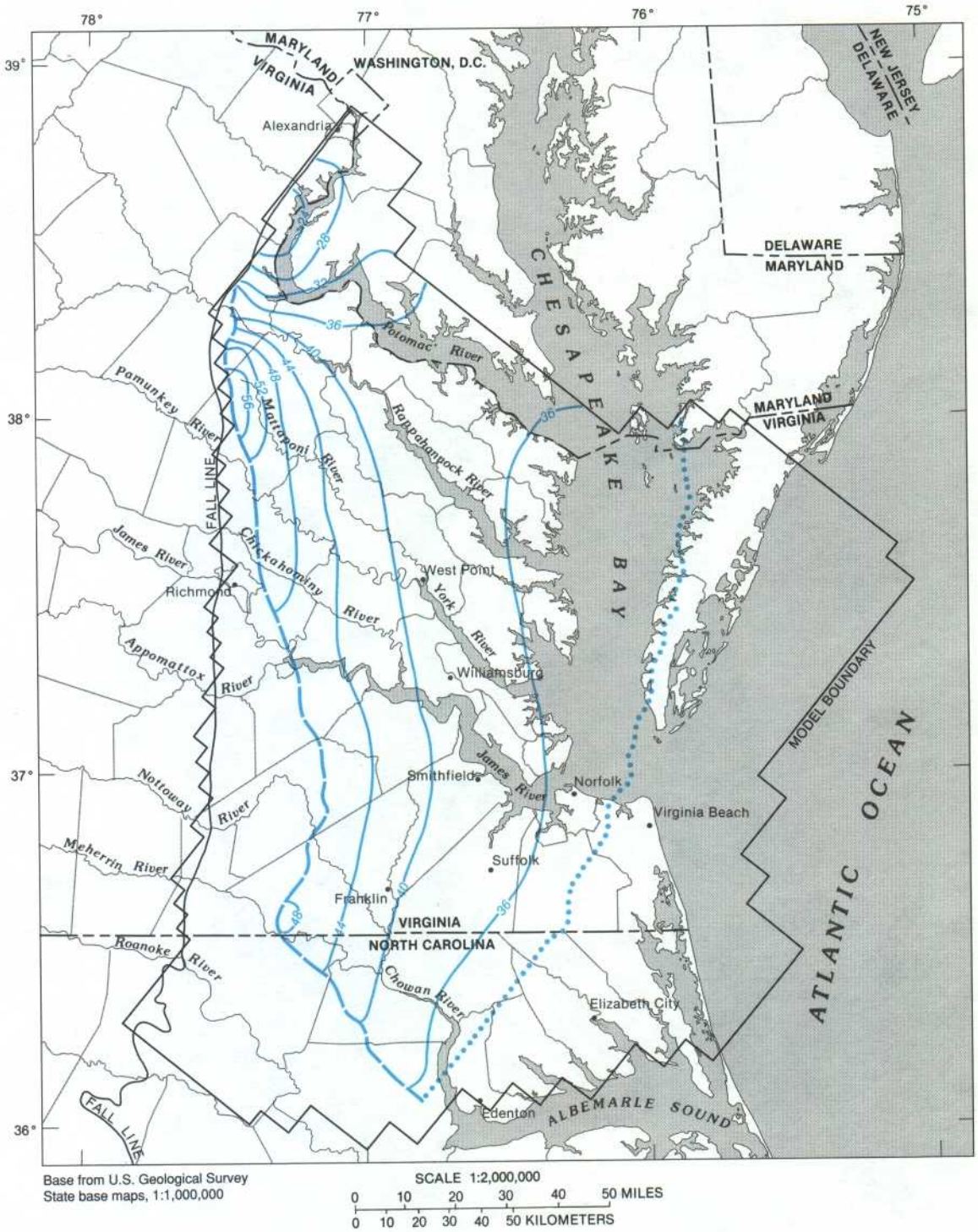
—20— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 20 feet. Datum is sea level

APPROXIMATE LIMIT OF MIDDLE POTOMAC AQUIFER

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

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

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



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

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

— — APPROXIMATE LIMIT OF LOWER POTOMAC AQUIFER

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

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

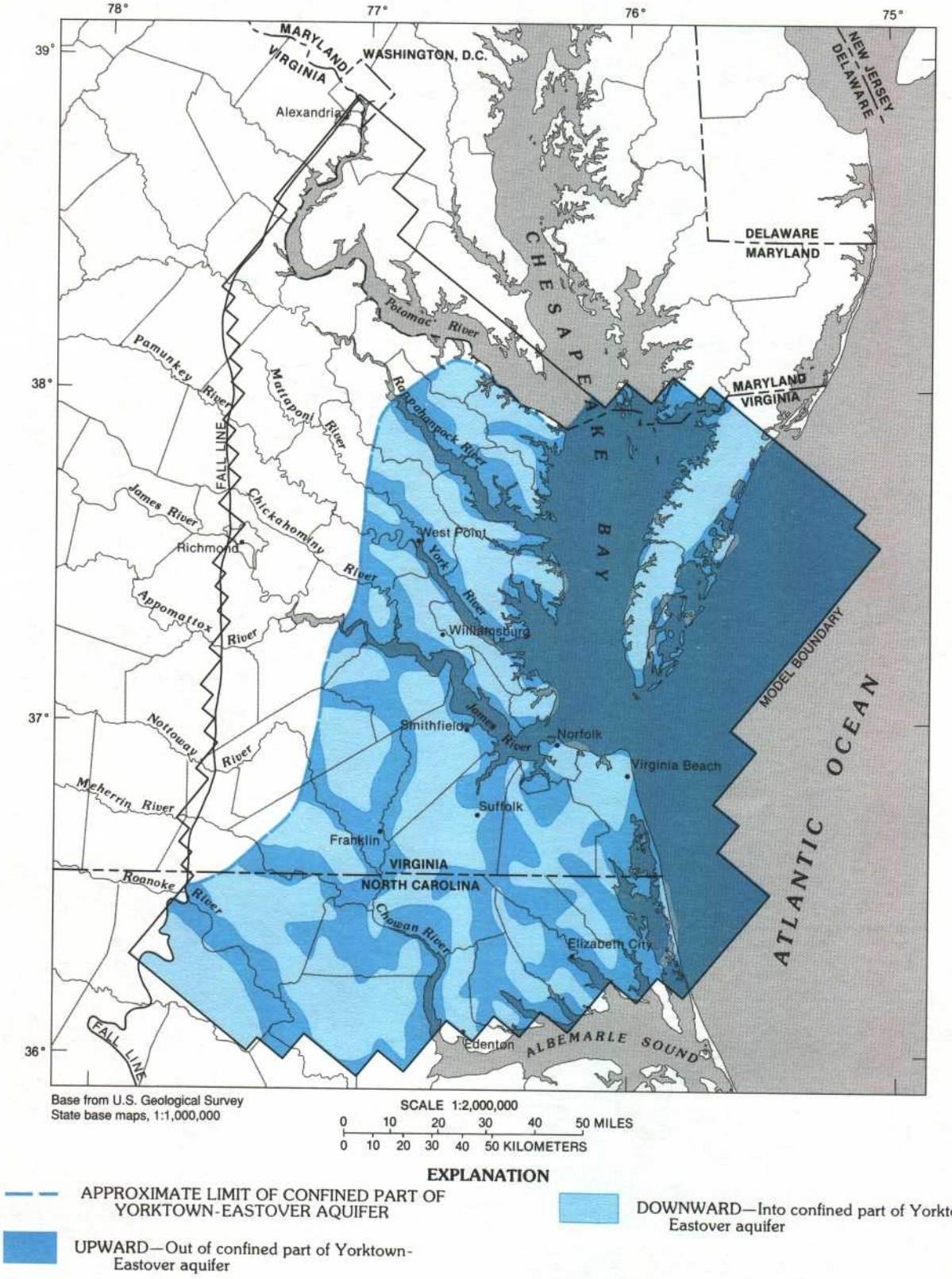


FIGURE 41.—Direction of simulated prepumping flow across the Yorktown confining unit.

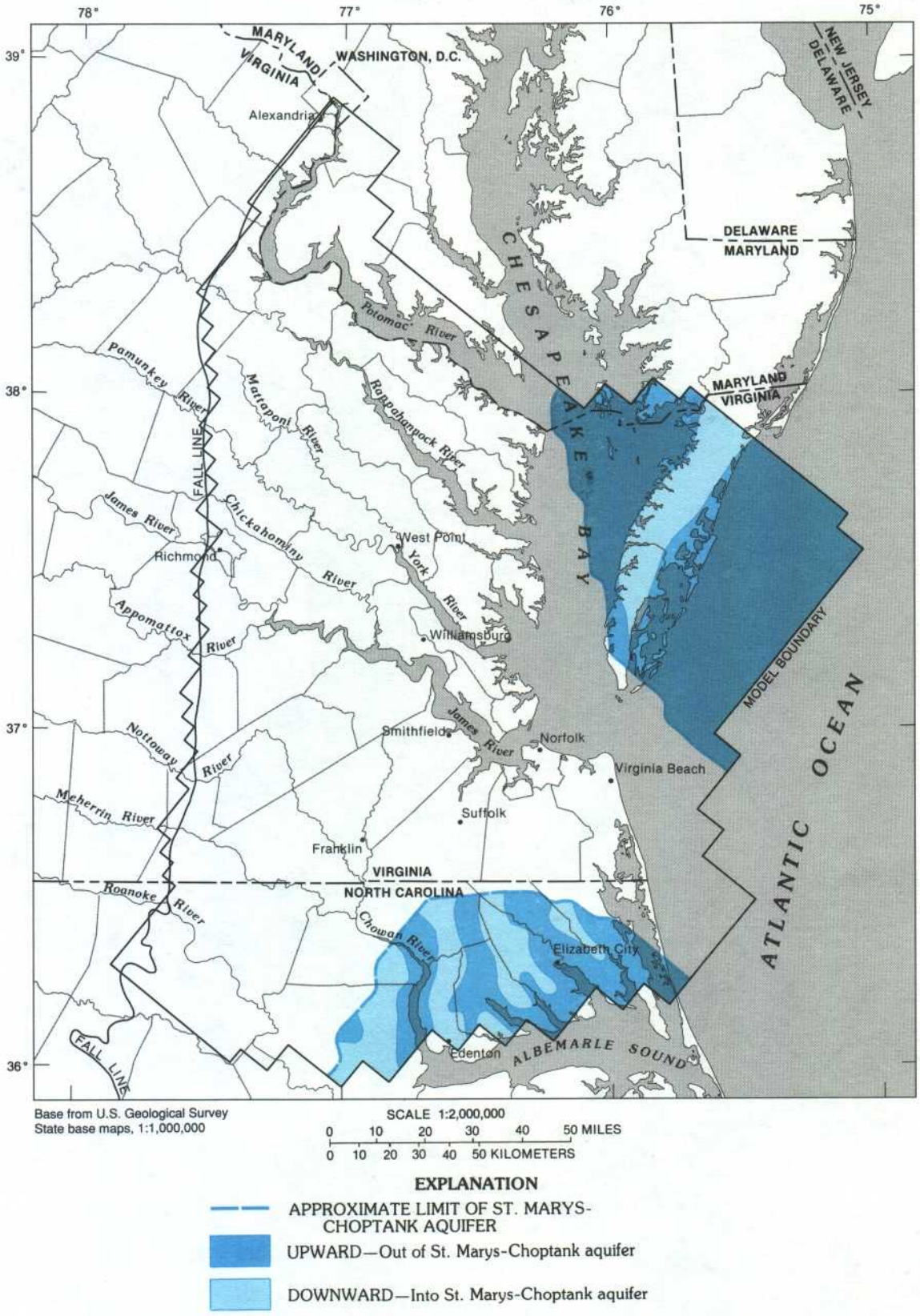


FIGURE 42.—Direction of simulated prepumping flow across the St. Marys confining unit.

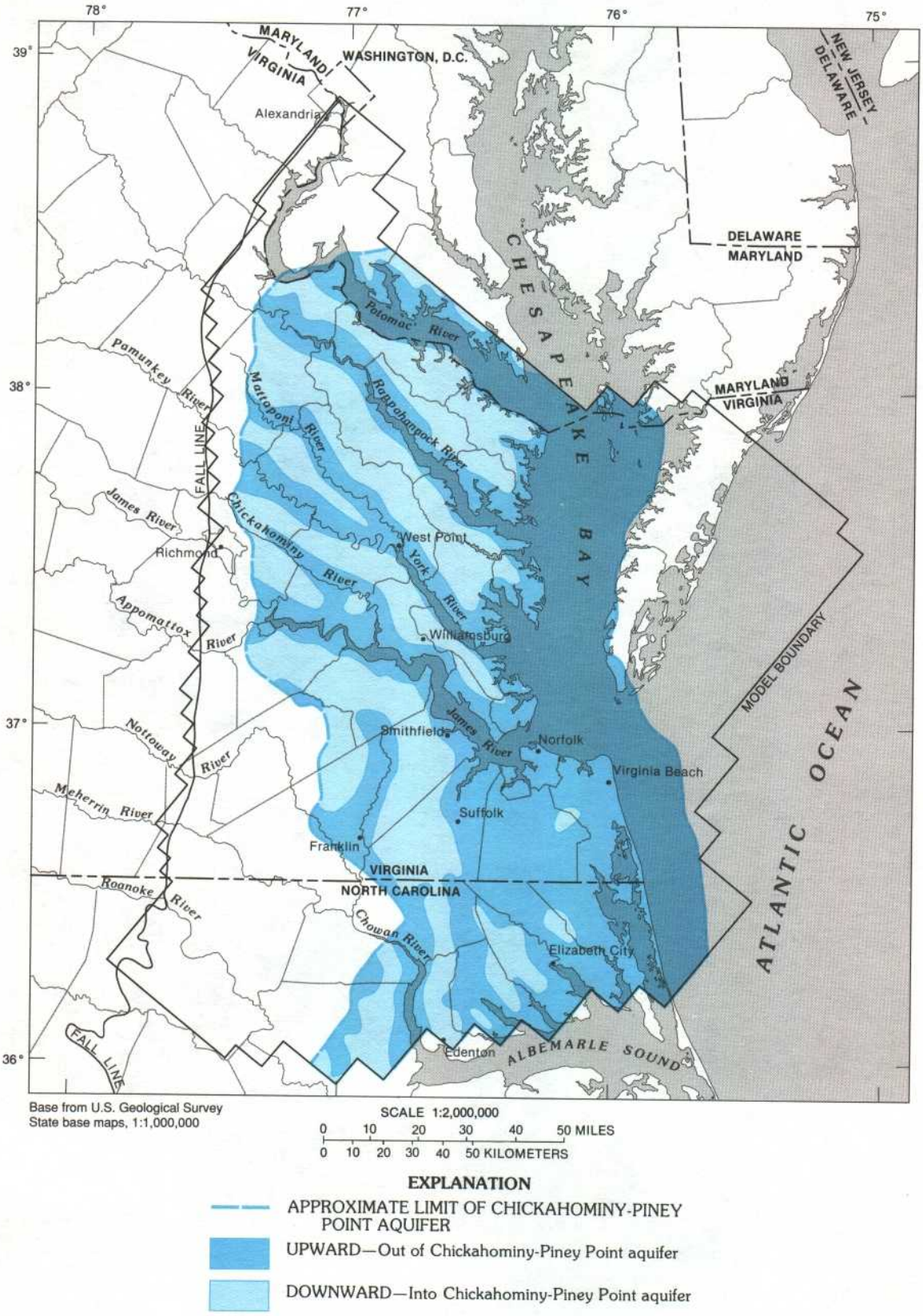


FIGURE 43.—Direction of simulated prepumping flow across the Calvert confining unit.

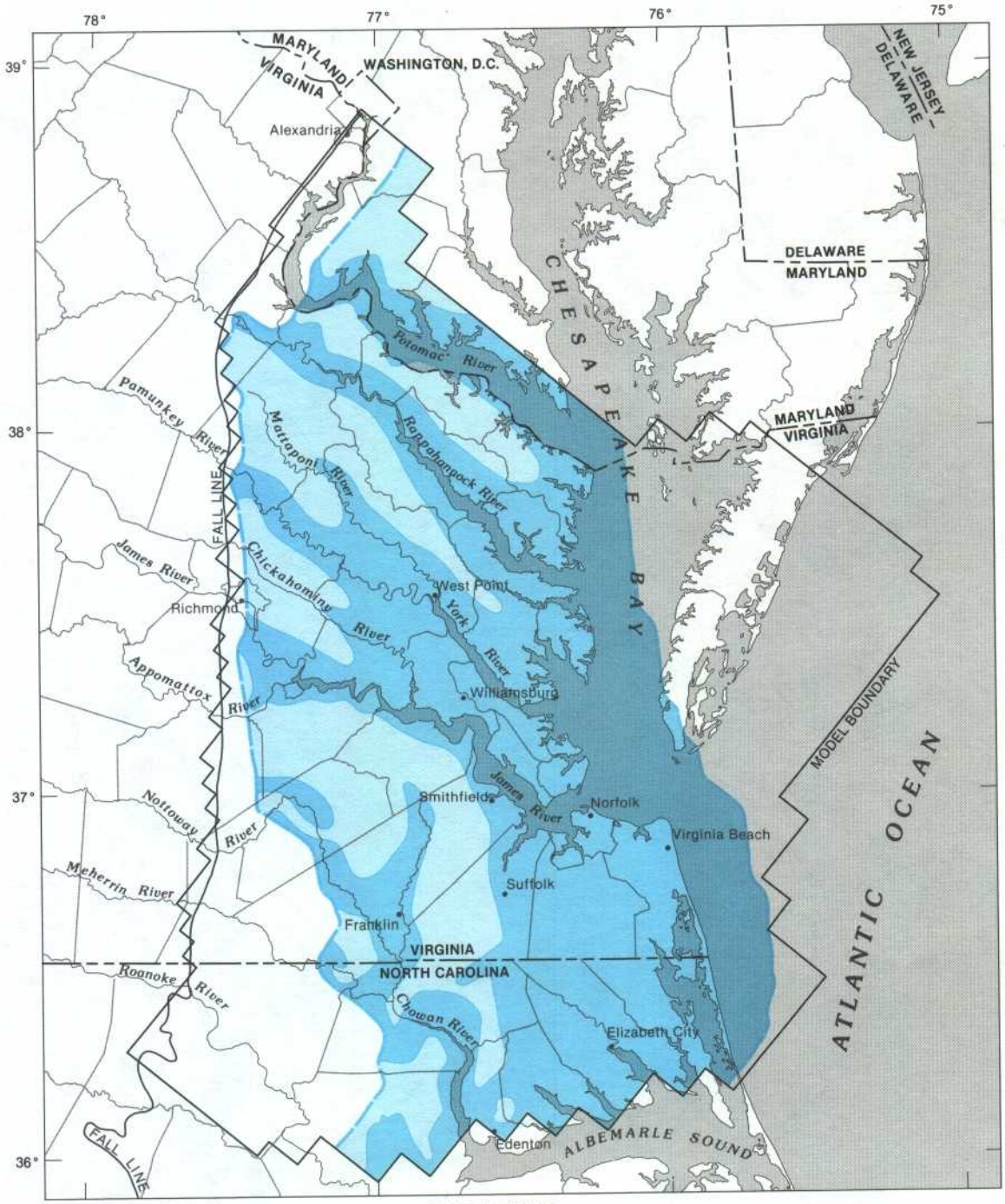


FIGURE 44.—Direction of simulated prepumping flow across the Nanjemoy-Marlboro confining unit.

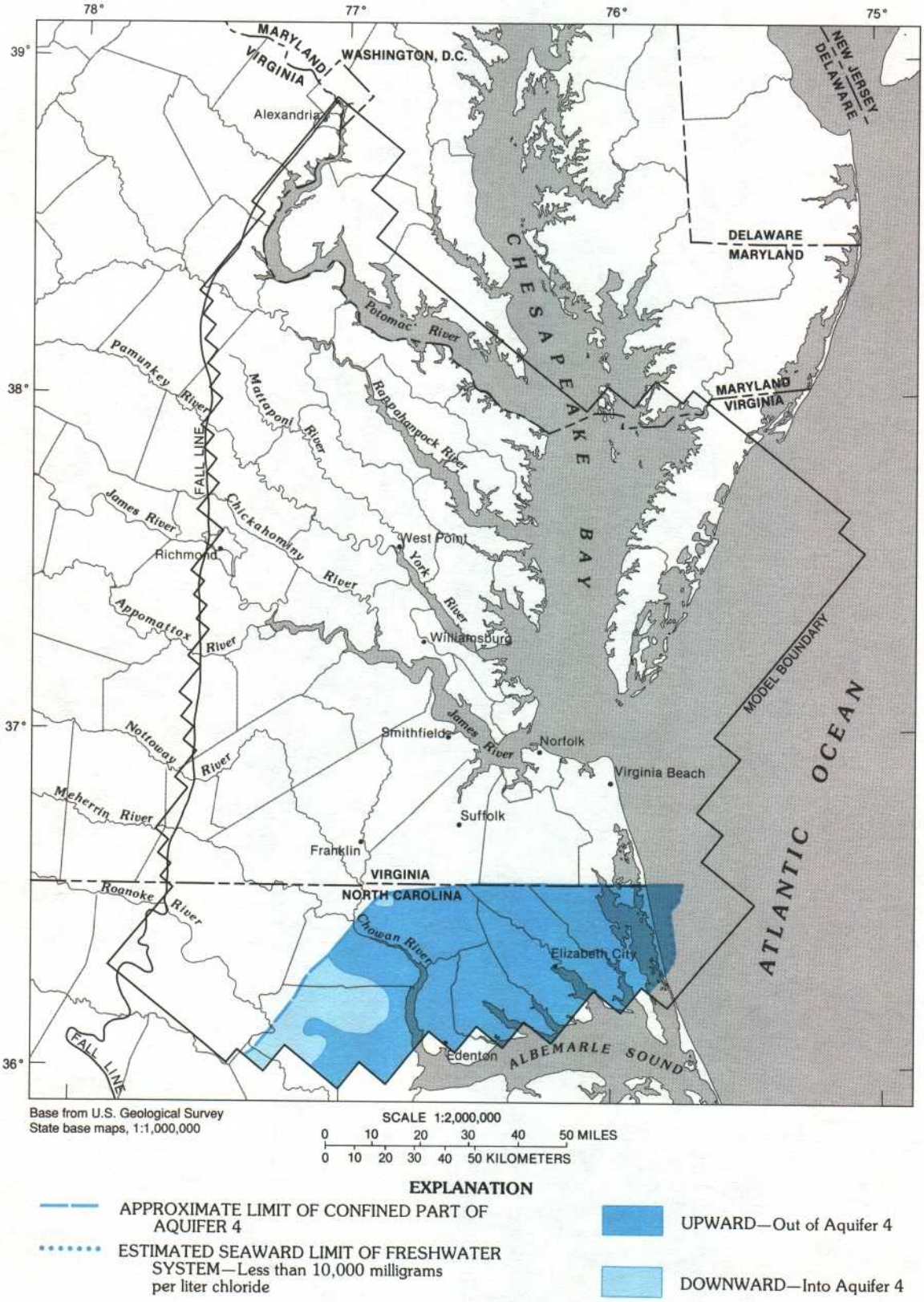


FIGURE 45.—Direction of simulated prepumping flow across confining unit 4.

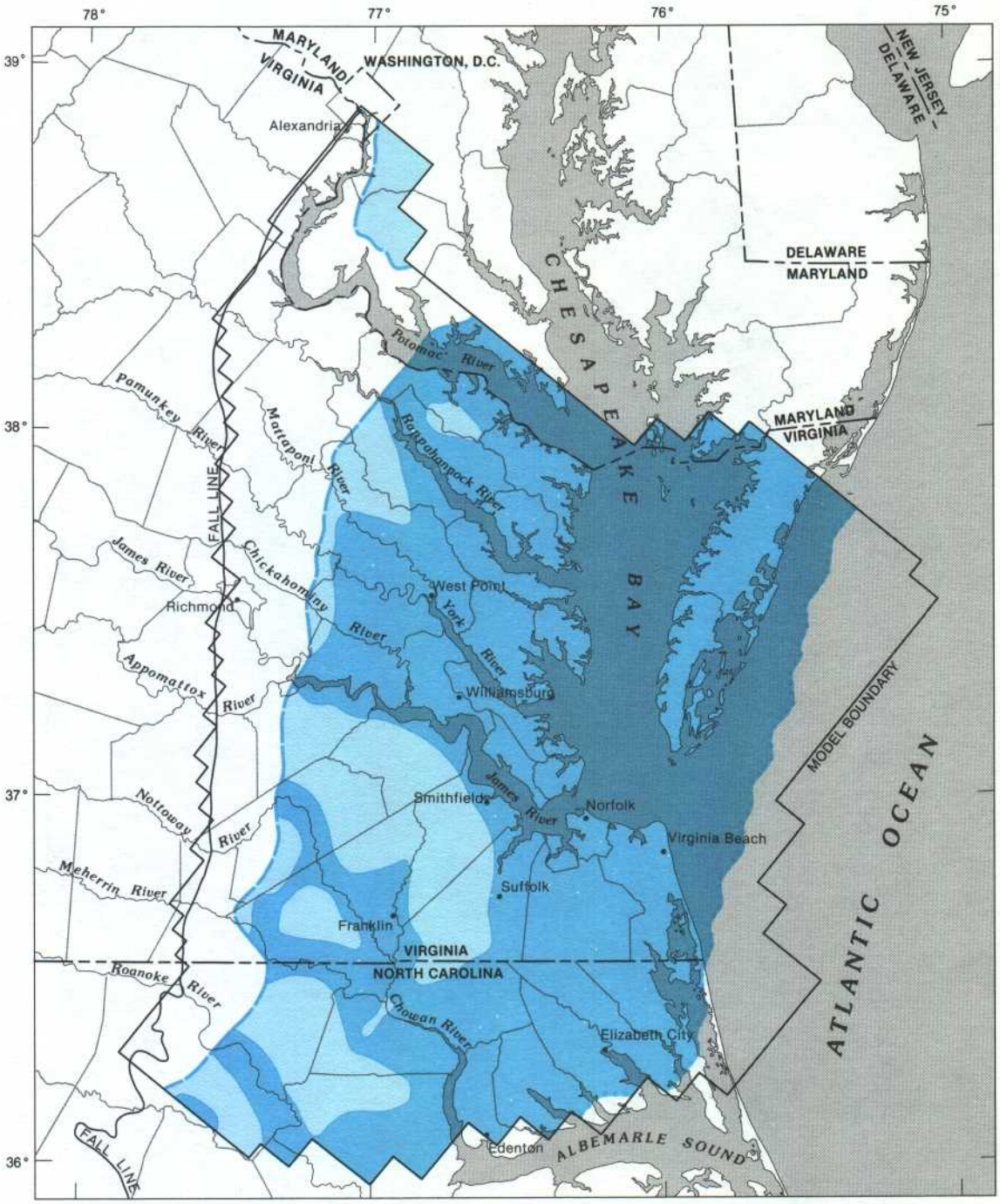


FIGURE 46.—Direction of simulated prepumping flow across the Brightseat-upper Potomac confining unit.

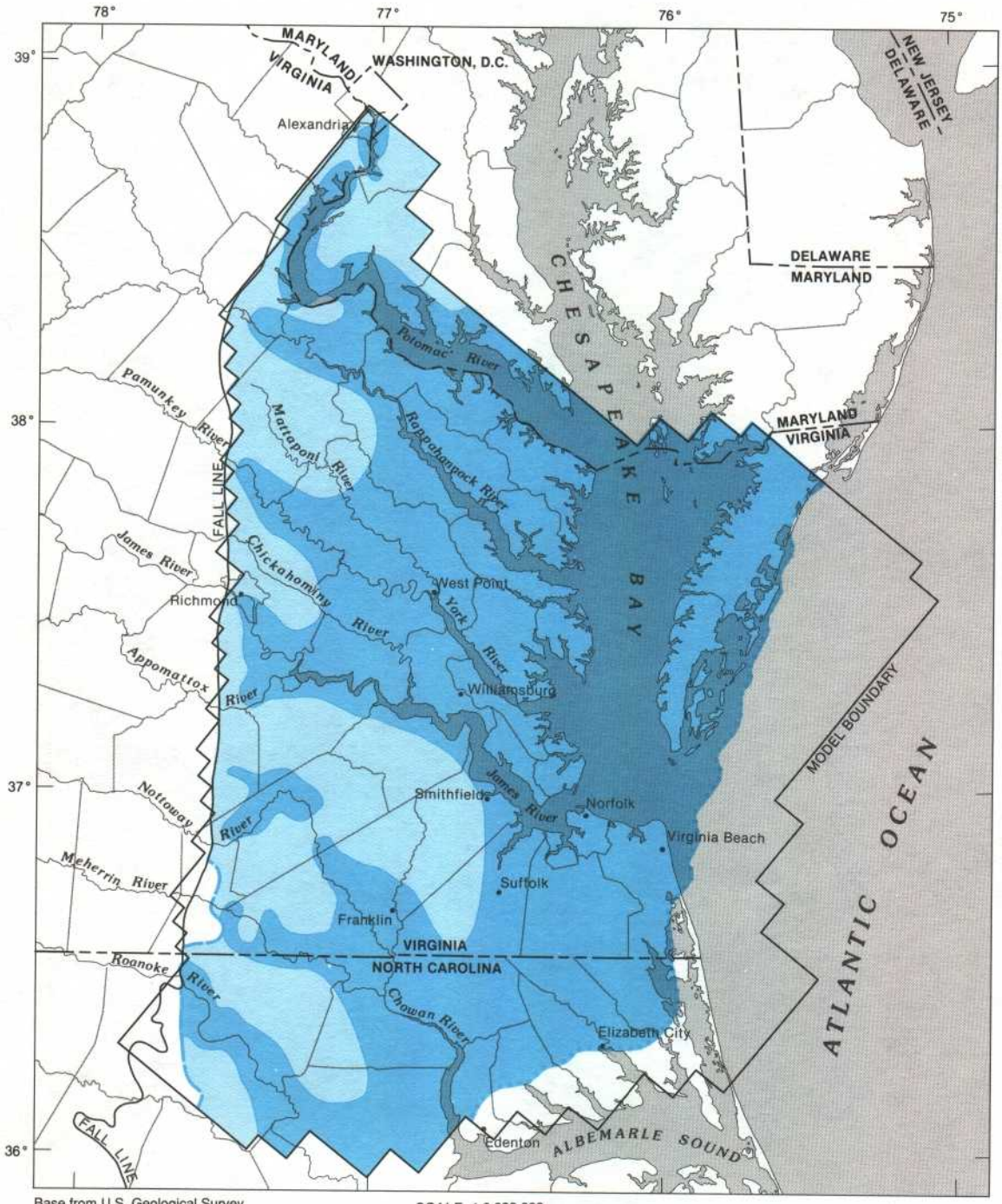


FIGURE 47.—Direction of simulated prepumping flow across the middle Potomac confining unit.

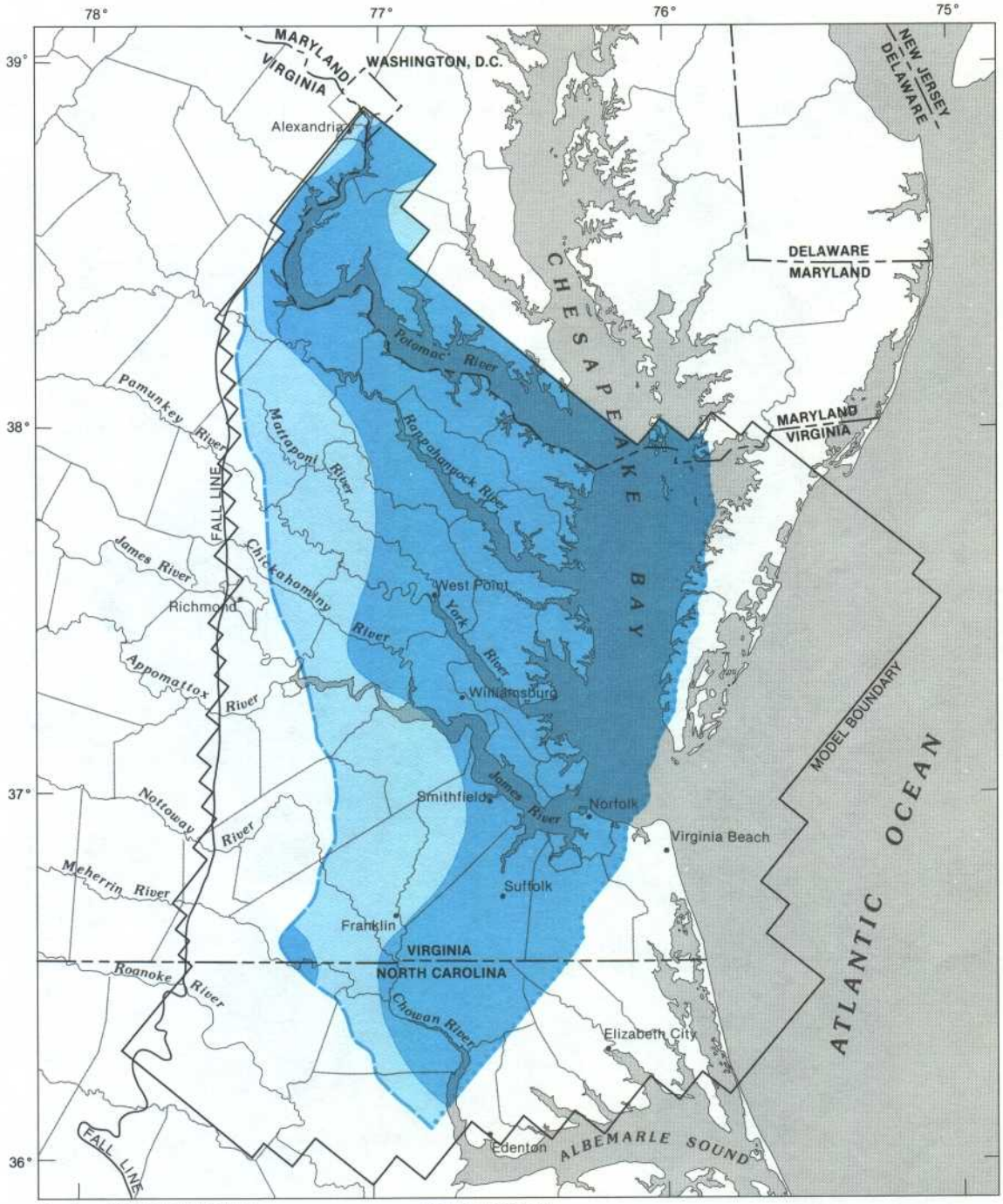


FIGURE 48.—Direction of simulated prepumping flow across the lower Potomac confining unit.

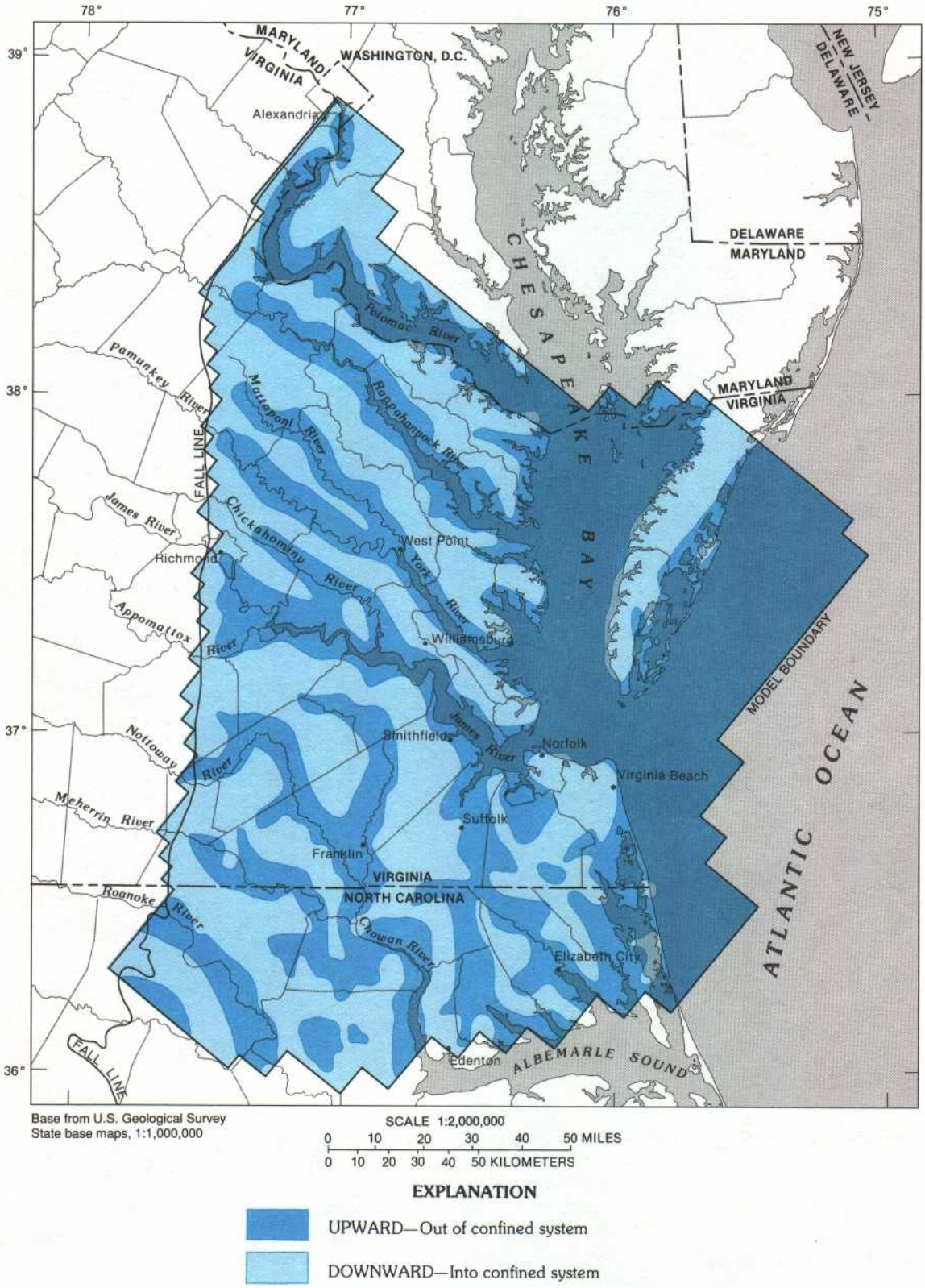


FIGURE 49.—Direction of simulated prepumping flow into and out of confined system.

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

Pumping Conditions

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

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

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

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

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

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

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