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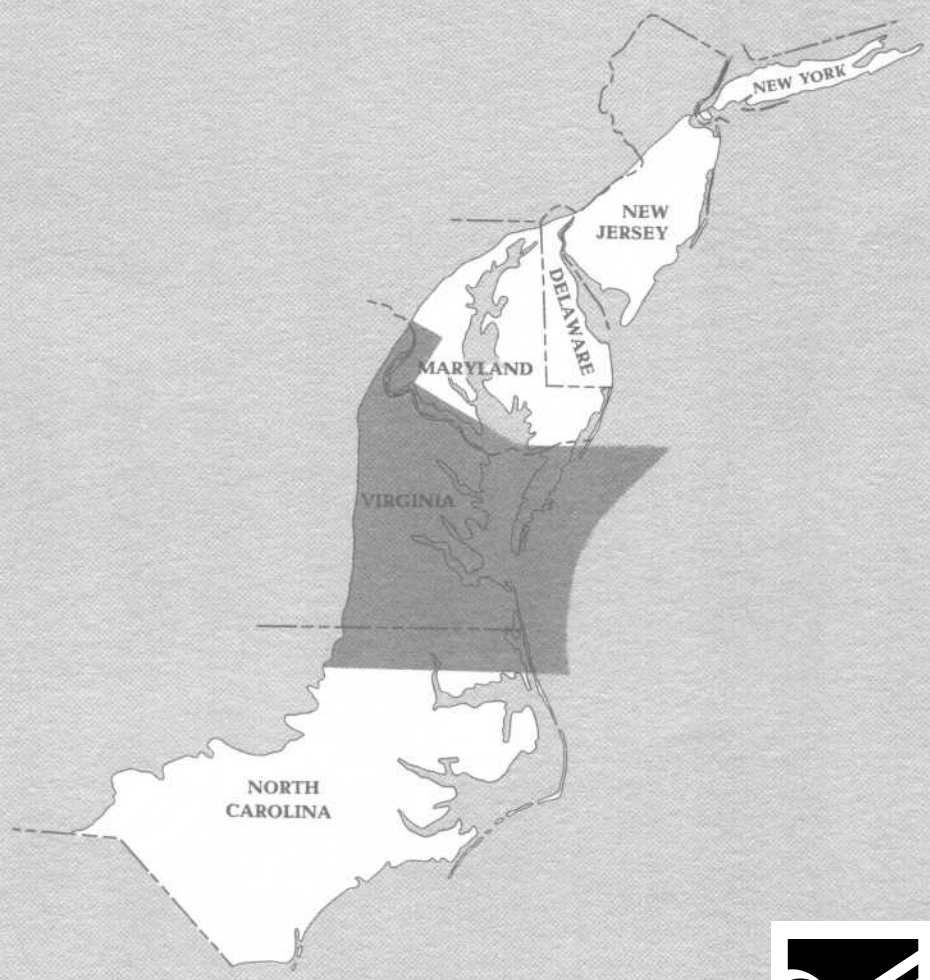
CONCEPTUALIZATION AND ANALYSIS OF GROUND-WATER FLOW SYSTEM IN THE COASTAL PLAIN OF VIRGINIA AND ADJACENT PARTS OF MARYLAND AND NORTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1404—F

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

Pumping Conditions

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

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

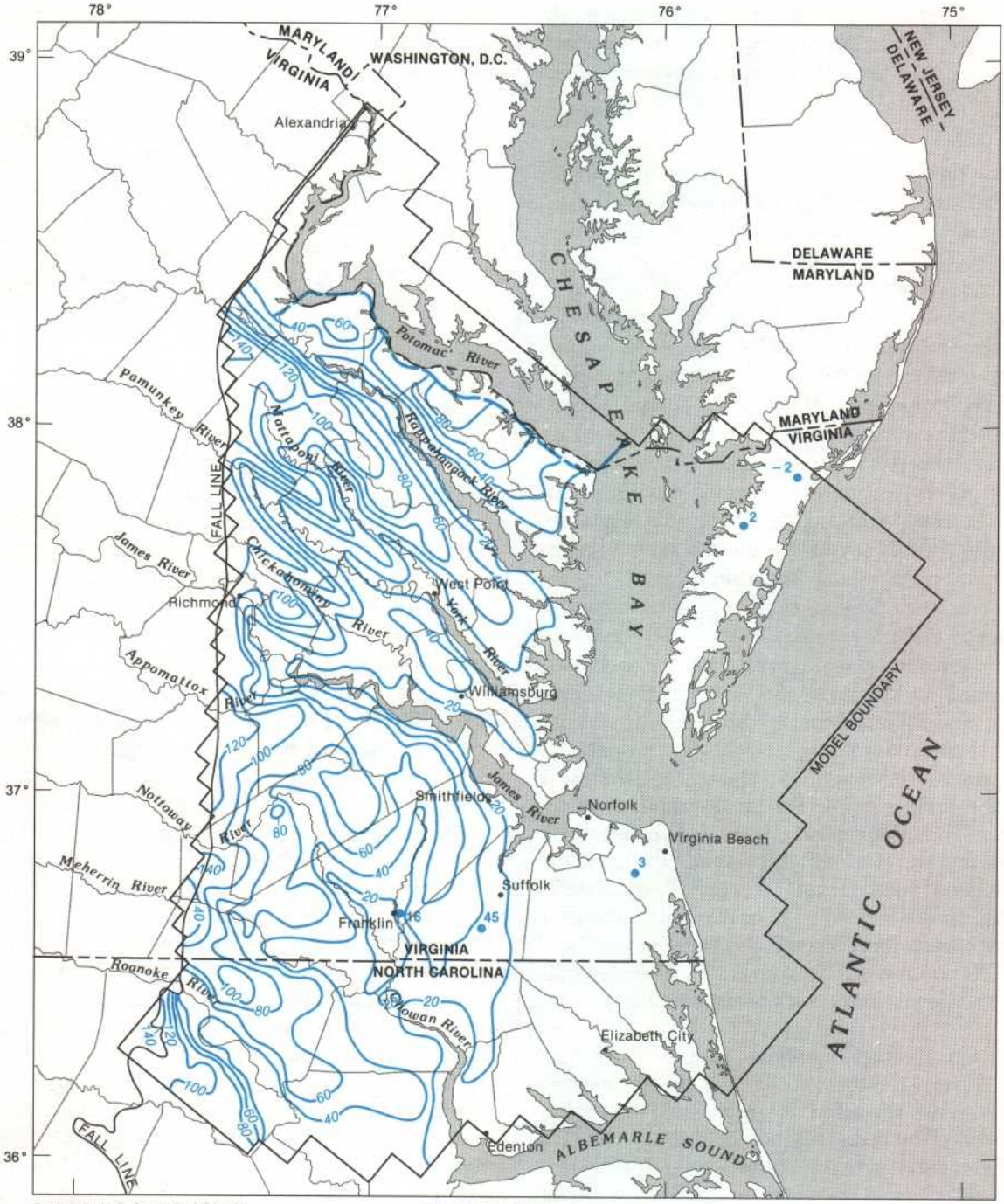
A comparison of prepumping potentiometric-surface maps (figs. 33 through 40) with the 1980 potentiometric-surface maps shows the effect of ground-water development on the water-level distribution in each aquifer. The maps of the simulated ground-water flow system in 1980 show lower water levels and cones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

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

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

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

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



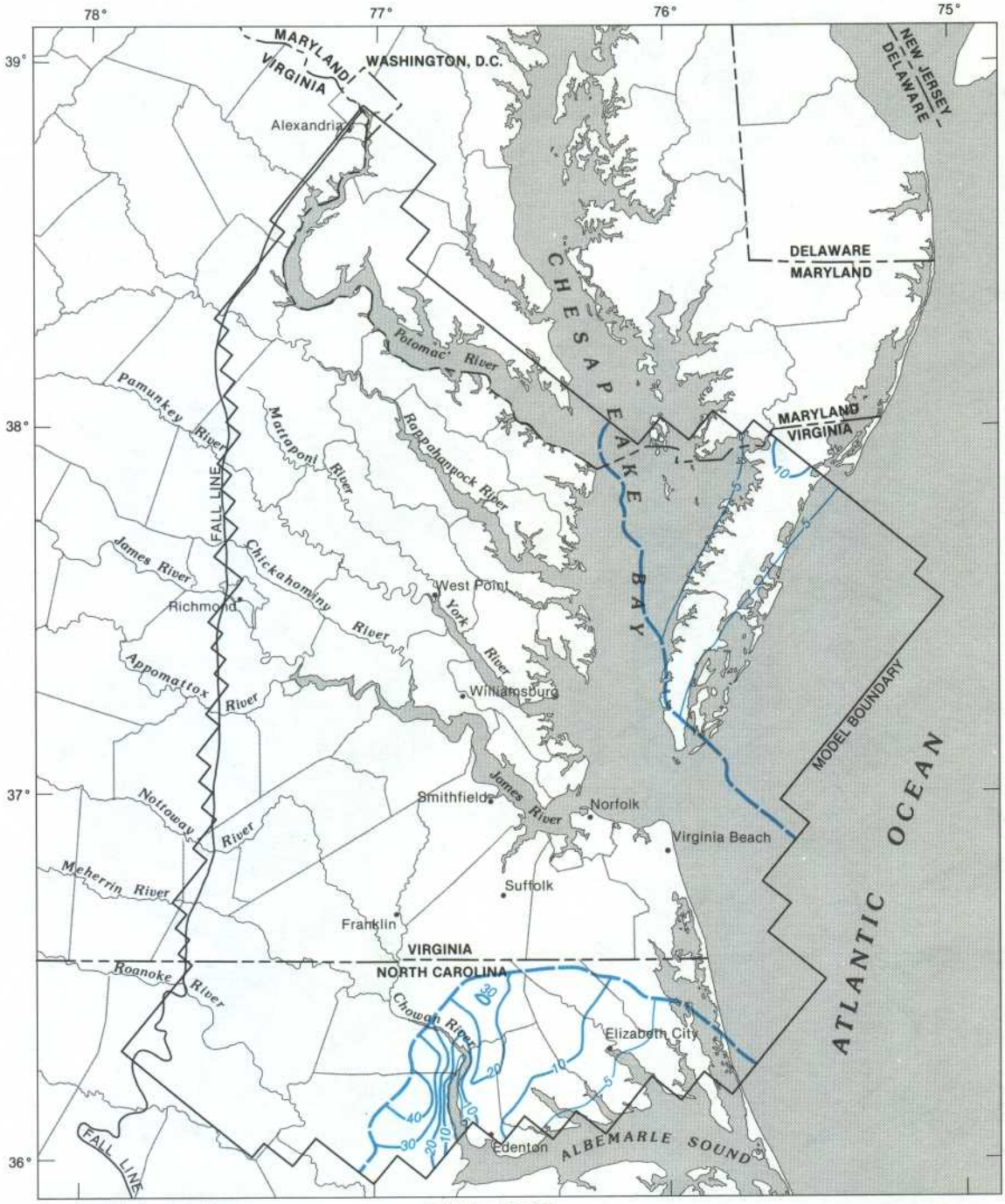
EXPLANATION

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

—— APPROXIMATE LIMIT OF YORKTOWN-EASTOVER AQUIFER

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

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

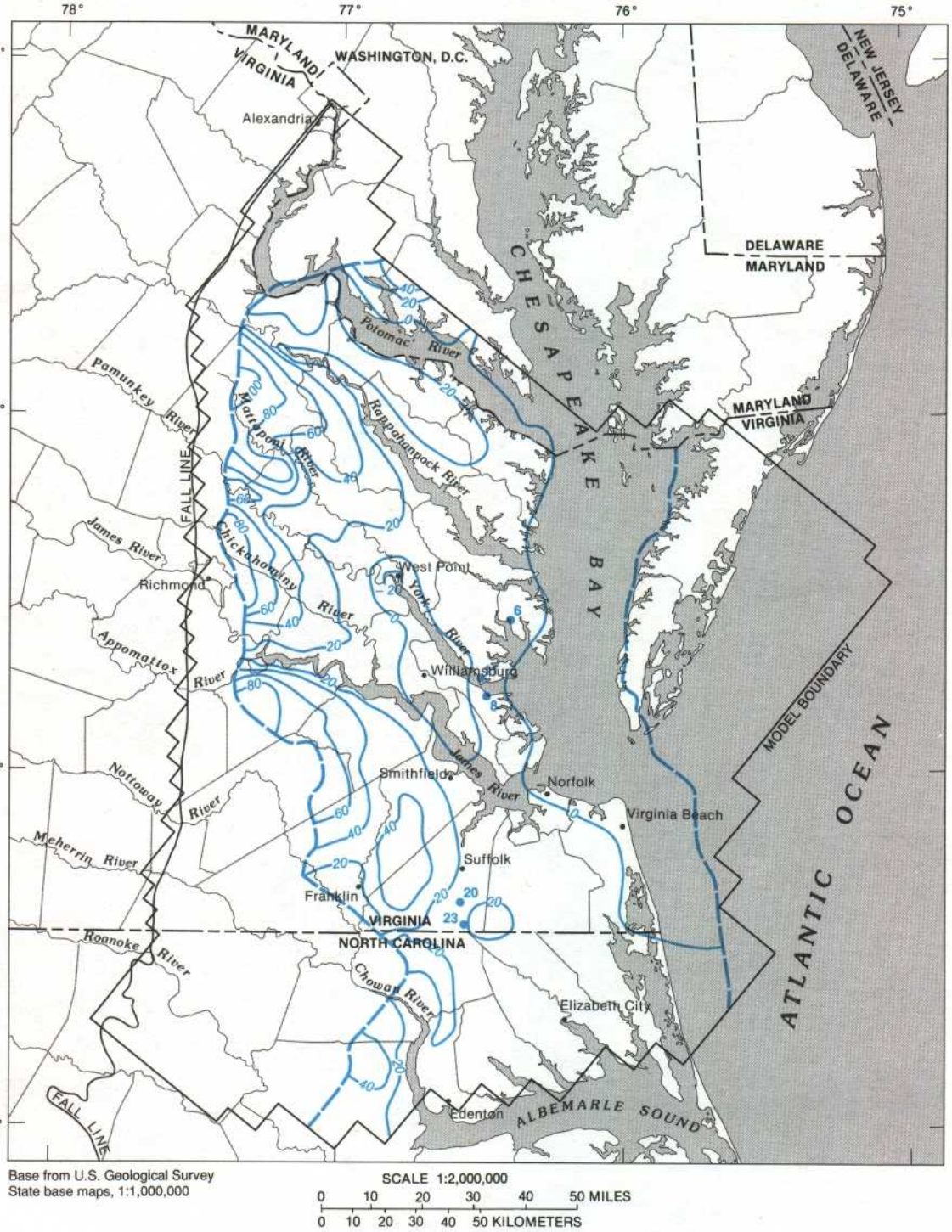


EXPLANATION

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

— — APPROXIMATE LIMIT OF ST. MARYS-CHOPTANK AQUIFER

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



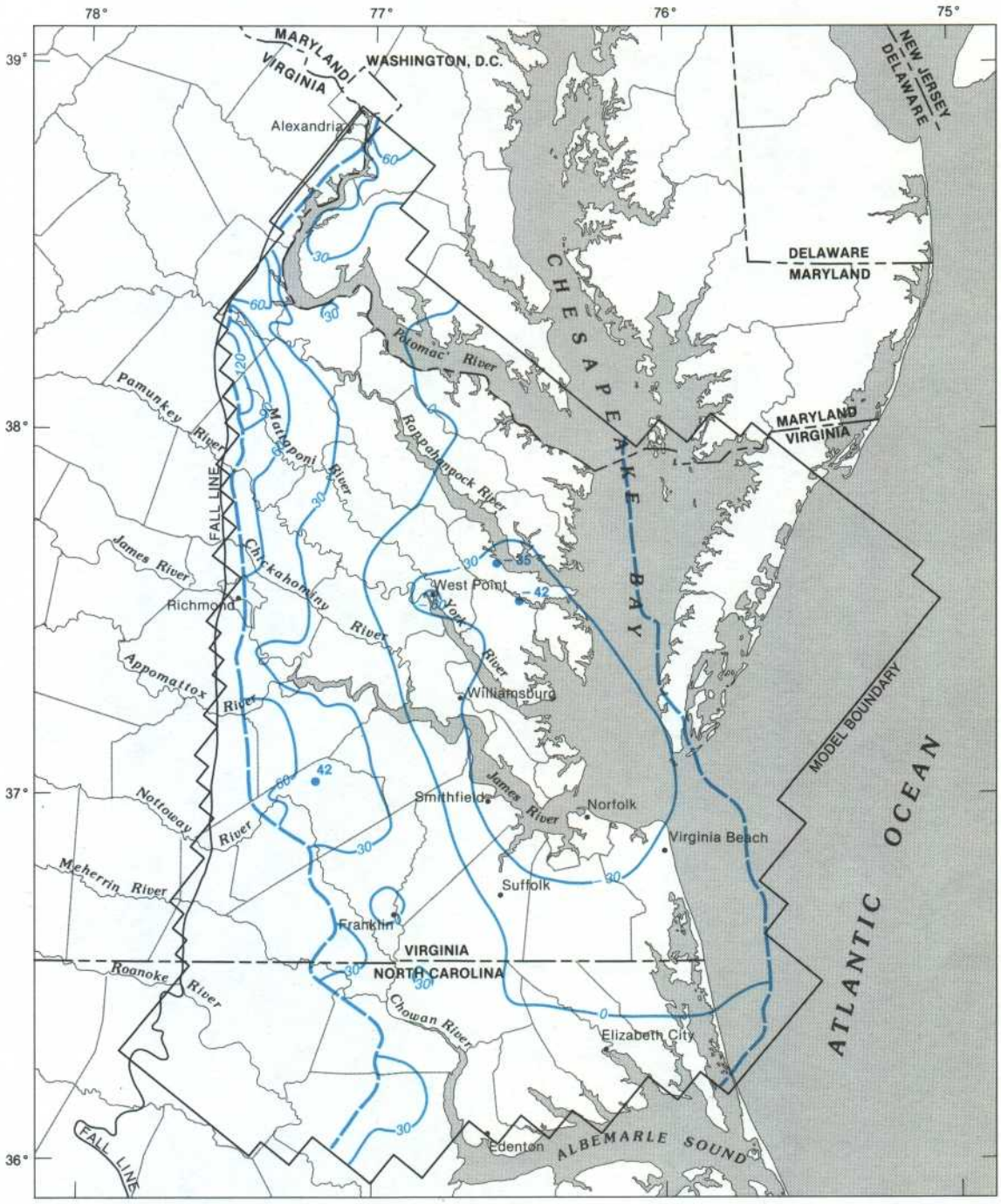
EXPLANATION

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

— — APPROXIMATE LIMIT OF CHICKAHOMINY-PINEY POINT AQUIFER

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

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



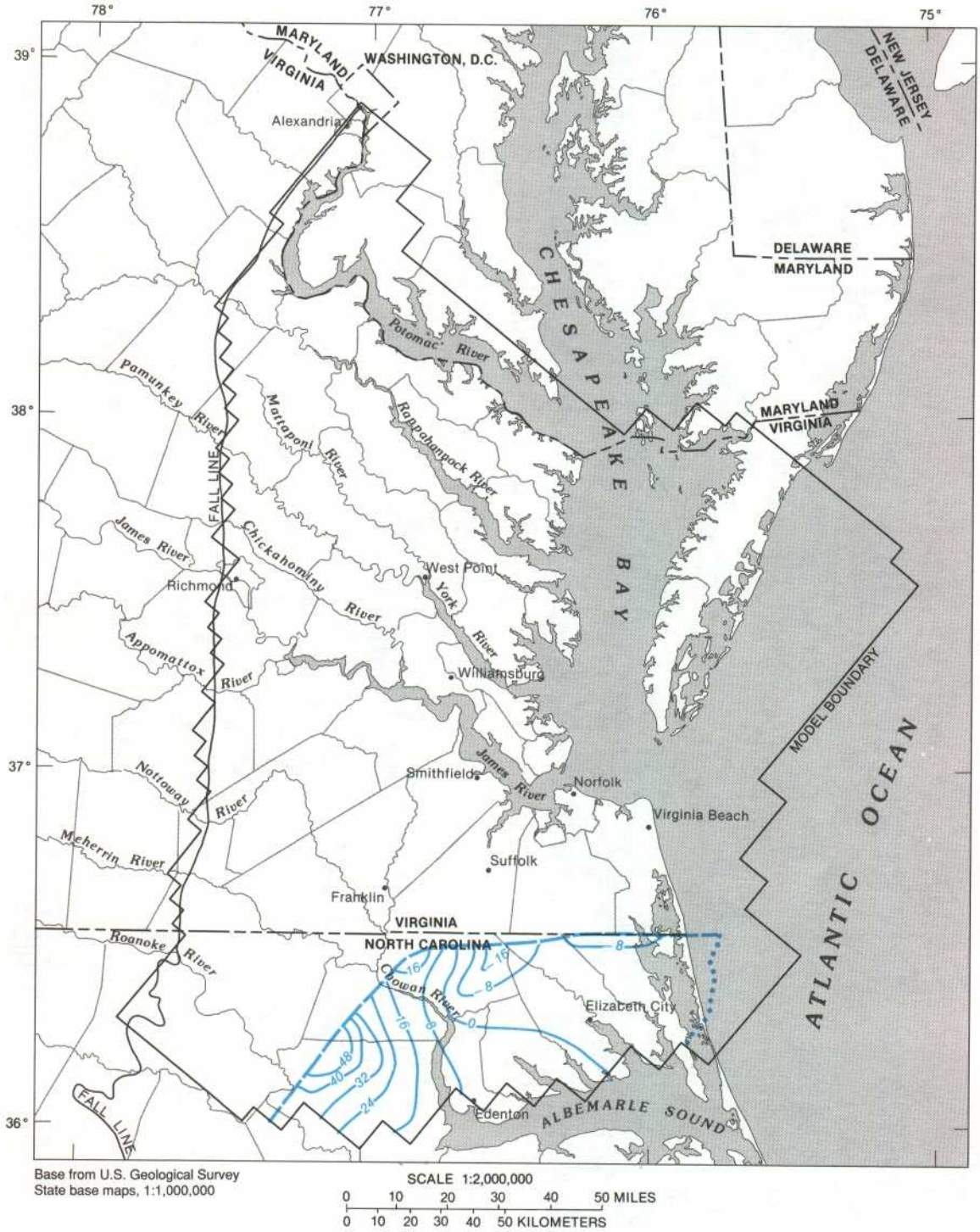
EXPLANATION

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

— — APPROXIMATE LIMIT OF AQUIA AQUIFER

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

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



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

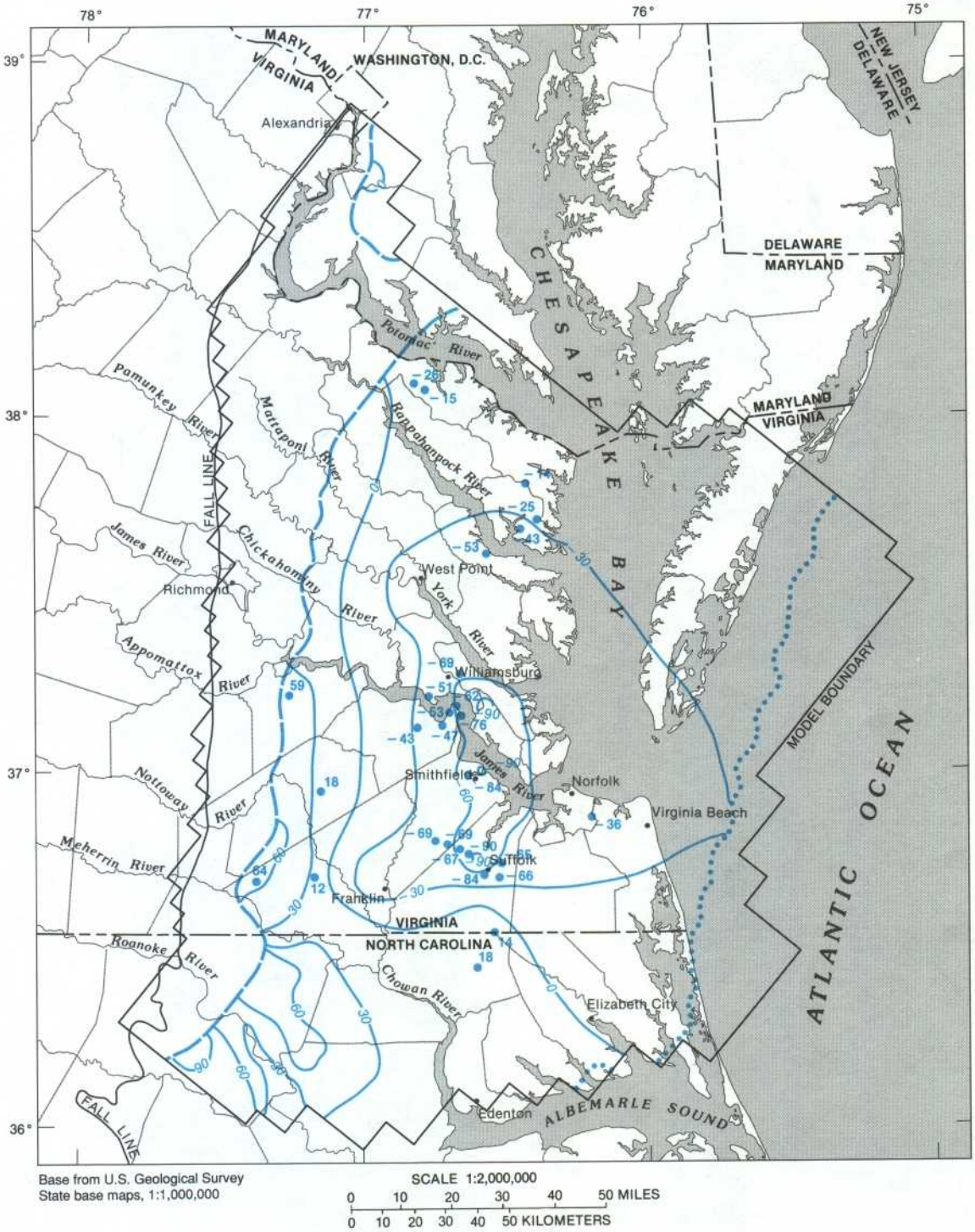
EXPLANATION

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

— — APPROXIMATE LIMIT OF AQUIFER 4

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

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



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

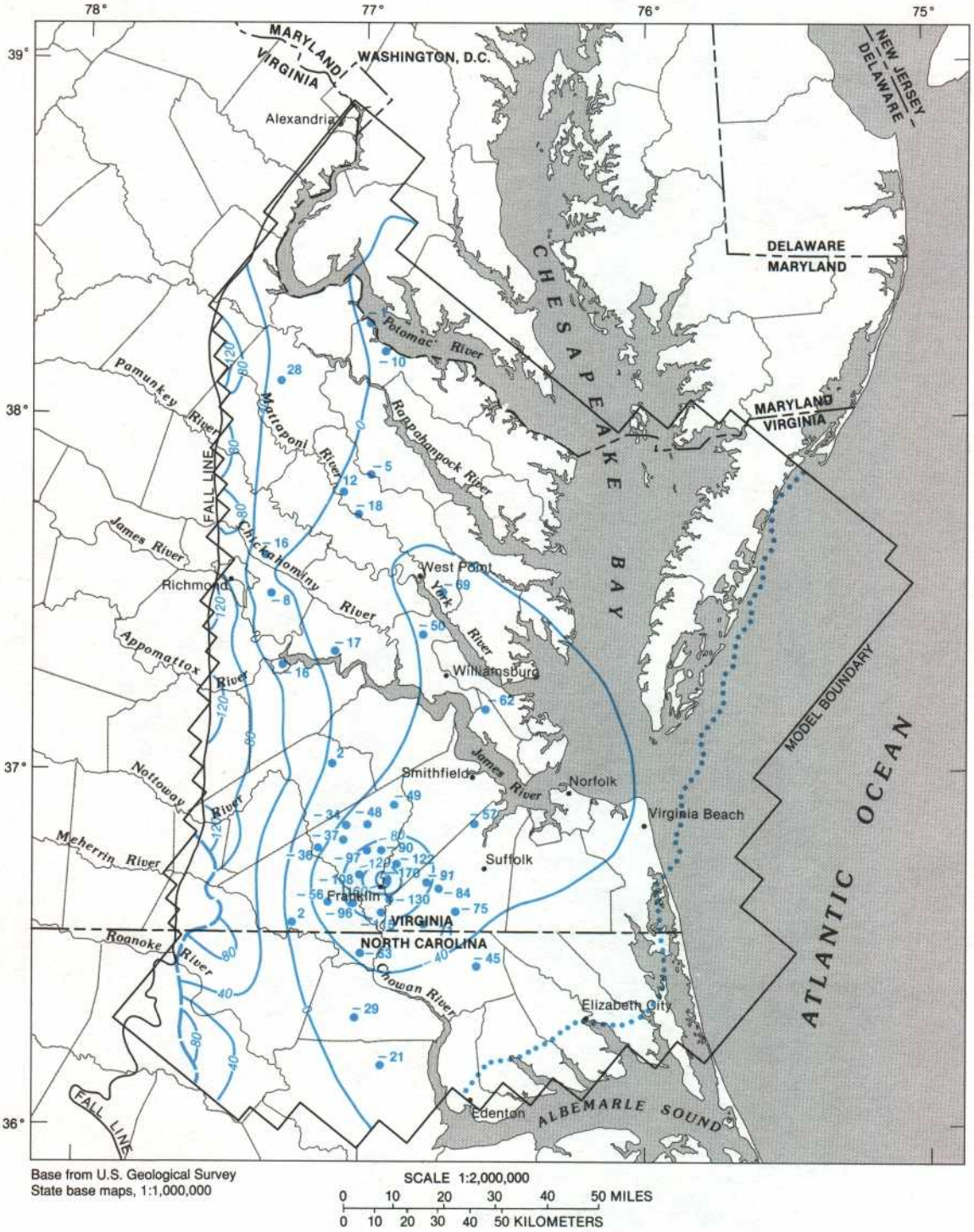
—30— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 30 feet. Datum is sea level

APPROXIMATE LIMIT OF BRIGHTSEAT-UPPER POTOMAC AQUIFER

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

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

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



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

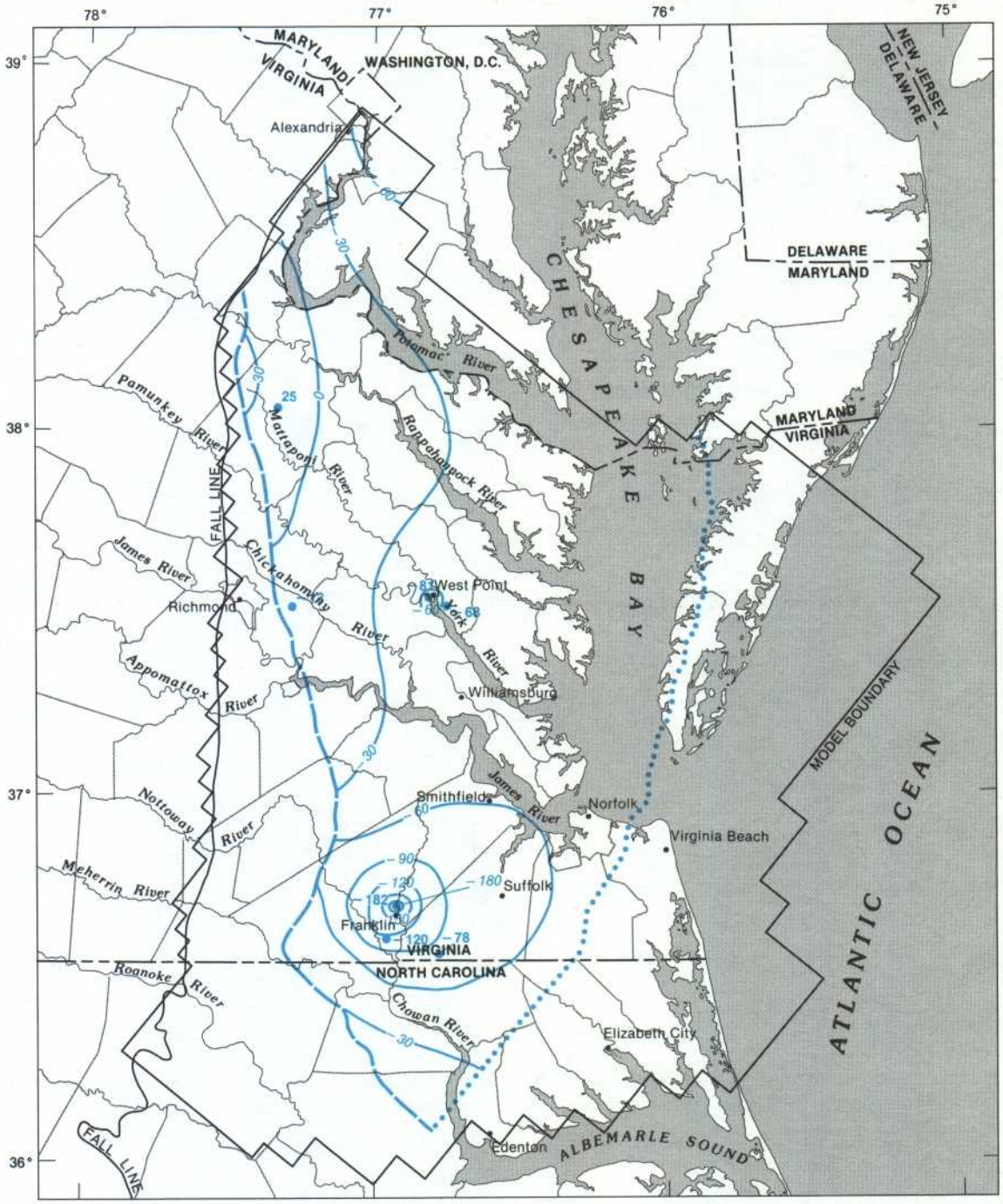
—40— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface. Contour interval is 40 feet. Datum is sea level

— — APPROXIMATE LIMIT OF THE MIDDLE POTOMAC AQUIFER

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

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

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



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

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

APPROXIMATE LIMIT OF LOWER POTOMAC AQUIFER

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

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

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

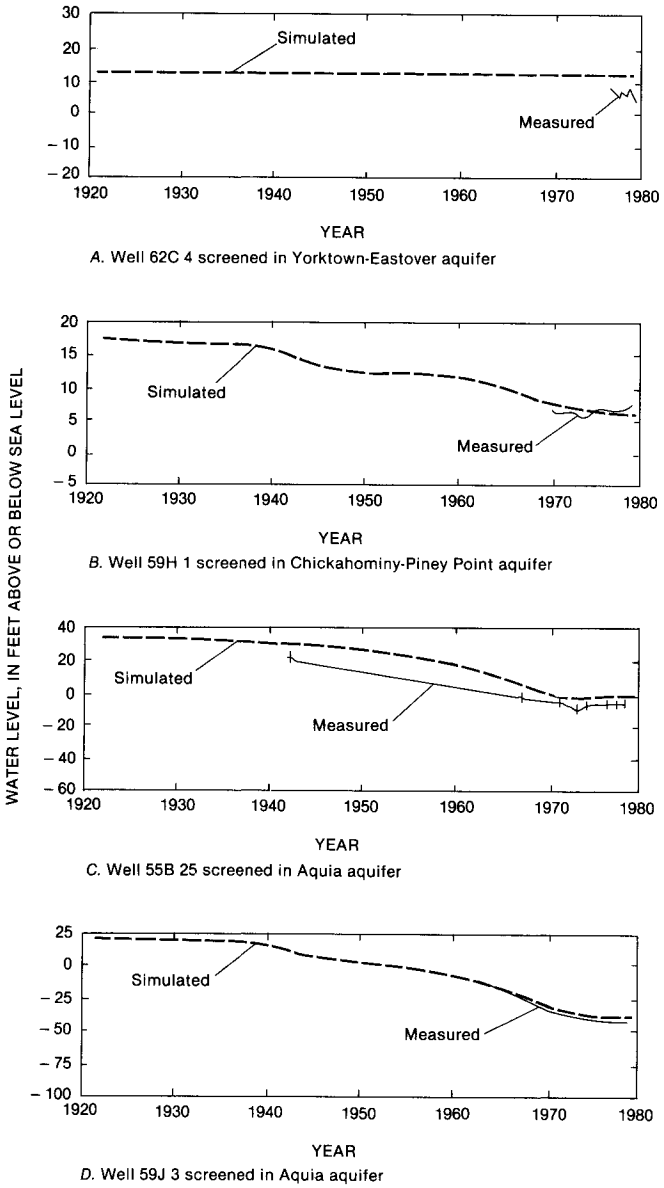


FIGURE 58.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

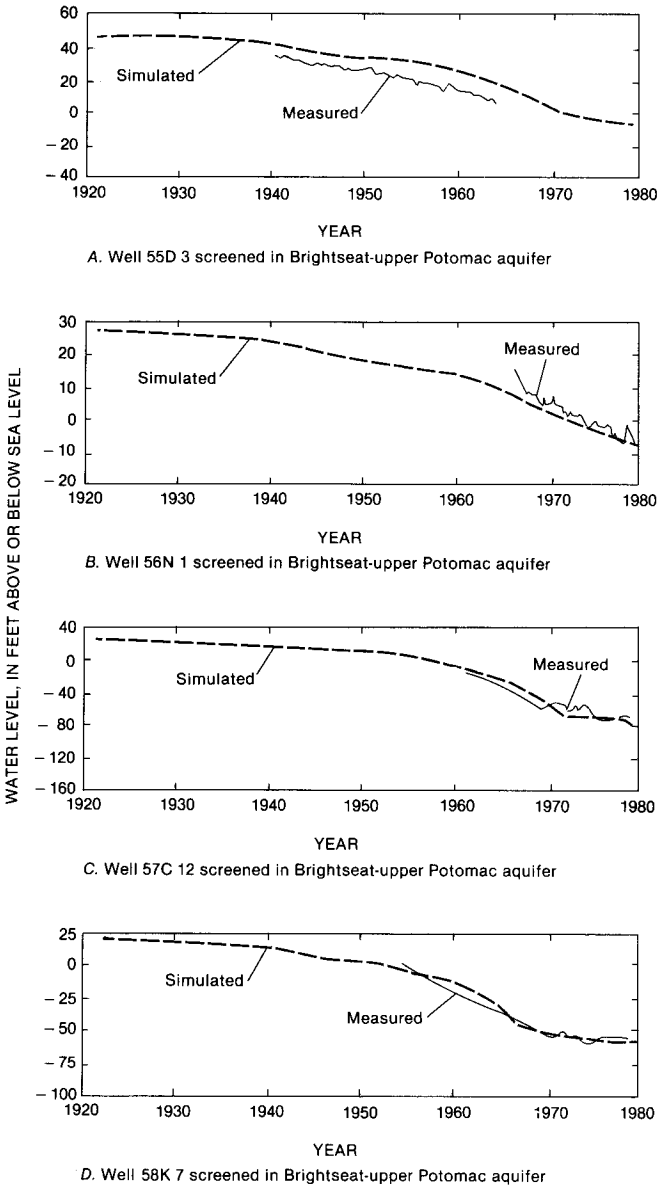


FIGURE 59.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

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

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

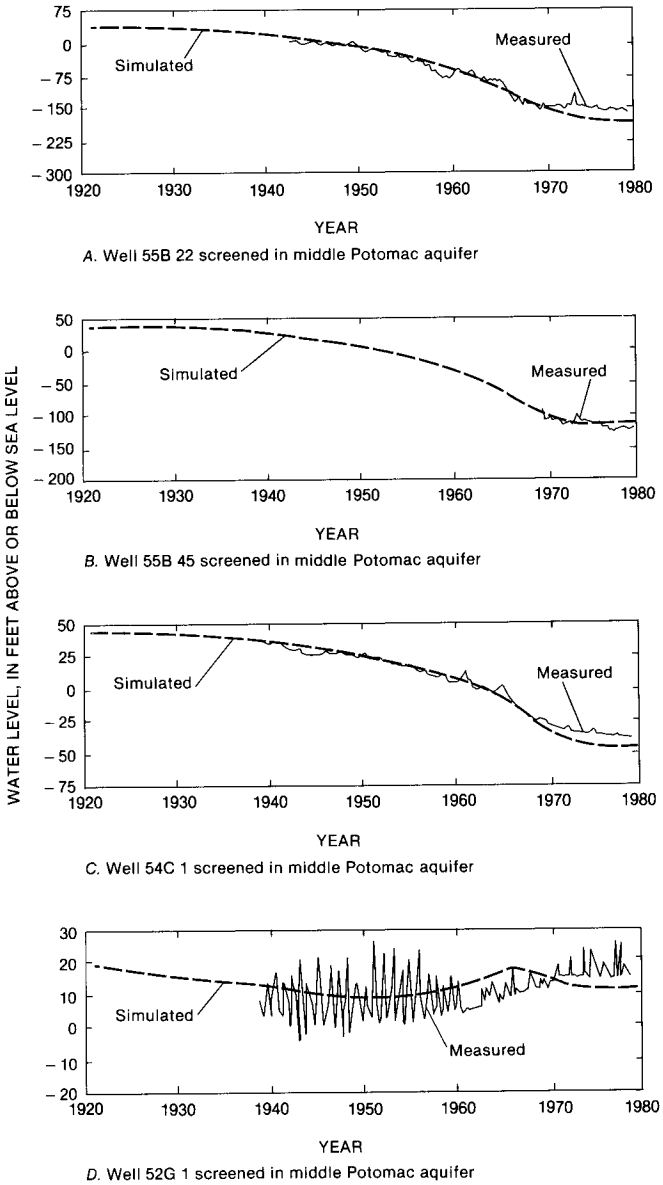


FIGURE 60.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

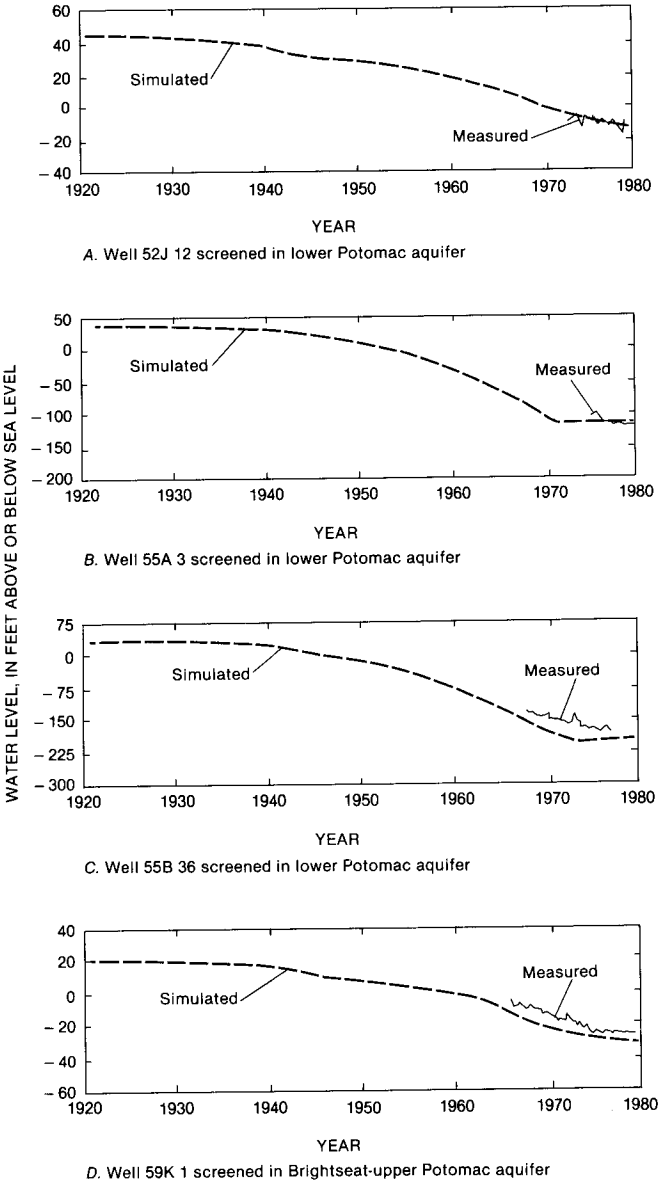
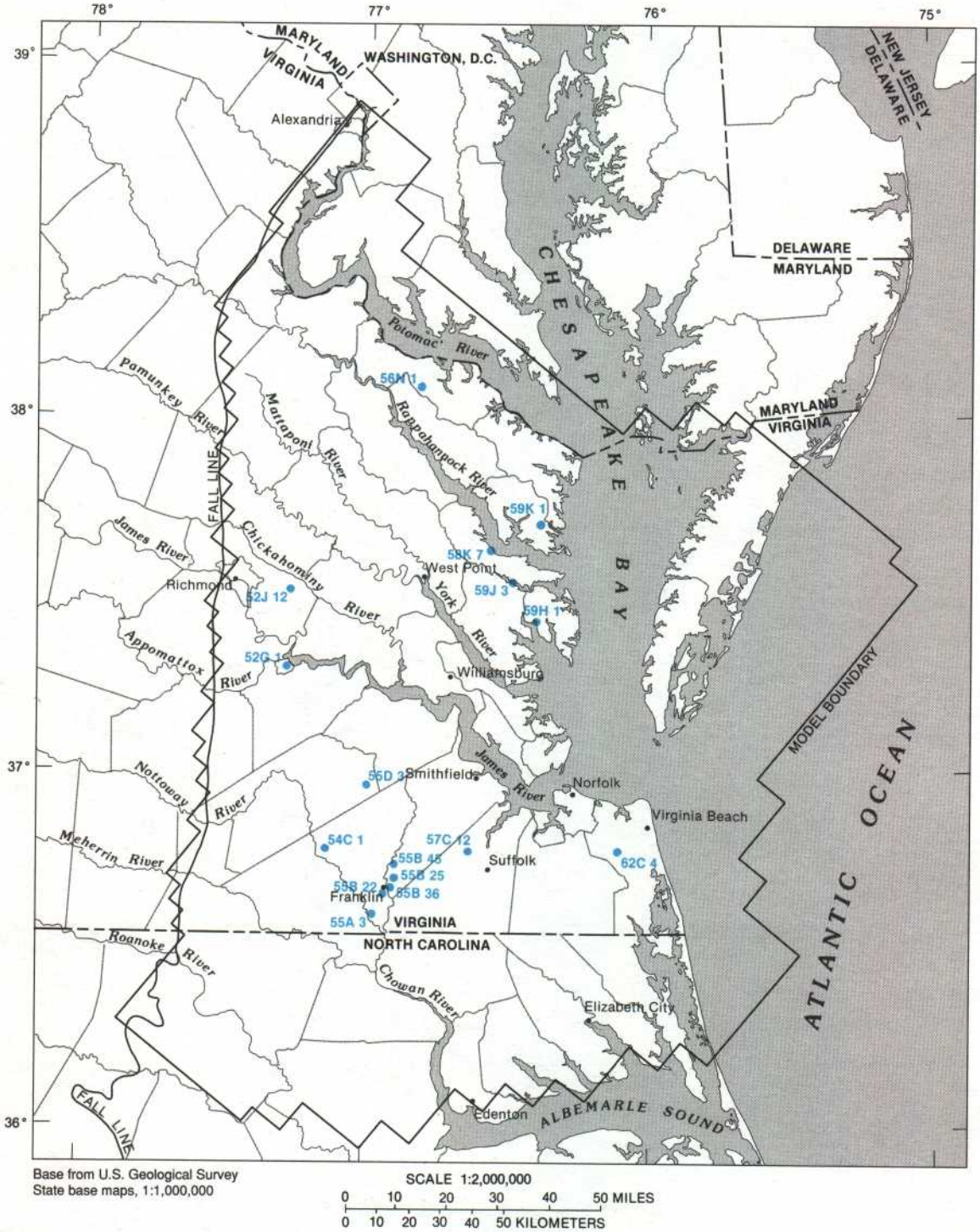


FIGURE 61.—Simulated and measured change in water levels for history of ground-water development. (Location of wells shown in fig. 62.)

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

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



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

• 58K 7 OBSERVATION AND LOCAL WELL NUMBER SHOWN IN FIGURES 58 - 61 AND FIGURES 72 - 79

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

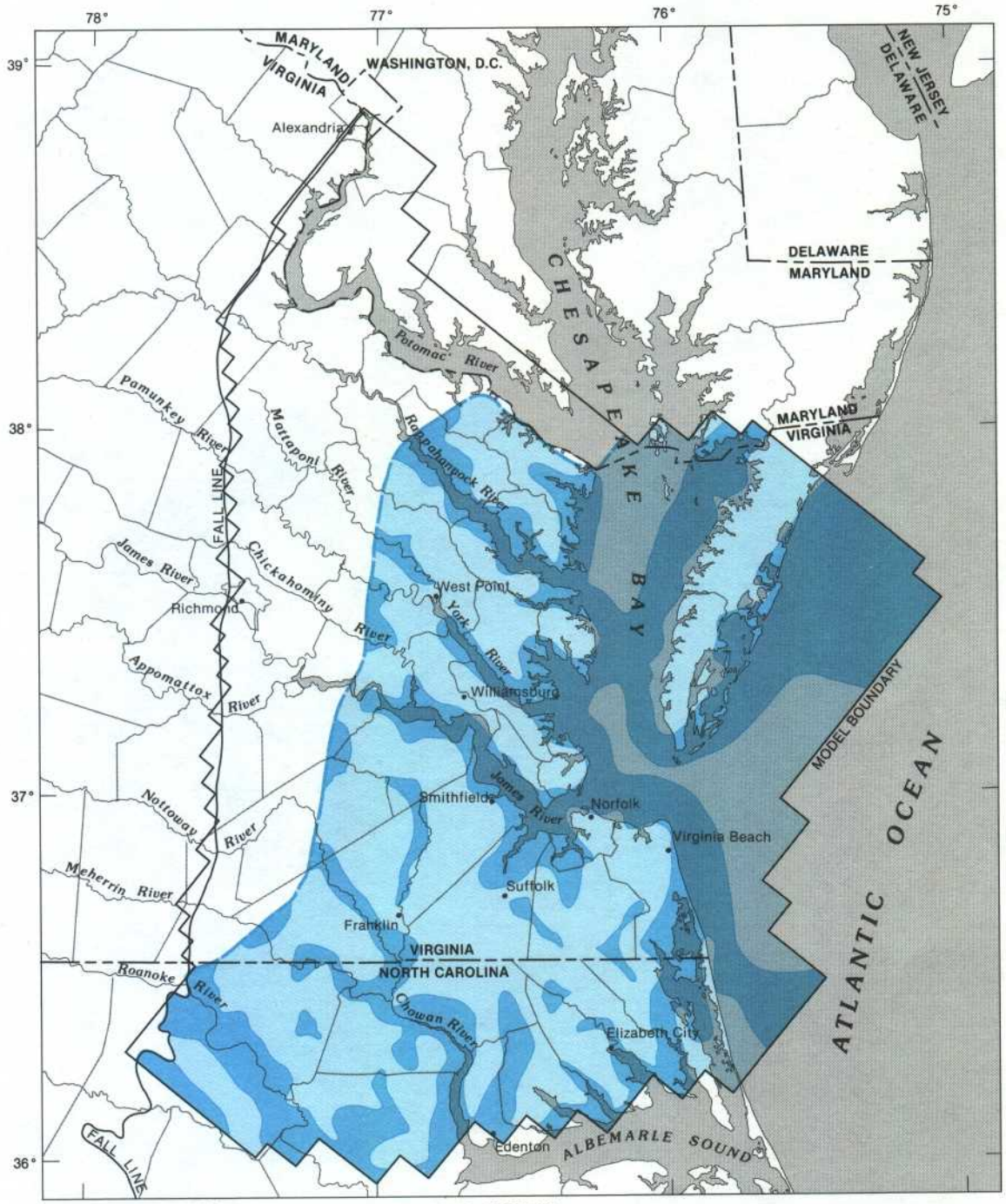


FIGURE 63.—Direction of simulated flow across the Yorktown confining unit, 1980.

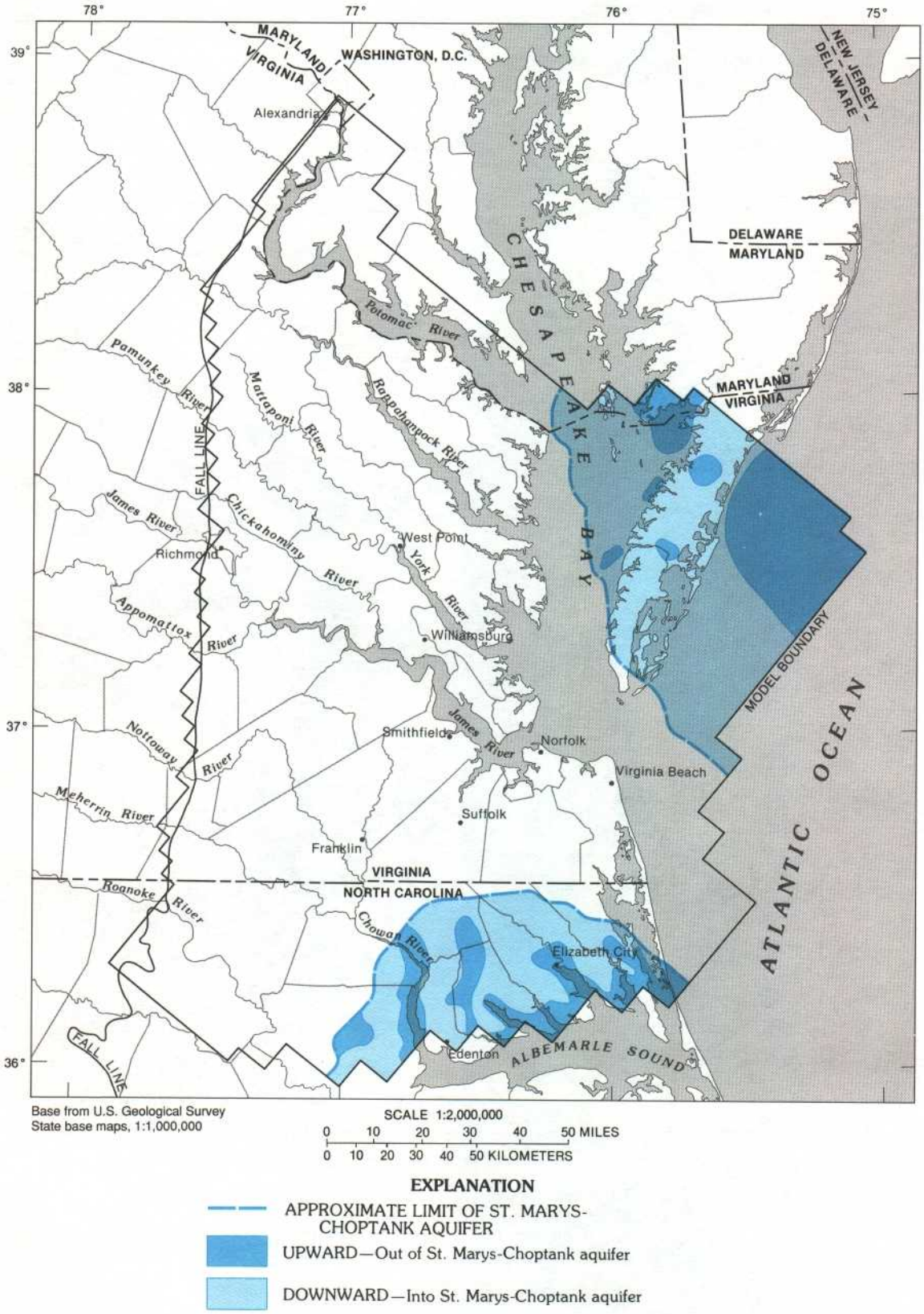


FIGURE 64.—Direction of simulated flow across the St. Marys confining unit, 1980.

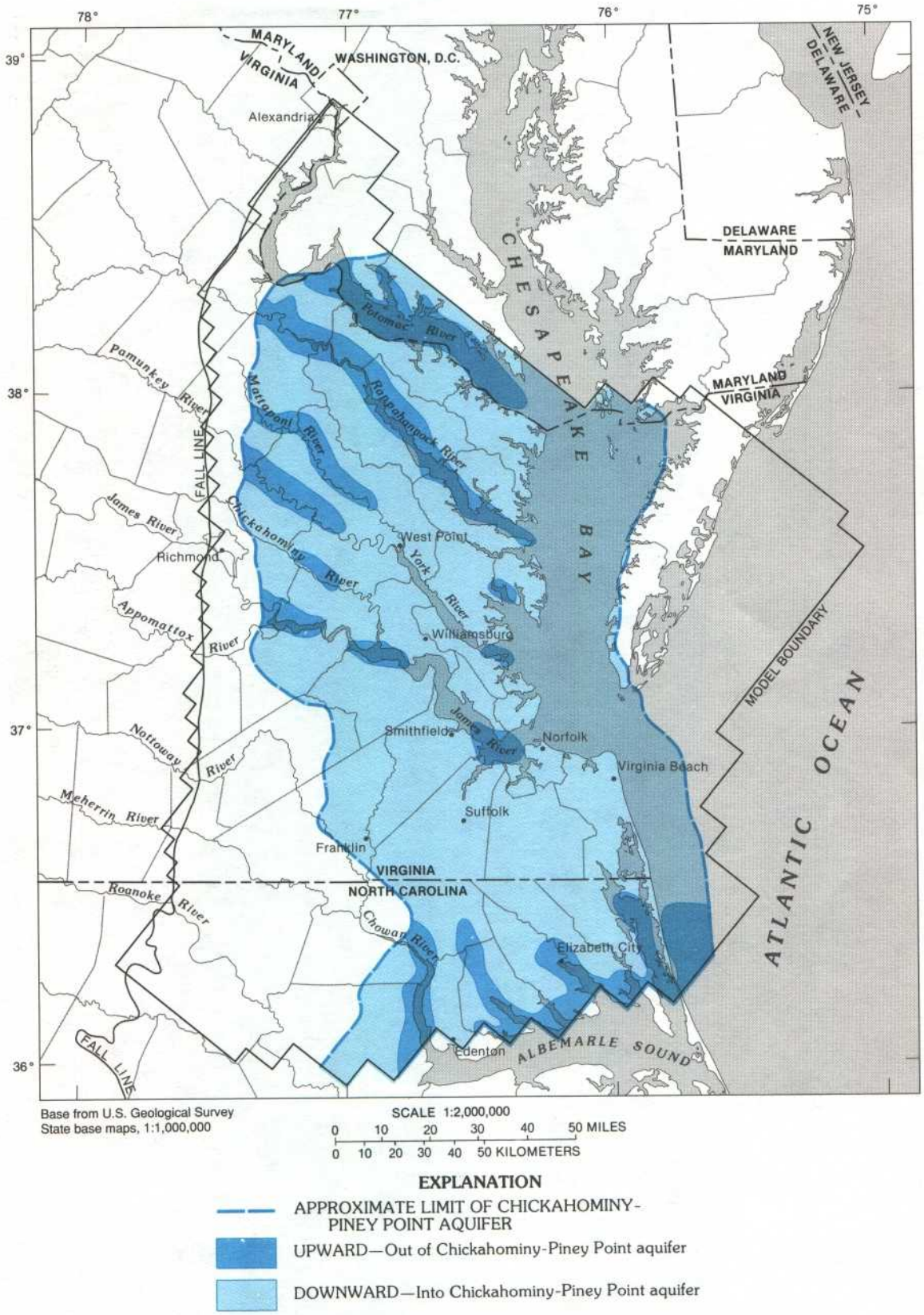
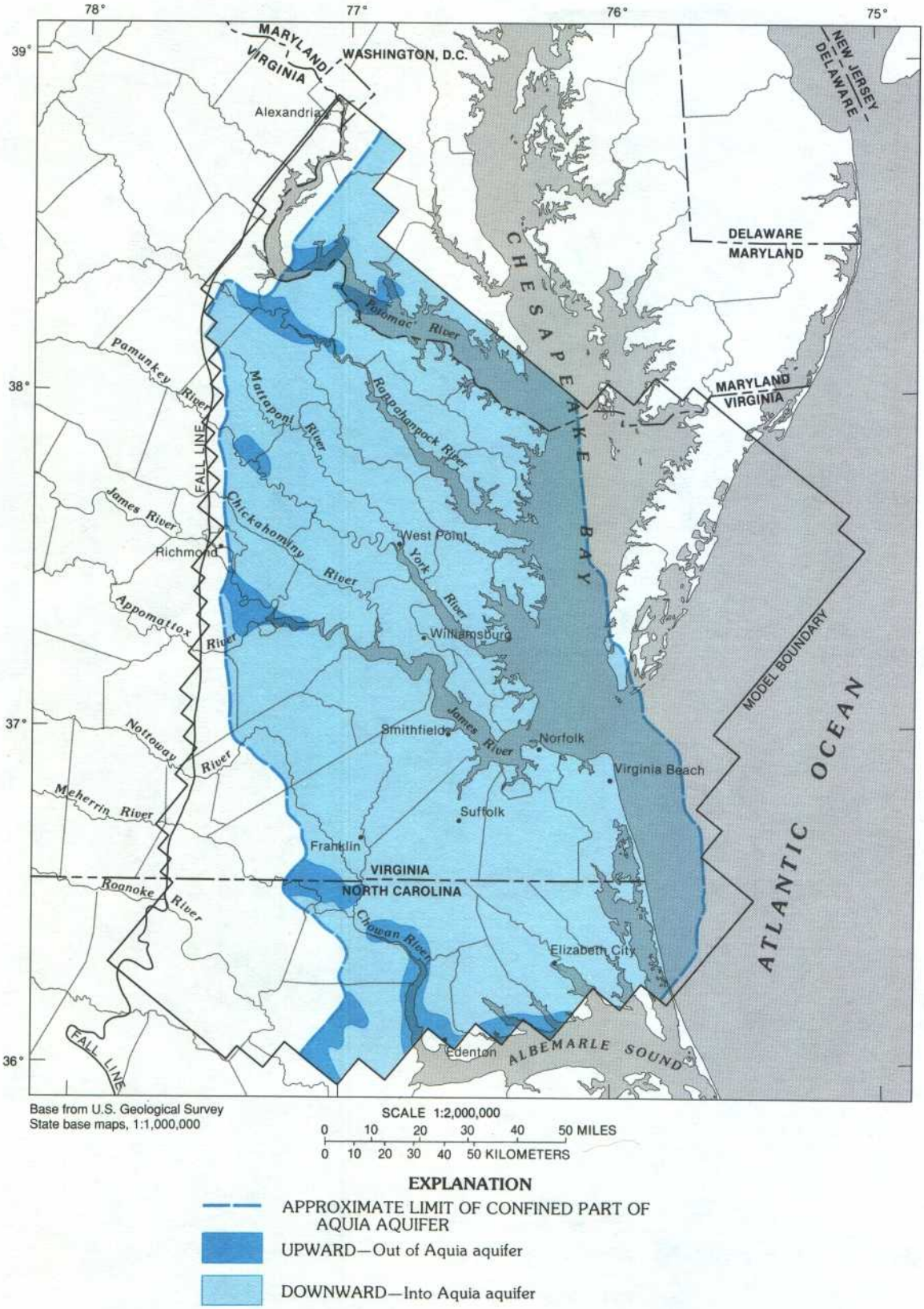


FIGURE 65.—Direction of simulated flow across the Calvert confining unit, 1980.



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

APPROXIMATE LIMIT OF CONFINED PART OF AQUIA AQUIFER

UPWARD—Out of Aquia aquifer

DOWNWARD—Into Aquia aquifer

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

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

APPROXIMATE LIMIT OF AQUIFER 4

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

UPWARD—Out of Aquifer 4

DOWNWARD—Into Aquifer 4

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

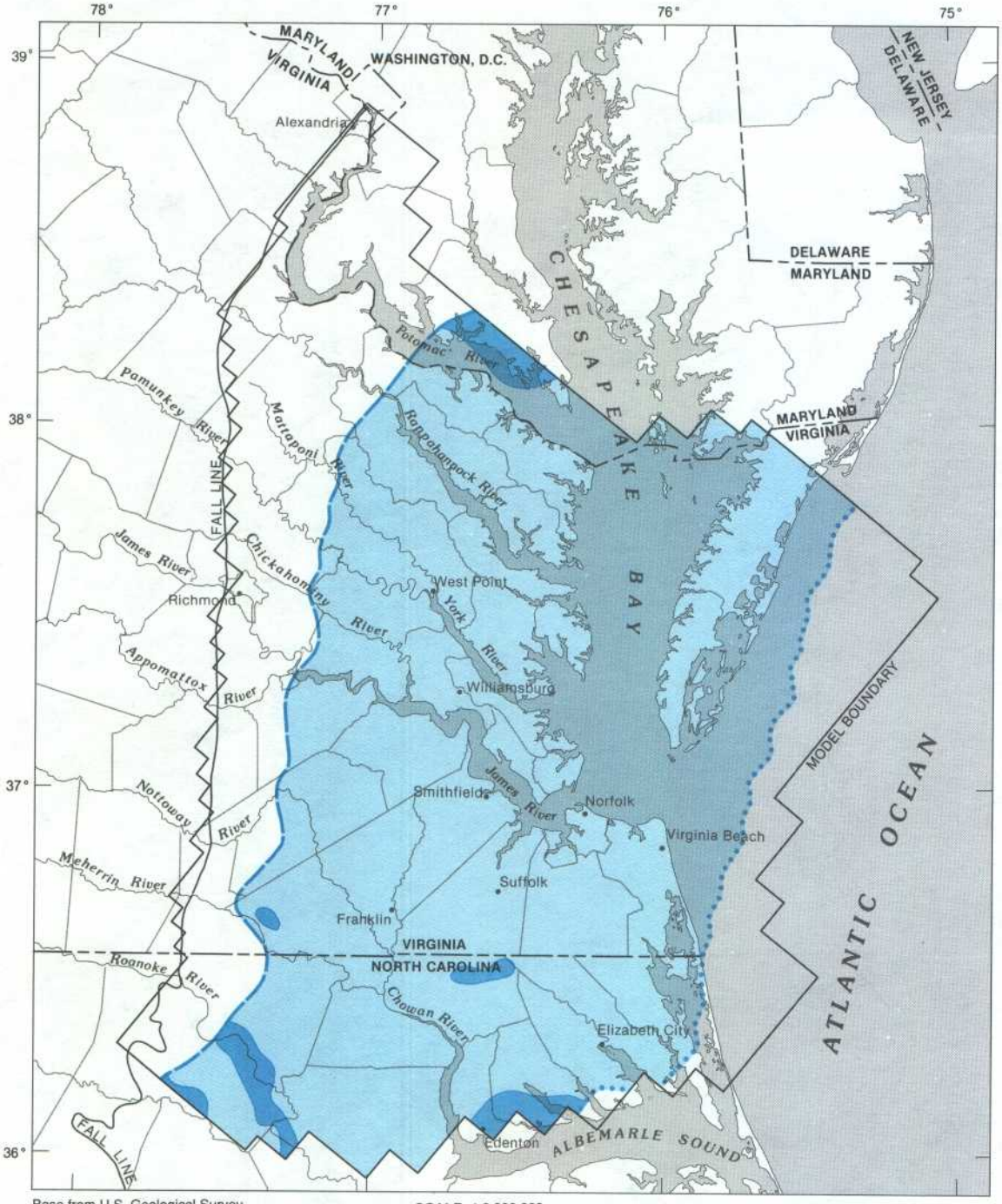


FIGURE 68.—Direction of simulated flow across the Brightseat-upper Potomac confining unit, 1980.

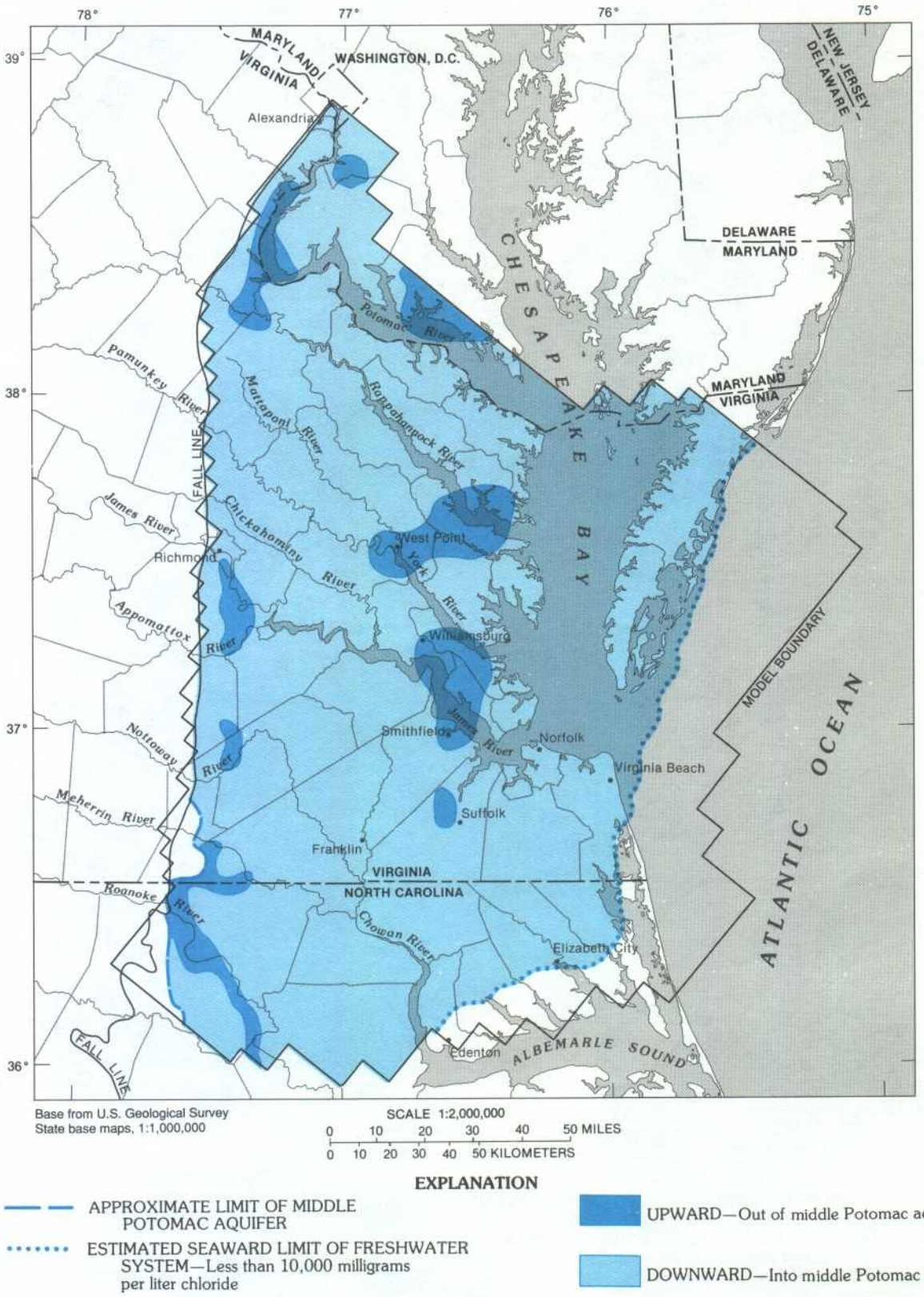
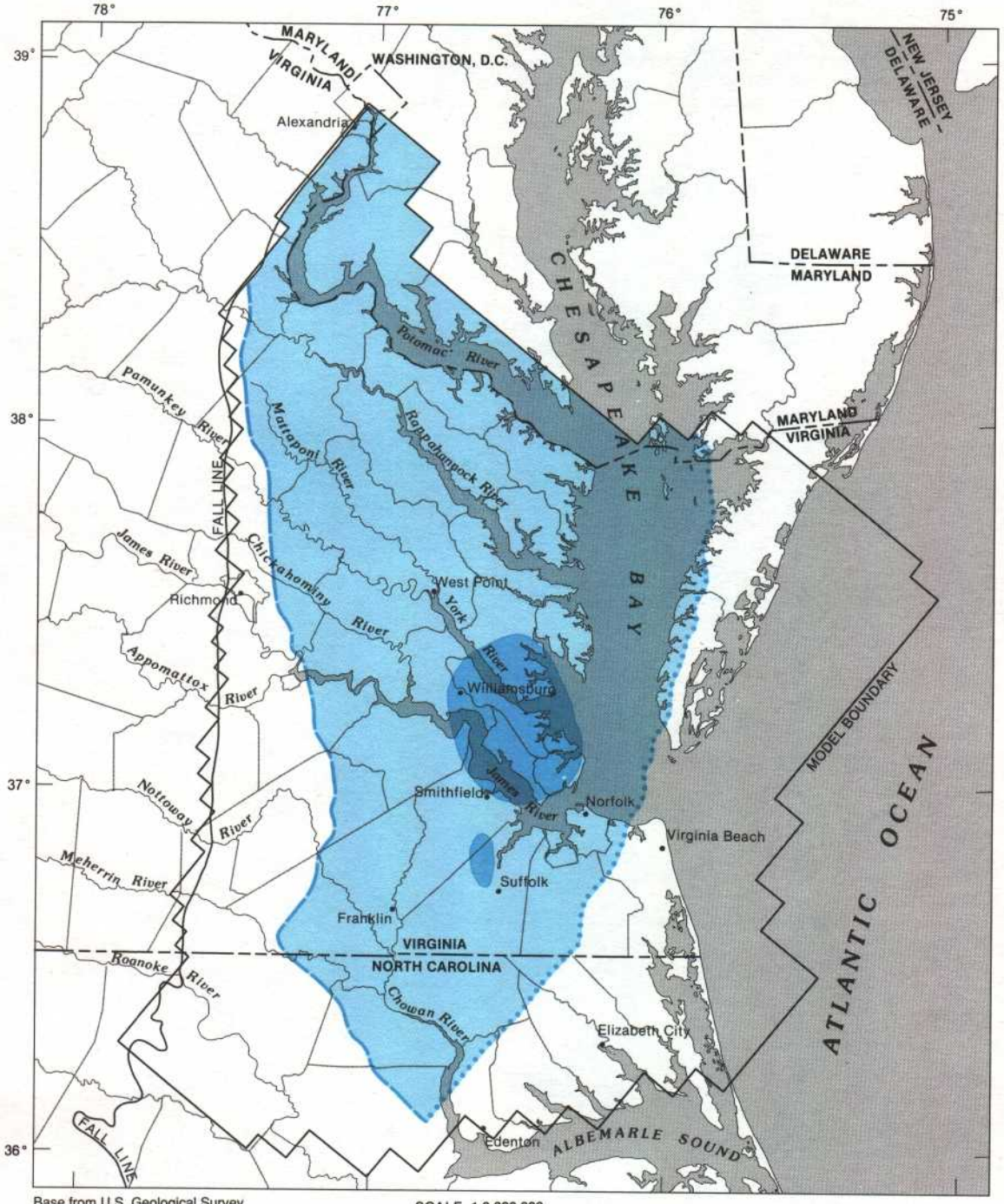


FIGURE 69.—Direction of simulated flow across the middle Potomac confining unit, 1980.



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

— — APPROXIMATE LIMIT OF LOWER POTOMAC AQUIFER

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

UPWARD—Out of lower Potomac aquifer

DOWNWARD—Into lower Potomac aquifer

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

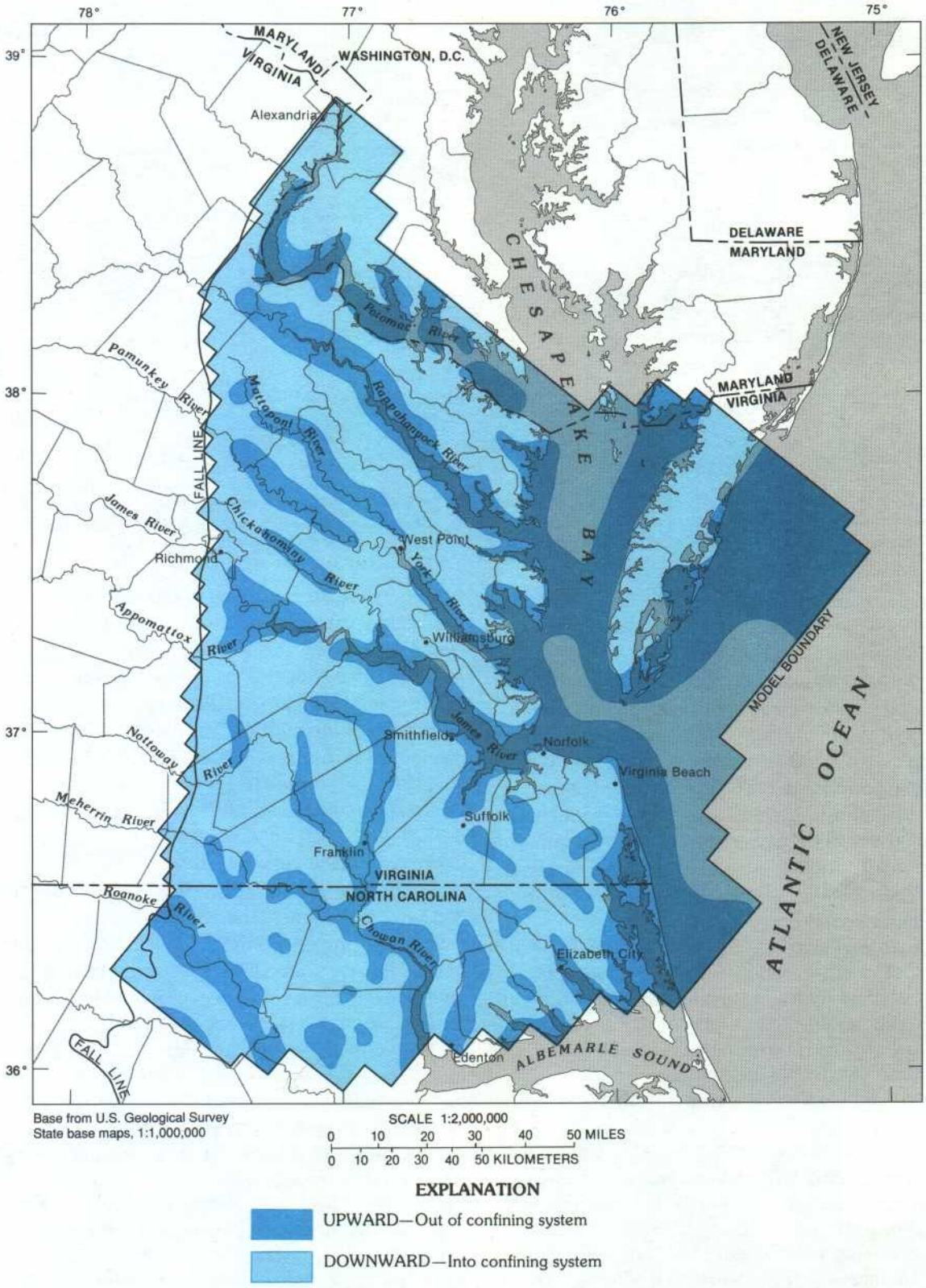


FIGURE 71.—Direction of simulated flow into and out of the confined system, 1980.

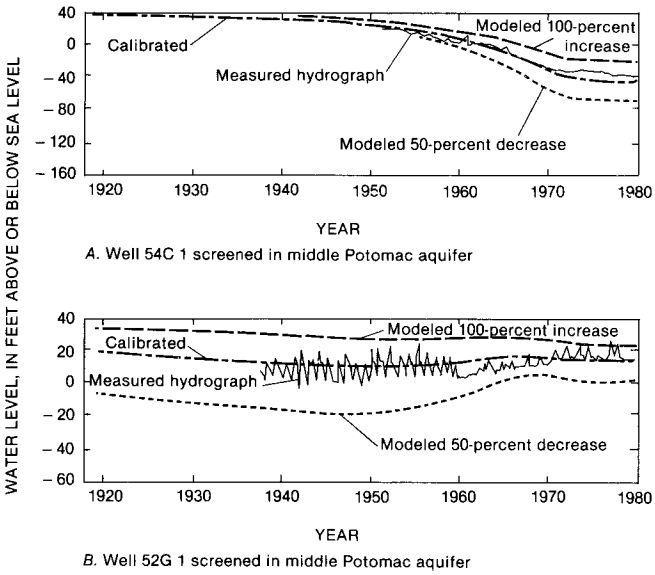


FIGURE 72.—Effects on simulated heads of varying the calibrated value of transmissivity of the middle Potomac aquifer. (Location of wells shown in fig. 62.)

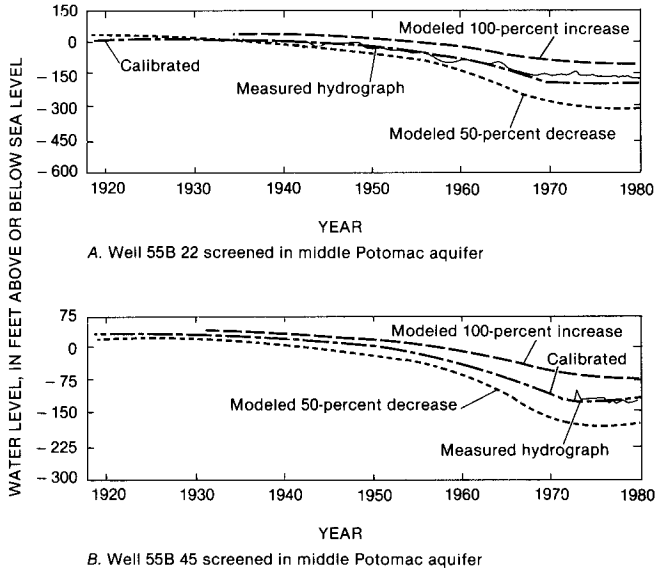


FIGURE 73.—Effects on simulated heads of varying the calibrated value of transmissivity of the middle Potomac aquifer. (Location of wells shown in fig. 62.)

SENSITIVITY ANALYSIS

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

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

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

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