Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

A DIGITAL SIMULATION MODEL OF THE AQUIA AQUIFER IN SOUTHERN MARYLAND

by
G. W. Kapple and H. J. Hansen

Information Circular 20

1976

Prepared in cooperation with the Geological Survey
United States Department of the Interior

For those readers who may prefer to use the metric system of measurement, metric equivalents of English units are shown throughout the text. The conversion factors for the terms used in this report are listed below:

English Unit	Multiply	Metric Unit
feet (ft)	0.3048	metres (m)
feet per mile (ft/mi)	0.1894	metres per kilometre (m/km)
feet squared per day (ft^2/d)	0.0929	metres squared per day (m^2/d)
cubic feet (ft^3)	0.02832	cubic metres (m^3)
million gallons per day (M gal/d)	3785.	cubic metres per day (m^3/d)
miles (mi)	1.609	kilometres (km)
square miles (mi^2)	2.590	square kilometres (km^2)

Four significant figures are shown for the conversion factors; however, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

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A DIGITAL SIMULATION MODEL OF THE AQUIA AQUIFER IN SOUTHERN MARYLAND

BY

G. W. KAPPLE[1] AND H. J. HANSEN

ABSTRACT

A digital finite-difference method was used to model about 3,800 square miles (9,840 square kilometres) of the Aquia aquifer underlying southern Maryland. The Aquia Formation (Paleocene) is a confined aquifer throughout the project area, except in outcrop, and reaches depths of 500 feet (152 metres) below sea level. Aquifer test results indicate that transmissivity ranges from 670 to 4,000 feet squared per day (62 to 372 metres squared per day) and thickness ranges from 75 to 200 feet (23 to 61 metres). The majority of the pumpage has occurred in the vicinity of the Patuxent Naval Air Training Station (PNATS) which is the focus for much of the work done on this project.

Over most of the project area the Aquia is overlain by the Marlboro Clay Member of the Nanjemoy Formation, a relatively tight, homogeneous confining bed 15 to 30 feet (5 to 9 metres) thick. Laboratory values of hydraulic conductivity range from 3.4×10^{-5} to 4.5×10^{-4} feet per day (1.0×10^{-5} to 1.4×10^{-4} metres per day). The lower confining bed, the Brightseat Formation, is sandier and more permeable and ranges in thickness from 10 to 35 feet (3 to 11 metres).

The model was calibrated for the PNATS area by comparing observed and calculated water-level records for the period 1943-51. The cone of depression had stabilized during this period. Fair agreement between observed and calculated drawdown was achieved by adjusting the value of the hydraulic conductivity of the confining bed which was found to be the most important parameter controlling recharge. After calibration, the model was used to predict future water-level declines based on hypothetical rates of withdrawal from pumping centers in the vicinity of the PNATS. The final, 10-year prediction run, involving a total pumpage of 21 million gallons per day (79,490 cubic metres per day), resulted in more than 400 feet (122 m) of drawdown and partial dewatering of the aquifer over a 12 square mile (31 square kilometre) area of the PNATS.

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[1] U.S. Geological Survey

INTRODUCTION

The Aquia aquifer, a unit of the Atlantic Coastal Plain sequence (Glaser, 1971; Hansen, 1974), provides an important source of groundwater in southern Maryland. This report concerns the digital modeling of about 3,800 square miles (9,840 km2) of the Aquia in Calvert, St. Marys, and Charles Counties, Maryland (fig. 1.) The majority of pumpage has occurred at the Patuxent Naval Air Training Station (PNATS) which is the focus of most of the work done for this study.

Considerable geohydrologic data for the Aquia have been obtained during the course of several cooperative U. S. Geological Survey—Maryland Geological Survey ground-water investigations (Ferguson and others, 1953; Otton, 1955; Rasmussen and Slaughter, 1957; Overbeck and Slaughter, 1958; Weigle, Webb, and Gardner, 1970). The Aquia is a confined aquifer except for an irregular band of outcrop along the western edge of the project area. Flow patterns within the aquifer are quite complex and recharge occurs in parts of the outcrop area and also from leakage through adjacent confining beds. Ground-water discharge occurs by upward leakage through overlying confining beds beneath Chesapeake Bay and the Potomac and Patuxent Rivers (fig. 12). Discharge also occurs by pumpage.

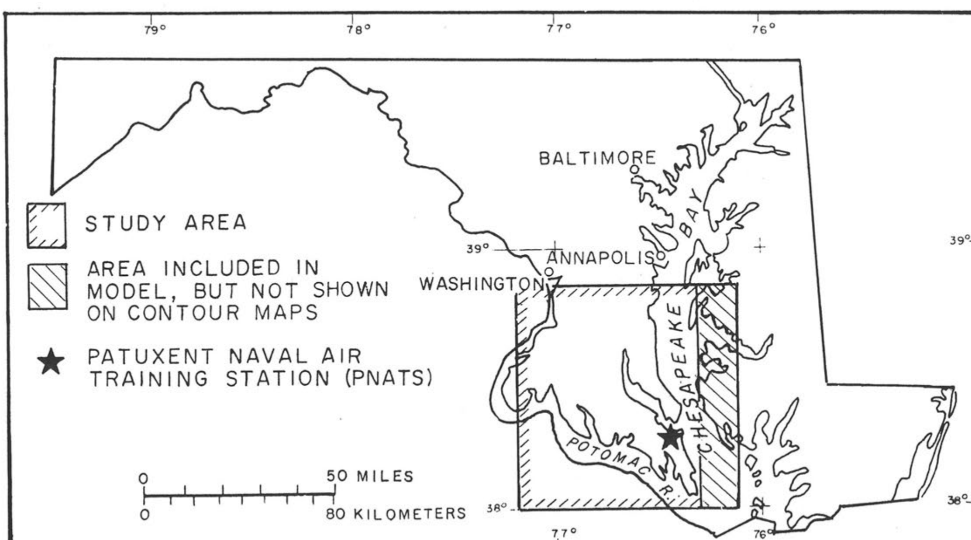


Figure 1.—Map of Maryland showing location of study area.

Table 1—Geologic units in Southern Maryland and their geohydrologic characteristics. (Weigle, Webb, and Gardner; 1970)

GEOLOGIC UNITS IN SOUTHERN MARYLAND AND THEIR GEOHYDROLOGIC CHARACTERISTICS.

System	Series	Group	Geologic unit	Average thickness (feet)	Occurrence and extent	Physical character	Water-bearing characteristics and hydrology
QUATERNARY	Holocene and Pleistocene		Lowland deposits	0-140	Underlies near-shore terraces below 50± feet above sea level. Extends below sea level and beneath estuaries; deepest along southern shore of St. Marys and Charles Counties.	Tan to orange stratified clay, silt, medium to coarse sand, and gravel.	Yields limited quantities of water to large-diameter wells. Potential for larger yields, especially along southern shores of St. Marys and Charles Counties, probably accompanied by local susceptibility to resultant contamination by sea water.
QUATERNARY AND TERTIARY(?)	Pleistocene and Pliocene(?)		Upland deposits	0-50	Underlies dissected southeastward-sloping upland surfaces, above 50± and below 200± feet above sea level. Little remains in southern Calvert County.	Tan to orange clay, silt, and sand mixture in upper loam member, and sand and gravel in lower gravel member.	Bottom few feet saturated. Yield moderate amounts of water to large-diameter wells. Primary source of water for shallow domestic and farm wells. Absorb precipitation and release it slowly to underlying deposits. Commonly, streams have cut downward through the deposits permitting the deposits to drain rapidly.
TERTIARY	Miocene	Chesapeake	St. Marys Formation	0-50	Underlies southern one-third of Calvert County and half of St. Marys County. Thickens southeastward.	Greenish-blue to yellowish-gray fossiliferous clay, sand, and sandy clay.	Yields limited supplies of water to wells. Functions generally as an aquitard.
			Choptank Formation	0-100	Underlies most of Calvert and St. Marys Counties. Thickens southeastward.	Interbedded brown to yellow clayey silt and fine to very fine sand. Fossiliferous and indurated layers.	Yields small amounts of water to wells. Functions generally as an aquitard.
			Calvert Formation	0-150	Underlies most of southern Maryland, except extreme western Charles County. Thickens southeastward.	Greenish, bluish, and gray fossiliferous, diatomitic sandy clay and fine sand. 10-20 feet of sand at base locally.	Yields small quantities of water to large-diameter wells. Basal sand yields some water. Functions generally as an aquitard.
	Eocene		Piney Point Formation	10-60	Underlies southern one-third of Calvert County and four-fifths of St. Marys County. Thickens southeastward.	Gray to brownish-yellow slightly glauconitic medium to coarse sand; interbedded layers of shell and sand, locally indurated.	A principal source of water in southern Calvert County and eastern and southern St. Marys County. Yields reported up to 200 gpm from wells. Vertical variations in permeability due to presence of interbeds of cemented shell. Is hydraulically connected with the underlying Nanjemoy Formation.
			Nanjemoy Formation	175-250	Underlies southern Maryland except extreme western Charles County. Thickens eastward to about 250 feet under central Calvert County.	Dark-green to gray fine to medium glauconitic sand; layers of shell fragments, silt and clay. Marlboro Clay Member at base (20± feet thick) is pink, red, or	A principal source of water in Calvert and St. Marys Counties. Yields reported in excess of 60 gpm from wells. Permeability in western half of report area low. Vertical variation in permeability is considerable. Transmissibility increases eastward. Aquifer part of unit not restricted to one vertical position in unit. Hydraulically connected with overlying

		Pamunkey				gray plastic clay.	Piney Point Formation.
	Paleocene	Pamunkey	Aquia Formation	100-170	Crops out in northwestern Charles County and dips southeastward under most of area.	Greenish to yellow-brown well-sorted glauconitic sand with locally-indurated shell beds. Interbedded very fine sand, silt, and clay in Charles County.	A principal source of water in Calvert and St. Marys Counties and southeastern Charles County. Yields reported as great as 300 gpm from wells. Permeability increases eastward and southeastward and transmissibility increases southeastward.
	Paleocene		Brightseat Formation	20-40	Extent not known.	Gray to dark-gray micaceous, silty, sandy clay.	Not known to supply water to wells in southern Maryland. Functions generally as an aquitard.
CRETACEOUS	Upper Cretaceous		Monmouth and Matawan Formations	20-60	Extent not known. Thicken northeastward.	Gray to gray-black glauconitic micaceous silt, clay, and fine sand.	Yield modest supplies locally from lenticular sand beds. Probably function generally as aquitards.
CRETACEOUS	Upper Cretaceous		Magothy Formation	0-100	Underlies Calvert County (at least as far south as Prince Frederick); parts of eastern Charles County; and northern St. Marys County. Thickens northward.	Light-gray to white "loose" sand and fine gravel, containing interbedded lignitic, pyritic, and clay layers.	Potentially economically important source of water where it occurs in southern Maryland, but not utilized there yet. Yields of several hundred gpm probably available. Aquifer thickens northward from Prince Frederick. Transmissibility increases northward.
CRETACEOUS	Upper Cretaceous		Raritan[1] Formation	100?	Probably underlies entire area.	Variegated gray, brown, red, and yellow clay and silt, containing interbedded lenses (?) of sand.	Moderate yields to wells in south-central Charles County. Not explored in Calvert and St. Marys Counties.
CRETACEOUS	?						
CRETACEOUS	Lower Cretaceous	Potomac	Patapsco Formation	(100-600)?	Probably underlies entire area and thickens southeastward.	Tan, brown, red, and yellow variegated fine sand, silt, and clay containing interbedded coarser sand.	Principal water-bearing formation in western half of Charles County. Wells commonly screened in more than one sand layer. Formation not tested elsewhere in southern Maryland.
CRETACEOUS	Lower Cretaceous	Potomac	Arundel Clay	(100-200)?	Probably underlies entire area.	Red, brown, and gray clay, locally lignitic and sideritic.	Not generally a water-bearing formation.
CRETACEOUS	Lower Cretaceous	Potomac	Patuxent Formation	(100-500)?	Probably underlies entire area.	Chiefly gray, yellow, and brown sand and interbedded silt and clay.	One of principal aquifers in western Charles County. Untested elsewhere in southern Maryland, but potentially important throughout area.
PRECAMBRIAN			Crystalline rocks		Underlies entire area. Top slopes southeastward from about 700 feet below sea level near northwest corner of Charles County to about 3,400 feet below sea level near southern tip of St. Marys County.	Untested. Probably gneiss and schist.	Not explored. Not considered a water source in southern Maryland.

[1] The Maryland Geological Survey considers the Raritan Formation to be in the Potomac Group.

The objective of this study has been to develop a model of the Aquia aquifer in southern Maryland to: (1) illustrate the sensitivity of the model to the various input parameters, (2) illustrate the procedures used to calibrate the model, and (3) present examples of how the model can be used for predictive purposes.

E. G. Otton participated in the early planning of the project and provided useful comments during its initial stages. I. H. Kantrowitz edited the report in its final form and helped prepare it for publication after the senior author had left the State. He made several additional model runs to clarify aspects of the data presented in the "Predictions" section of the report.

The illustrations were drafted by J. F. Goodell.

GEOLOGY

The Coastal Plain formations of the project area (fig. 1) are wedge-shaped in cross section, increasing in thickness from about 550 feet (170 m) in western Charles County to an estimated 3,200 feet (975 m) beneath Point Lookout, St. Marys County (geographic references are located on fig. 9). Table 1 taken from Weigle, Webb, and Gardner (1970) is a general description of the stratigraphic sequence. The formations slope 10 to 100 feet per mile (1.9 to 19 m/km) in an east-southeasterly direction, although local dip reversals, such as the Brandywine Structure (Jacobeen, 1972), have been mapped in the area. The older and "deeper" formations crop out in the north-western part of the project area. Nonmarine Cretaceous sediments (the Potomac Group) comprise about 60 percent of the Coastal Plain section. A relatively thin marine section unconformably overlies the Potomac Group. In the lower tricounty area of southern Maryland (Calvert, Charles, St. Marys Counties), several Tertiary and Upper Cretaceous marine formations function, at least in part, as aquifers (Otton, 1955). Specifically, these are the Piney Point-Nanjemoy, Aquia, and Magothy aquifers (table 1). Of the three, only the Aquia crops out in the project area; the other two are restricted to the subsurface.

The stratigraphic relationship between the various geologic units in the project area are shown in figures 2 and 3. These figures do not distinguish Pleistocene deposits from the underlying Miocene formations, and only the upper part of the Potomac Group is shown. Well sections are shown schematically by reduced geophysical logs which are either single point electric or natural gamma ray logs (denoted by "E log" or "gamma log" in figures 2 and 3). The several formations penetrated by each well are assigned to one of four categories based on approximate transmissivity ranges: "fair to good aquifer," "poor to fair aquifer," "leaky confining bed," and "tight confining bed." First order facies are shown schematically; however, the several types of formation contacts are not differen-tiated.

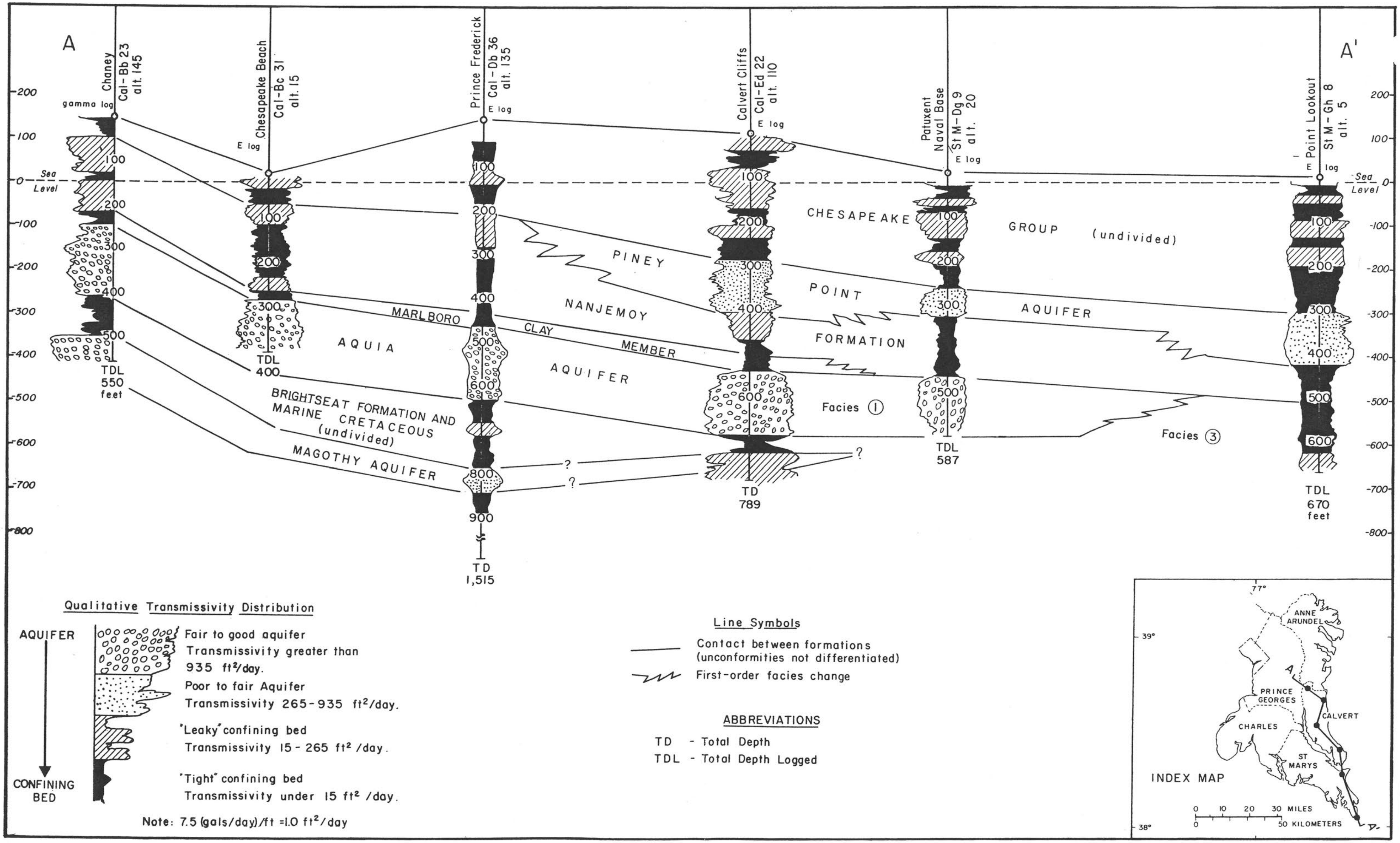


Figure 2.—Geologic section from northern Calvert County to southern St. Marys County.

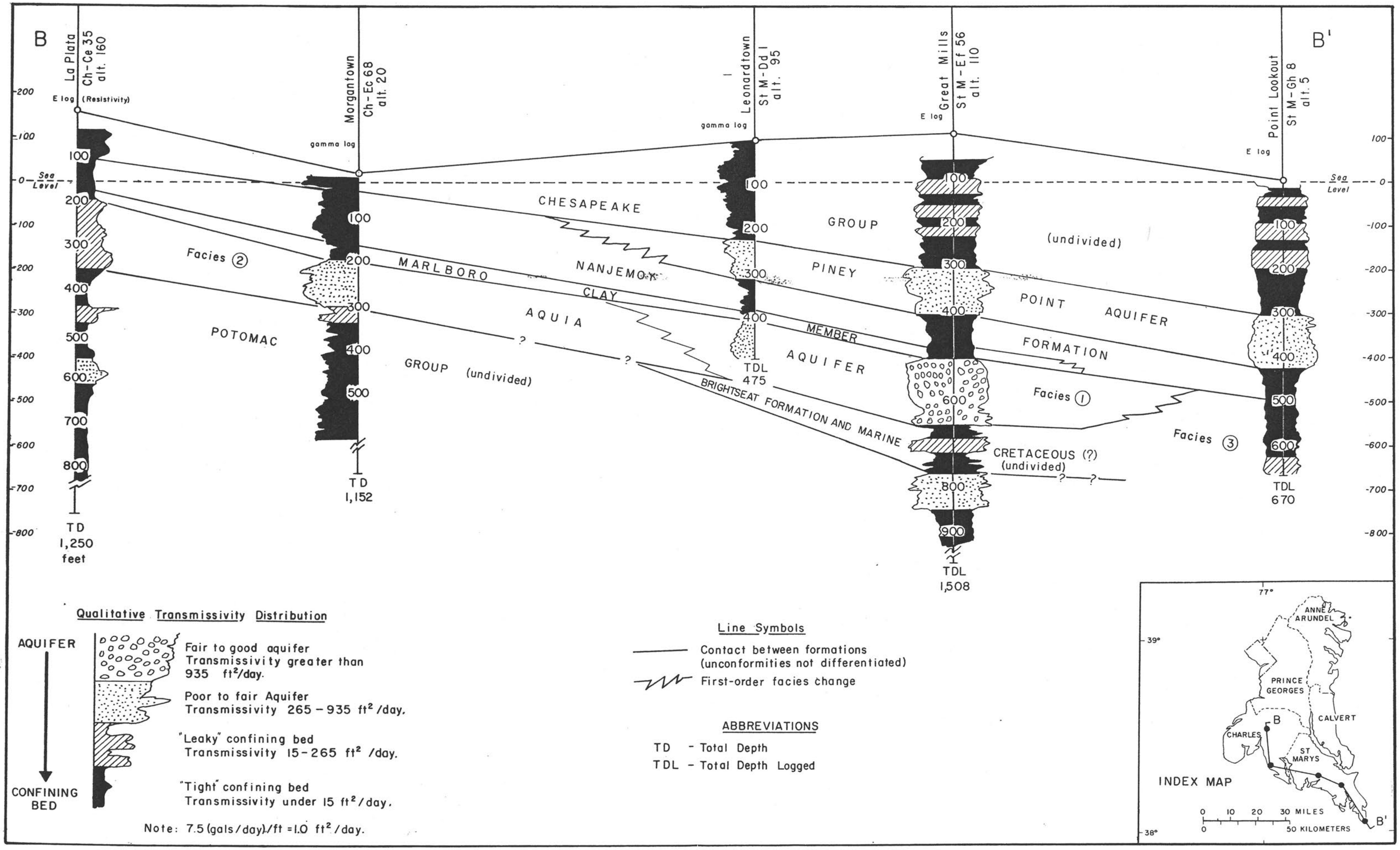


Figure 3.—Geologic section from central Charles County to southern St. Marys County.

Upper Confining Beds

The Aquia aquifer is overlain by the Nanjemoy Formation which functions as a "leaky" to "tight" confining bed. It consists of greenish to blackish silt, clay (principally montmorillonite), and fine sand beds. It coarsens, however, northwestward along strike so that in northern Calvert County (for example, Chaney, fig. 2) the sands yield modest amounts of water. In much of southern Maryland, the basal 15 to 30 feet (5 to 9 m) of the Nanjemoy is composed of a lithologically distinct kaolinitic unit called the Marlboro Clay Member (Glaser, 1971). Parts of the Marlboro are a diagnostic pinkish red, suggesting subaerial exposure, perhaps as an ancient marine mud flat deposit. Where it exists (fig. 4), the Marlboro Clay Member functions as the "tightest" confining bed overlying the Aquia.

The Marlboro becomes increasingly marine to the southeast, grading into an open marine sequence of greenish gray, montmorillonitic clays and silts. Here the Marlboro Member is difficult to separate from the upper part of the Nanjemoy Formation. The pinkish facies of the Marlboro Clay Member has not been recognized in southern St. Marys County (figs. 2, 3, and 4); nor does it seem to be present beneath the Eastern Shore (Rasmussen and Slaughter, 1957, p. 60).

Aquia Formation

In southern Maryland the Aquia Formation of Paleocene age crops out (fig. 5) as a very irregular band from the Potomac River bluffs in western Charles County to Broad Neck peninsula in Anne Arundel County (Glaser, 1971, p. 12-14). The Aquia slopes gently east-southeastward at rates of about 10 to 20 feet per mile (1.9 to 3.8 m/km) (fig. 5) reaching a depth of almost 500 feet (150 m) below sea level at Point Lookout, St. Marys County.

The Aquia is a marine unit deposited on an ancient continental shelf. In Maryland, it exhibits three first order facies (fig. 3). These have been described by Hansen (1974) and consist of: **One**, a thick, medium-to-coarse-textured sandy facies extending southwesterly in outcrop from Kent County on the Eastern Shore, to about the Patuxent River where it swings south into the subsurface and trends toward southern St. Marys County (sand-bank complex); **Two**, a finely-textured sandy to silty facies occurring in Charles, southern Prince Georges, and western St. Marys Counties (inner marine shelf); and **Three**, a thinner, very muddy facies, which in southern Maryland occurs only beneath southernmost St. Marys County and does not occur in outcrop (outer marine shelf).

Only the first of these facies is considered a principal aquifer capable of supplying large water-supply systems. Transmissivities associated with the facies in southern Maryland are, however, less than might be expected on the basis of thickness and texture, chiefly

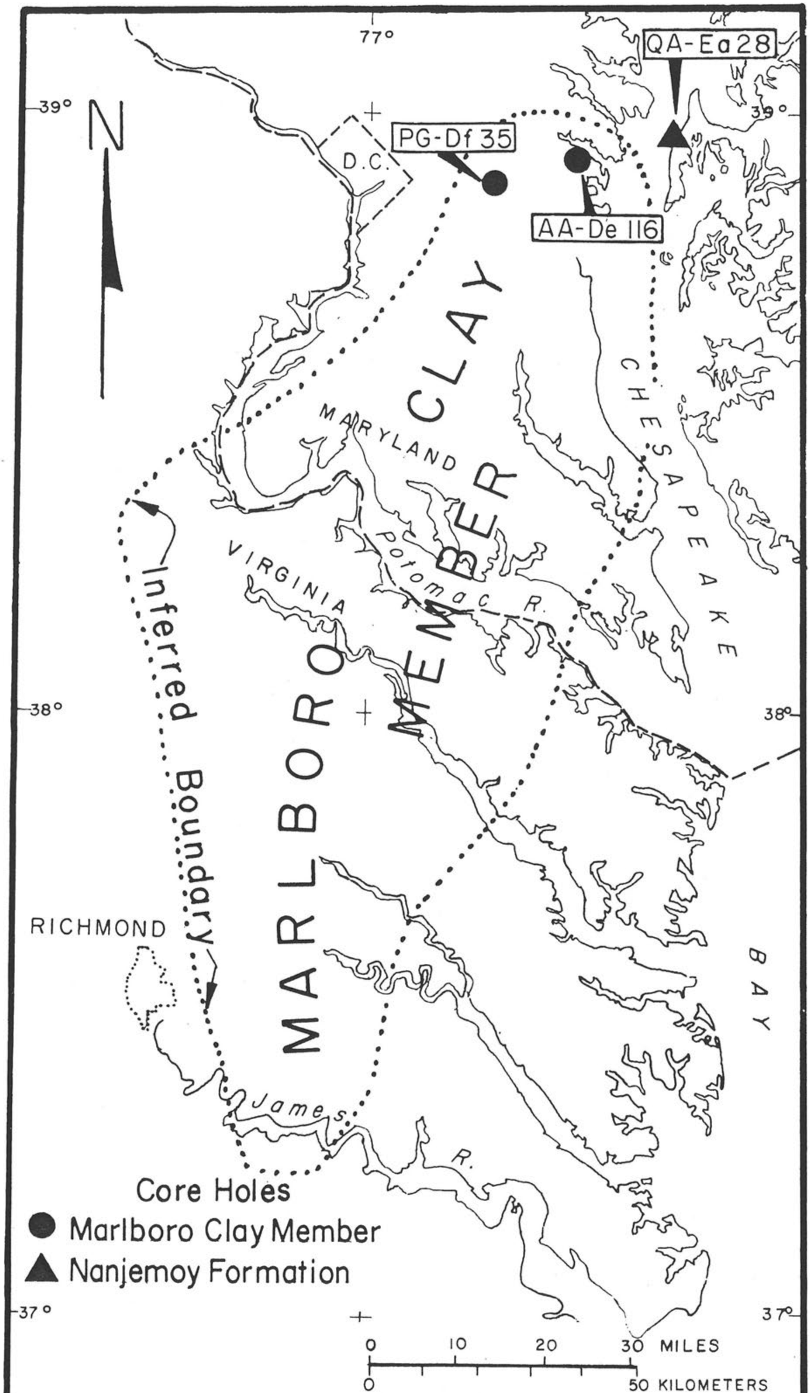


Figure 4.—Regional map showing distribution of the Marlboro Clay Member of the Nanjemoy Formation and location of core holes (after Glaser, 1971).

because of a loss of effective porosity caused by calcium carbonate cementation. In Anne Arundel and Queen Annes Counties, where the coarser-textured facies of the Aquia crops out, acidic ground-water recharge has largely dissolved the carbonate cement, leaving a less pervasive iron oxide/clay residue; transmissivities are accordingly higher (Overbeck and Slaughter, 1958, p. 72).

Sand-count data from electric logs indicate Facies One is characteristically 60 to 85 percent sand, Facies Two, less than 60 percent sand, and Facies Three, less than 25 percent sand. Figure 6 shows the percentage of Aquia sand footage described in drillers' logs as medium- or coarse-grained. Although broadly generalized, this map depicts the tripartite facies distribution characteristic of the Aquia. The 25 and 75 percent contours are useful for mapping the areal distribution of the three Aquia facies described above. In addition to being sandier and more coarsely textured, Facies One is the thickest part of the Aquia Formation (fig. 7). Also, it exhibits more intense ferric staining of the quartz grains, higher percentages of pelletal goethite, and thicker accumulations of calcareously cemented sandstone ("ledges"), often in the form of sandpacked shell beds (or coquinas).

The Aquia sands consist chiefly of quartz and glauconite, the former predominating. Although generally accounting for less than 50 percent of the sand grains, the glauconite imparts a characteristic greenish or greenish-black cast to the unweathered formation; in fact, the formation is frequently called a "greensand" or "salt and pepper" sand. In Facies One, however, the quartz grains are more intensely iron-stained, the glauconite is more frequently encrusted with limonite, and authigenic goethite pellets (hydrated ferric oxide) are present in significant percentages. Consequently, these sands frequently bear a "brown" or "orange-brown" description.

Lower Confining Beds

The Aquia unconformably overlies beds ranging in age from Lower Cretaceous (Potomac Group) to lower Paleocene (Brightseat Formation) (Hazel, 1969). Beneath much of the project area, the Brightseat Formation, which is undifferentiated from the marine Cretaceous in the geologic sections (figs. 2 and 3), underlies the Aquia forming a relatively homogeneous confining bed. It is a marine unit deposited in an outer shelf environment and consists of grayish-black, micaceous, very fine to fine sand and silty clay. Thickness varies from about 10 to 35 feet (3 to 11 m). In updip areas, particularly in western and southern Charles County, the Aquia Formation has overlapped Brightseat, marine Cretaceous, and Magothy(?) strata and rests upon the Potomac Group, a relationship seen in outcrop along the Potomac River bluffs in the Indian Head area (Glaser, 1968, p. 16) and depicted schematically in cross-section B-B' (fig. 3). Wherever sand of the Potomac Group directly underlies the Aquia, the two aquifers act as a hydrologic unit.

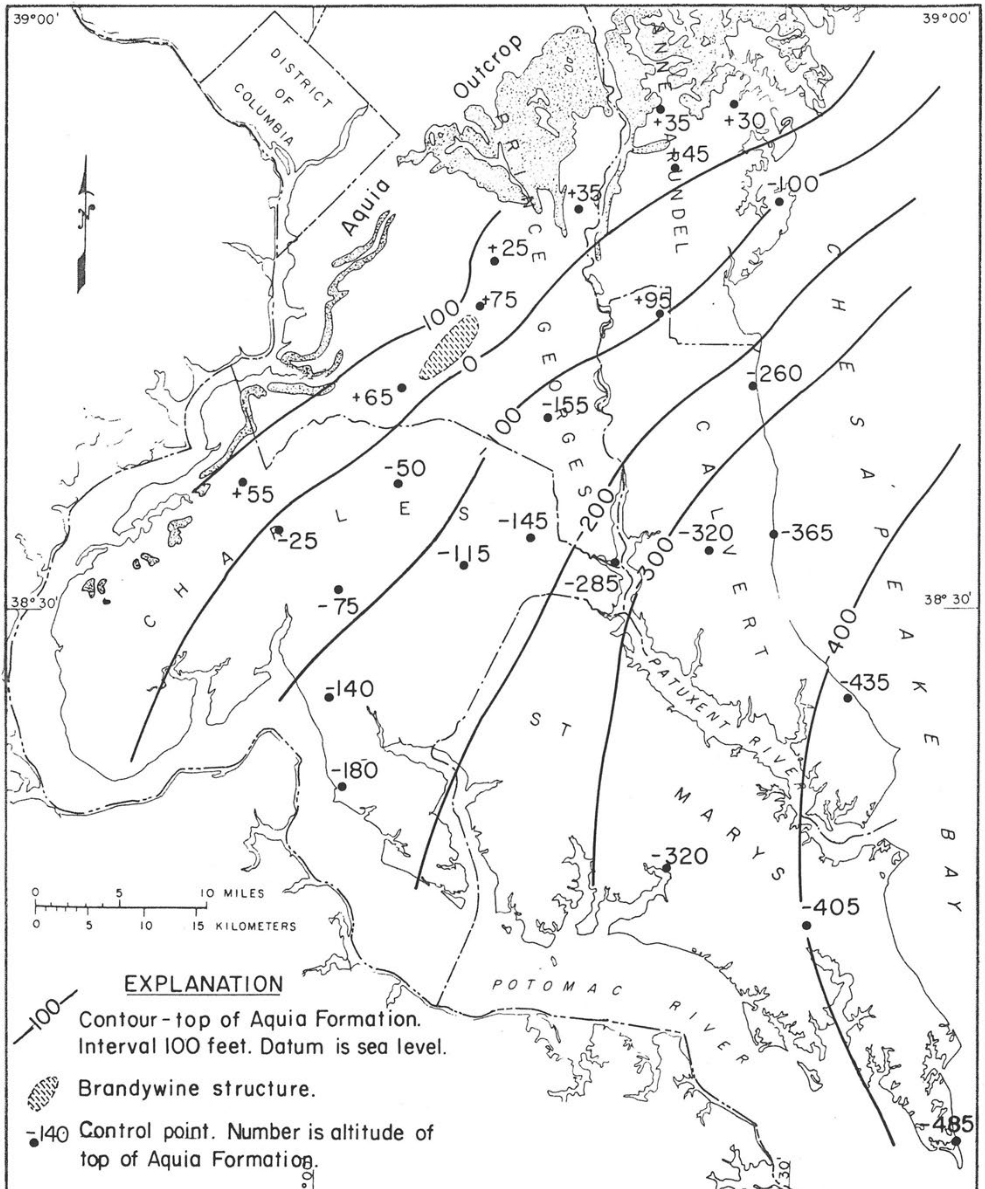


Figure 5.—Map showing the altitude of the top of the Aquia Formation.

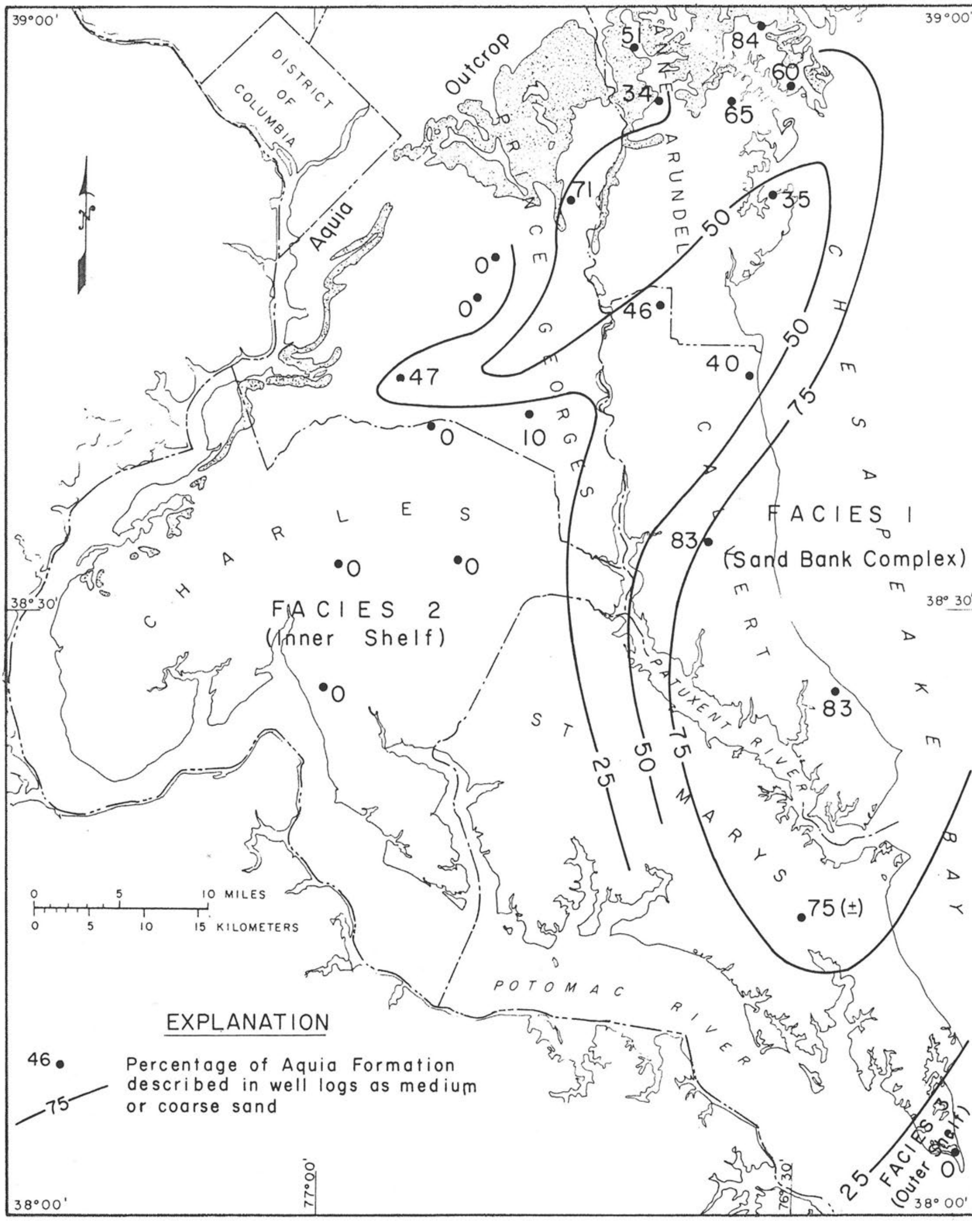


Figure 6.—Map showing the percentage of the Aquia Formation described as medium- to coarse-grained sand.

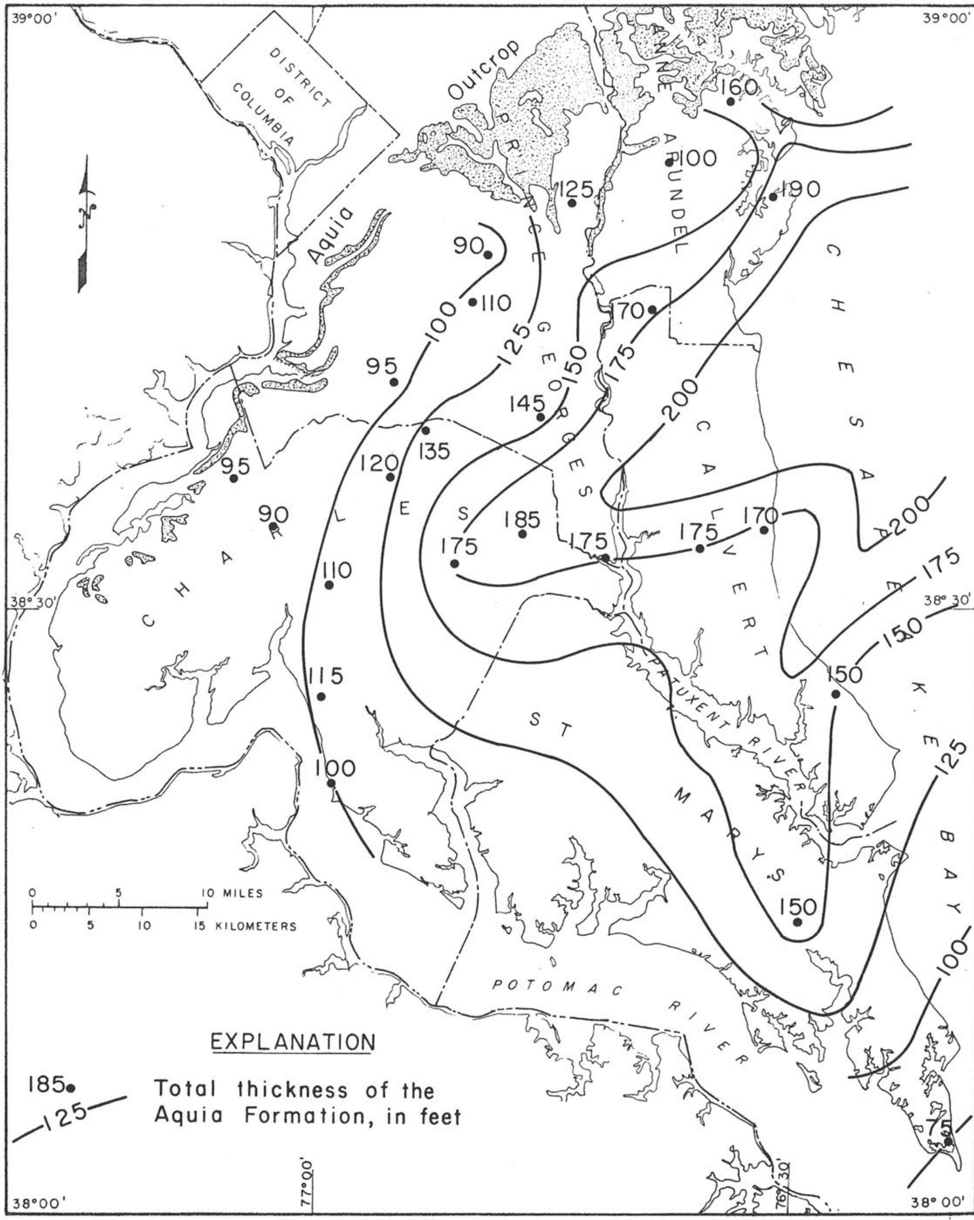


Figure 7.—Map showing the thickness of the Aquia Formation.

AQUIA DIGITAL MODEL

A digital finite difference model of the Aquia aquifer was constructed which simulates horizontal flow through the aquifer and vertical flow through a single confining bed. These directional flow assumptions have been shown by Neuman and Witherspoon (1969) to introduce less than 5 percent error when the hydraulic conductivity of the confining bed is at least two orders of magnitude smaller than that of the aquifer. The differential equation describing ground-water flow for this situation may be written as:

$$\frac{\partial}{\partial x}\left(T(x,y)\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T(x,y)\,\frac{\partial h}{\partial y}\right) = S(x,y)\,\frac{\partial h}{\partial t} + W(x,y,t),$$

where

h is the hydraulic head (L);
S (x,y) is the storage coefficient (dimensionless);
t is time (T);
T (x,y) is the transmissivity ($L^2\ T^{-1}$); and
W (x,y,t) is the flux term (LT^{-1}).

This equation applies to two-dimensional flow of a compressible fluid in an elastic, non-homogeneous porous media. The flux term, which may be either a source or sink term, describes pumpage, boundary recharge, and vertical leakage through a confining bed. Either no-flow, constant-head, or constant-gradient boundaries may be simulated. Transient leakage from a confining bed is calculated by an equation that takes into account storage in the confining bed, as well as leakage from an adjacent aquifer (Bredehoeft and Pinder, 1970).

The ground-water differential equation cannot be solved analytically for problems involving complex variations in aquifer transmissivity, storage coefficient, or in the flux term. It may, however, be approximated as a finite-difference equation by using the Taylor expansion theorem (Pinder and Bredehoeft, 1968). By requiring that the finite-difference equation hold true at each node of a rectangular grid, a system of simultaneous, linear equations results which can be solved by computer. A program written by Pinder (1970), with minor modifications made by the senior author, was used for solution of the finite-difference equation. This equation is solved at each node of the grid by the iterative alternating direction implicit procedure (IADIP) introduced by Peaceman and Rachford (1955). A generalized flow chart for the IADIP computer program is shown in figure 8. Principal output from the program consists of calculated water-level changes at each node of the grid network and mass-balance information for the system as a whole.

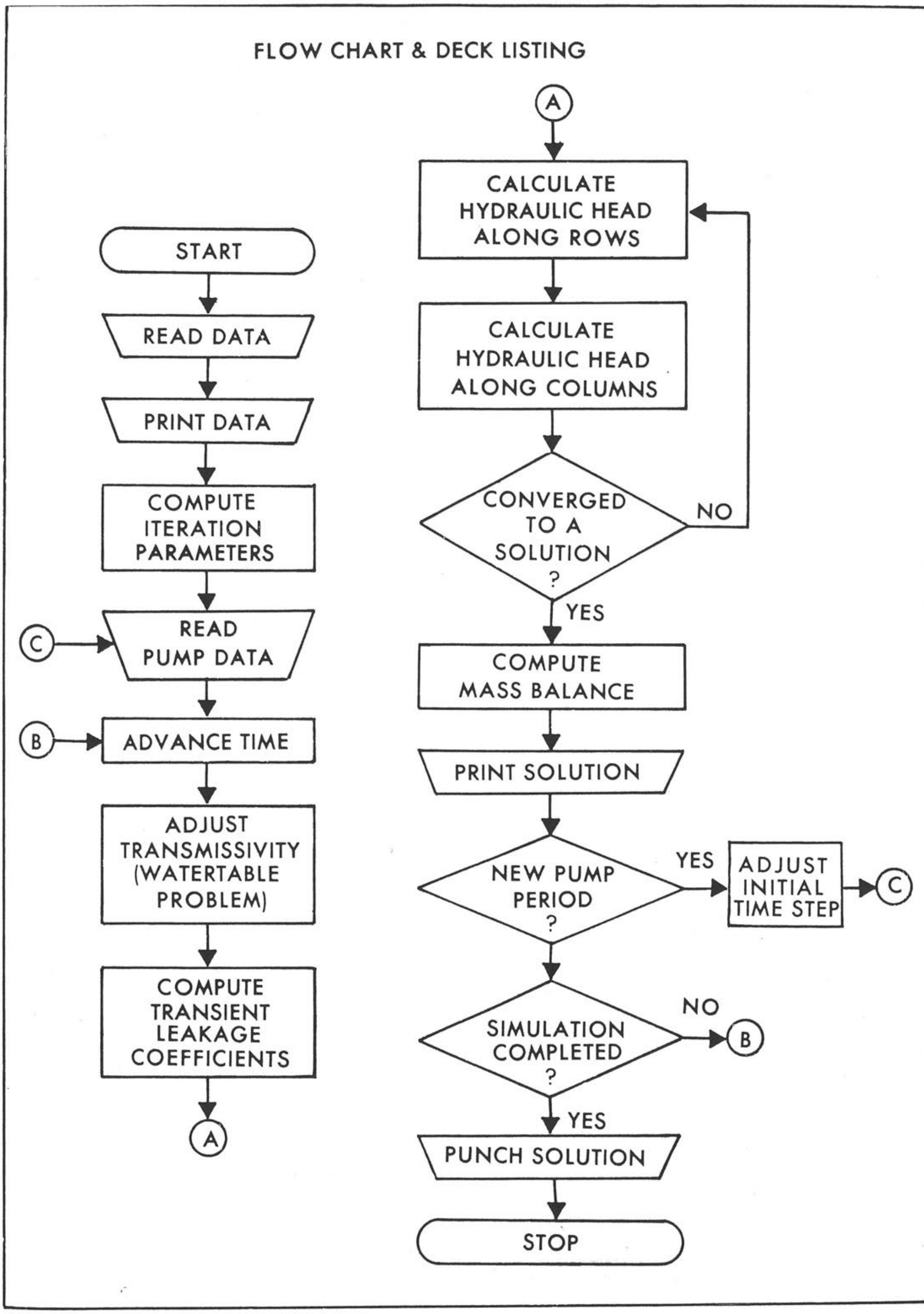


Figure 8.—Generalized flow chart for the digital model.

Input Data

The required hydrologic data for the digital model include the transmissivity (T) and storage coefficient (S) of the aquifer, and the hydraulic conductivity (K), thickness (L), and specific storage (SS) of the confining bed[1]. Also required are pumping rates and the potentiometric heads in the pumped aquifer and the aquifer above (or below) the confining bed at the beginning of the stimulation period. Aquifer transmissivity and storage coefficient data were prepared by superimposing a rectangular grid network on contoured data maps and determining data values at each node. Equivalent confining-bed data were not available so that hydraulic conductivity, thickness, and specific storage values were assumed to be areally uniform. Potentiometric heads in the aquifer and at the top of the upper confining bed were made equal and uniform as discussed below.

Transmissivity and Storage Coefficient: Figure 9 is a map locating the sites in Maryland where Aquia aquifer test data are reported. Based on data from these tests, a contour map of the transmissivity of the aquifer was prepared for the project area (fig. 10). Values range from less than 300 feet squared per day (28 m^2/d) in the western part of the project area to about 3,000 feet squared per day (280 m^2/d) in the northeastern part.

Predictably, figure 10 shows a tract of high transmissivity more or less coincident with Facies One. Exceptions to this may occur where primary permeability has been degraded by carbonate or iron oxide/clay cementation. This may be the reason for the variety of transmissivity values found in the PNATS—Lexington Park area where values from aquifer tests range from 735 feet squared per day (68.3 m^2/d) to 4,400 feet squared per day (409 m^2/d).

1.
Transmissivity is a hydrologic parameter equal to the rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It represents an integration of hydraulic conductivity across the saturated thickness of an aquifer (Lohman and others, 1972, p. 13).

Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman and others, 1972, p. 13).

Hydraulic conductivity is the volume of water at the existing kinematic vicosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972, p. 4.)

Specific storage is the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head (Lohman and others, 1972, p. 13).

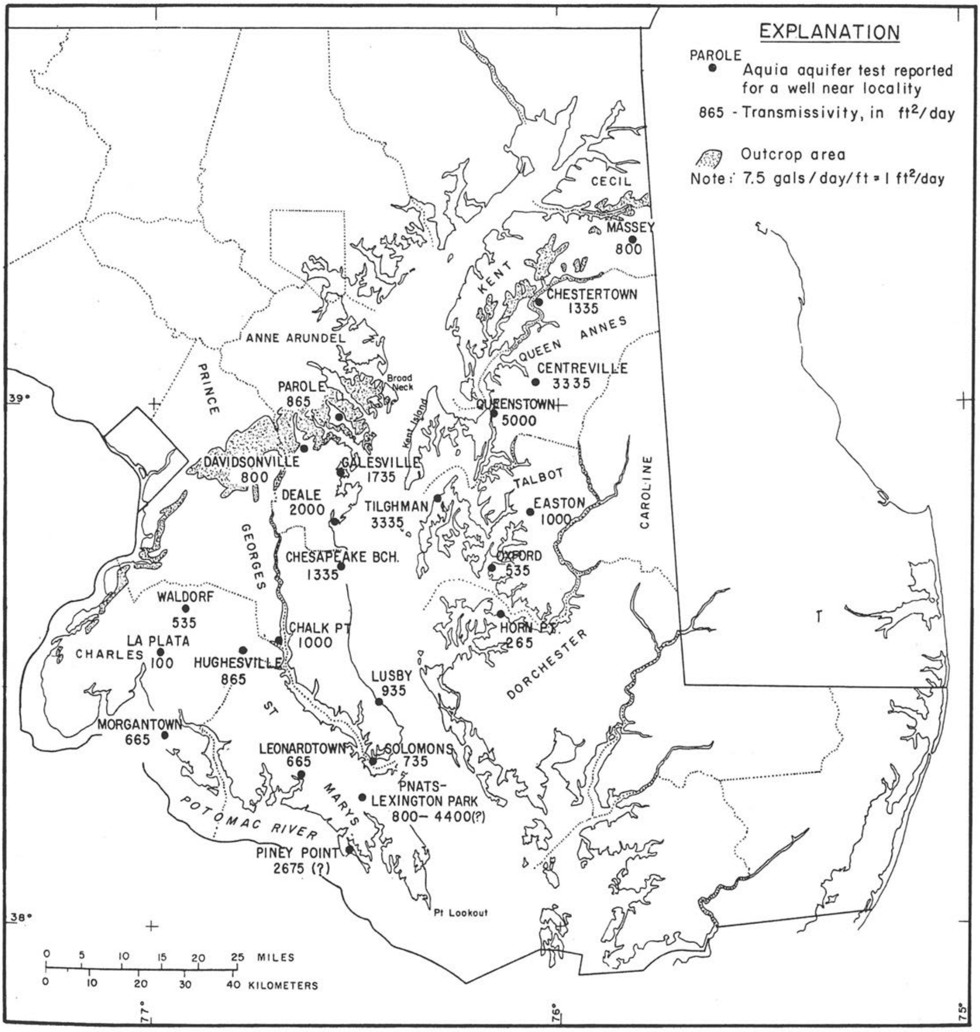


Figure 9.—Map showing selected test sites of the Aquia aquifer in Maryland.

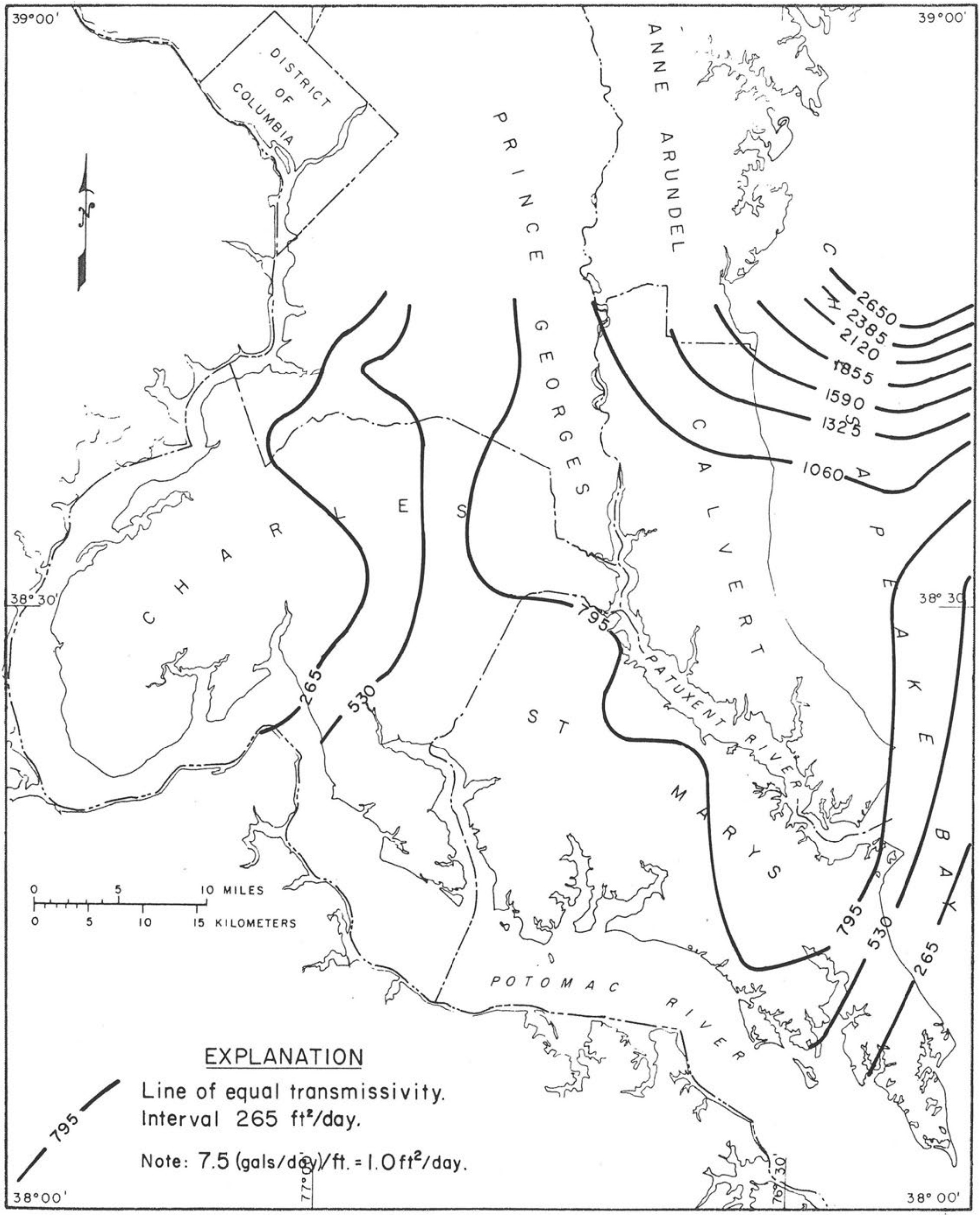


Figure 10.—Map showing transmissivity of the Aquia aquifer.

Storage coefficient data were available from only a few of the aquifer tests and range from 0.0001 to 0.0004. A value of 0.0003 was used in the model except in Facies Three where the coefficient was arbitrarily increased to 0.003 to account for increased clay content.

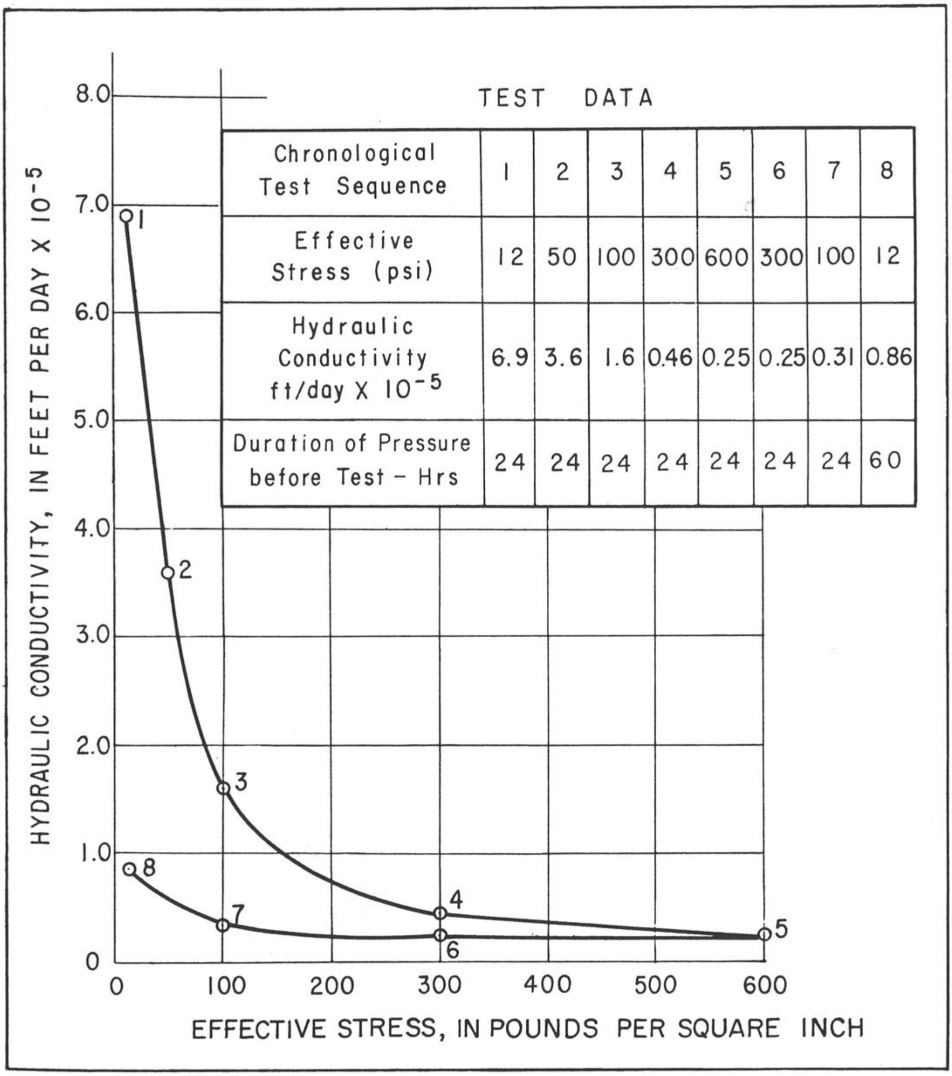
Confining Bed Parameters: Shelby tube and piston core samples of the Marlboro Clay Member and Nanjemoy Formation were used for laboratory analysis of the upper confining bed. Data are shown in table 2. The test sites shown in figure 4 were drilled in up-dip localities where samples could be more readily obtained. Consequently, the data derived from the core samples may not be representative of the confining bed throughout the project area. Furthermore, parameter values can vary with depth as a result of increased overburden pressure. This was evidenced by a test performed on part of the sample from well AA-De 116 in which hydraulic conductivity was determined at various effective stresses (fig. 11). For these reasons, confining-bed parameters were adjusted in the model to obtain the best match of calculated and observed water-level declines rather than relying strictly on the lab values.

A confining bed hydraulic conductivity of 1.4×10^{-4} feet per day (4.3×10^{-5} m/d) was used initially in the model, but was eventually decreased an order of magnitude to calibrate the model. A specific storage of 7.6×10^{-5} per foot (2.3×10^{-5} /m) was used for all calibration and prediction computer runs as was a thickness, determined from drilling logs, of 25 feet (7.6 m).

Confining bed parameters represent the tightest clay layer present, in this case the Marlboro Clay Member, rather than the composite overburden. The tightest layer is considered to be the effective factor controlling vertical leakage.

Although a second (lower) confining bed is not included in this model, leakage from below is indirectly calculated by the method of calibration; that is, by adjusting the confining bed parameters in the model to match observed water-level declines, vertical leakage from below is inherently accounted for. This adjustment does not "verify" confining bed parameters, but "calibrates" the model sufficiently for the predictive purposes of this study.

Potentiometric heads: The model was greatly simplified by making the initial heads in the aquifer and above the confining bed constant and equal. No errors are introduced in the calculation of water-level declines (drawdowns) by this simplification, assuming that the system is initially in equilibrium and that significant drawdowns do not occur near boundaries. However, to obtain a calculated potentio-



TEST DATA

Chronological Test Sequence	1	2	3	4	5	6	7	8
Effective Stress (psi)	12	50	100	300	600	300	100	12
Hydraulic Conductivity ft/day X 10^{-5}	6.9	3.6	1.6	0.46	0.25	0.25	0.31	0.86
Duration of Pressure before Test - Hrs	24	24	24	24	24	24	24	60

Figure 11.—Graph showing results of laboratory tests of hydraulic conductivity of samples of the Marlboro Clay Member of the Nanjemoy Formation at various pressures.

Table 2. Hydrologic laboratory data for cores from the upper confining beds.

	Marlboro Clay Member	Marlboro Clay Member	Nanjemoy Formation
County	Prince Georges	Anne Arundel	Queen Annes
Latitude Longititude	38° 52' 59" N 76° 43' 27" W	38° 55' 28" N 76° 33' 55" W	38° 57' 17" N 76° 21' 02" W
Well Number	PG-Df 35	AA-De 116	QA-Ea 28
Lithology	Silty Clay	Silty Clay	Muddy Sand
Depth in feet	Test #[1] One: 36-38 Two: 36-38 Three: 36-38	Test # One: 12	Test # One: 54-56 Two: 69-71
Effective Stress in psi[2]	40	One: 7	Not Reported
Hydraulic Conductivity in ft/d	One: $1.0x10^{-4}$ Two: $2.3x10^{-4}$ Three: $4.5x10^{-4}$	One: $3.4X10^{-5}$	One: $6.6x10^{-3}$ to $9.5x10^{-3}$ Two: $9.5x10^{-3}$ to $6.9x10^{-2}$
Specific Storage in 1 feet	One: $8.0x10^{-5}$ Two: $1.4x10^{-4}$ Three: $9.0x10^{-5}$	One: Not reported	One: Not reported Two: Not reported

[1] Separate tests were run on three portions of this sample taken from the top, middle and bottom of the coring tube.

[2] This is the lateral pressure applied during testing to simulate over-burden pressure on granular material. Does not include fluid pressure applied to force water thru sample.

metric surface, the calculated drawdowns would have to be superimposed on the initial potentiometric surface that existed at the beginning of the simulation period. This initial surface must be stable to meet the equilibrium assumption and prevent discrepancies between calculated and observed declines. The simulation period began in 1943 at which time the Aquia was essentially unstressed and in a condition of equilibrium.

Boundary Conditions: In accordance with the assumption of initial equilibrium and uniform initial heads, no-flow (impermeable) boundary conditions were used on all boundaries of the model except in the outcrop area. Constant head conditions were maintained in the outcrop area as it was assumed that sufficient recharge was available to prevent drawdowns.

Pumpage Data: Compilations of available pumping records were made for 1950 and 1960. Within the accuracy of the records, pumpage from PNATS area, including Lexington Park, was constant during the calibration period 1943-51. A pumping rate at PNATS of 0.9 M gal/d (3,410 m^3/d) was used for calibration.

Pumpage in the PNATS area accounted for about 60 percent of the total Aquia pumpage of 1.6 M gal/d (6,060 m^3/d) in 1950 and about 50 percent of the total of 1.9 M gal/d (7,190 m^3/d) in 1960. The remainder of the pumpage occurred at pumping centers that are either too small or too distant to greatly affect the potentiometric surface in the PNATS area. Domestic pumpage was considered relatively insignificant and was not included.

Grid Schemes

Two different grid schemes were developed for the project area. One scheme involved a 15 x 16 matrix with constant 4-mile (6.44-km) grid spacing and the other involved a 26 x 27 matrix with variable grid spacing. The constant grid was used for determining model sensitivity to various parameters and the variable grid for calibration and predictions. The fine portion of the variable grid was centered at the PNATS to improve accuracy in this area. Grid spacing, in miles, in the four grid directions was as follows:

0.2, 0.3, 0.4, 0.6, 0.9, 1.2, 1.8, 2.7, 4.0, 4.0 . . . .

Computational restrictions involved with the solution of the finite difference equations limit increases in spacing to a factor of 1.5.

Comparison of results using both grid schemes indicated no computational errors involved with large gridding. However, since water-level declines at each node represent an average over the grid area, finer gridding improves accuracy. This imposes increased cost inasmuch as the finer grid model, with 702 nodes, required four times as much computer time on an IBM 7094 as did the coarser grid model with 240 nodes.

Table 3.--Sensitivity analysis data.

Run No.	Aquifer		Confining Bed			Vol. of cone* $x10^{10}ft^3$	Leakage $x10^6ft^3$	Drawdown at pumped node (ft)	Time to stabilization (ft)	Comments
	T (ft^2/day)	S	K (ft/day)	SS (1/ft)	L (ft)					
1	T matrix	S matrix	$1.4x10^{-4}$	$7.6x10^{-5}$	25	2.11	433.8	21.8	1-2 yrs.	Standard run. Provides most reasonable fit.
2			X 0			113.0	0.0	88.4	Not Stable	Cone much too large.
3				X 10	X2	2.52	431.4	24.9	Not Stable	Too much water in confining bed to reach stabilization.
4				X 10		2.11	433.8	21.8	5	SS still too large--too long for stabilization.
5					X2	4.24	425.3	30.2	2	Leakage decreased, minimal change in stabilization.
6			X 2			1.06	437.8	14.6	1	Note effect of varying K/L ratio in next 3 runs.
7			X 10		X2	.42	440.1	7.5	.5	Too much leakage.
8			X 10			.20	440.8	4.2	<.5	Too much leakage.
9	X 2					2.11	433.4	15.1	1-2	Shape, but not volume, affected by change in T.
10	X 10					2.07	432.2	5.2	1-2	Cone extended to boundaries which probably affected results slightly.
11		X2				2.11	426.1	21.8	3	Stabilization, but not volume, affected by S change.
12		X10				2.06	367.4	21.7	10+	Cone not quite developed at end of simulation.
13	X 2	X2				2.10	425.3	15.1	3	Note from stabilization and drawdown that T and S produce results independently.

Total Pumpage= $439.2x10^6ft^3$

*This is the volume of the cone defined by the summation of drawdowns times the area of the grid.

Sensitivity Analysis

A series of computer runs were made to illustrate the sensitivity of the model to changes in aquifer transmissivity (T) and storage coefficient (S), and confining bed hydraulic conductivity (K), thickness (L), and specific storage (SS). These parameters were varied in the model and effects noted on drawdown, volume of drawdown cone, vertical leakage, and time required to reach steady-state conditions (stablization time). The four-mile (6.44 km) grid scheme was used for this analysis with a single pumpage of 0.9 M gal/d (3,410 m^3/d at the PNATS for a 10-year period. This allowed water-level records from PNATS for the period 1943-51 to be used as an indication of the general reasonableness of the model results. In particular, these records showed that the drawdown cone stablized in about two years and gave some indication of the volume of the stablized cone. This analysis was not intended as an actual simulation of water-level declines since the model had not been calibrated, and the grid spacing is too coarse for accurate simulation in the PNATS area.

Table 3 shows the parameter variations and calculated results for the sensitivity analysis. Initial estimates of input data were used in Run No. 1 and this run was used as a standard for comparison with subsequent runs. Parameters in Runs Nos. 2 through 13 are the same as Run No. 1 unless otherwise noted. Aquifer transmissivity and storage coefficient ("T matrix and S matrix") vary spatially in the model, but confining-bed parameters ("K," "SS" and "L") are uniform. It should be noted that the calculated "drawdown at pumped node" is an average drawdown over the grid area and, particularly with gridding as large as 4 miles (6.44 km), is not representative of actual drawdowns.

The model is most sensitive to changes in the hydraulic conductivity and thickness of the confining bed. With K set equal to zero (Run No. 2), drawdowns were extremely excessive indicating that considerable recharge via vertical leakage must occur. Runs Nos. 6 and 8 show that increases in hydraulic conductivity result in approximately proportional decreases in the volume of the stabilized cone. Conversely, Run No. 5 shows that an increase in the thickness of the confining bed results in an approximately proportional increase in cone volume. Time to steady state is also affected by changes in either hydraulic conductivity or thickness of the confining beds.

The model is less sensitive to aquifer transmissivity than to the hydraulic conductivity or thickness of the confining bed. Runs Nos. 9 and 10 show that varying the transmissivity values has little effect on the volume of the drawdown cone, but has significant effect on the distributions of drawdowns. Although leakage prior to steady state is affected slightly because of redistributed drawdowns, the time to steady state is not altered.

Calibration

As of the mid-1960's, the only notable cone of depression in the Aquia potentiometic surface resulted from pumpage at the PNATS-Lexington Park area. Large-capacity pumping began in 1943 and water-level records indicate that the cone of depression stabilized in 1 to 2 years. The variable grid model was calibrated for this area using water-level data from a map of the potentiometric surface of the Aquia in 1951 (fig. 12), taken from Otton (1955, plate 9).

Figure 13 shows calculated drawdowns for 1951 from three simulation runs and three observed values taken in an up-dip direction from the map. The 1951 potentiometric data were converted to drawdown values based on the assumption that heads were initially about 10 feet (3 m) above sea level near the naval base (Ferguson and others, 1953, p. 30). Figures 14 and 15 are maps of drawdown corresponding to curves 1 and 3 of figure 13 and are included to provide a better perspective of regional drawdowns.

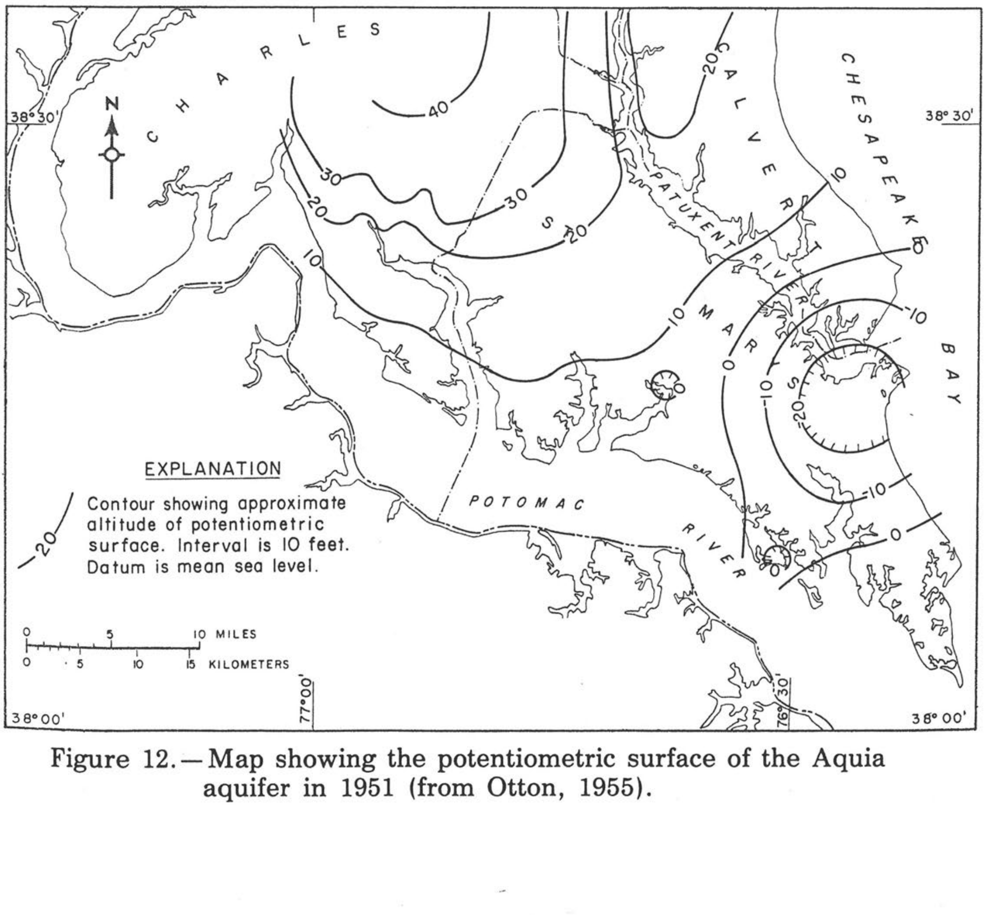


Figure 12.—Map showing the potentiometric surface of the Aquia aquifer in 1951 (from Otton, 1955).

The first simulation run (upper plot, fig. 13) was made with the parameter values of Run No. 1 shown in table 3 and figure 10, and a pumpage of 0.9 M gal/d (3,410 m^3/d). The computed drawdowns are much less than the observed drawdowns (fig. 13) and, thus, the volume of the computed drawdown cone (an indication of the quantity of water withdrawn from storage in the aquifer) is also much too small. To significantly change the volume of a stabilized drawdown cone, the amount of water transferred into or out of the aquifer must be adjusted. As shown by the sensitivity analysis, this cannot be done by changes in transmissivity or storage coefficient. In this case, either the pumpage should be increased or leakage decreased in the model to obtain a better match of observed and calculated drawdowns. A review of pumpage records indicated that pumpage could be reasonably increased from 0.9 to 1.0 M gal/d (3,410 to 3,790 m^3/d), and this change was made. Also, for the second run, leakage was decreased by halving the hydraulic conductivity of the confining bed and imposing a limit of 20 feet (6.1 m) on the head differential across the confining bed. This limit is based on published potentiometric maps (Otton, 1955, pl. 9 and 10) and allows for the drawdown that occurs in adjacent aquifers due to pumpage and vertical leakage to the Aquia. As can be seen (fig. 13), the combined effect of these changes was minor, resulting in about 5 feet of additional drawdown. Another run (not shown on figure 13) indicated that about 2 feet of the additional drawdown was due to the 20-foot head limit.

The third calibration run provided the best match with observed data (fig. 13). The changes made in the second run were used except the hydraulic conductivity of the confining bed was further reduced to 1.4×10^{-5} feet per day (4.3×10^{-6} m/d). As shown by figure 13 (curve 3) and the contoured drawdown map (fig. 15), drawdowns significantly increased as a result of this change. Further refinements were felt to be unwarranted due to the uncertainties in input data and observed water-level changes.

Predictions

After calibration, the 26 x 27 gridded model was used to predict future water-level declines resulting from hypothetical increased pumpage rates at the PNATS area and other pumping centers in the downdip parts of the Aquia. Predictions were not made in updip parts of the model area because little Aquia pumpage has occurred there, and the model was calibrated only for the PNATS area. The calibrated value of hydraulic conductivity was used uniformly in the model. Pumpage from PNATS, located in the finer grid portion of the model, was distributed among nine wells to approximate the actual well configuration.

Contoured water-level declines after 10 years of pumping at the indicated rates are shown in figures 16, 17, and 18. Pumpage for the first prediction run (fig. 16) was based on the best available

water use estimate for 1980. In the other two prediction runs (figs. 17 and 18), Hypothetically increased pumpage rates were used.

The first and second runs resulted in drawdowns of greater than 70 feet (21 m) and 200 feet (61 m), respectively, over several square miles. Drawdowns from the first and second runs (figs. 16 and 17) were such that water levels did not fall below the top of the aquifer, which is about 450 feet (137 m) below sea level in the PNATS-Lexington Park area. The third run, however, resulted in drawdowns of greater than 400 feet (122 m) over a 12-square mile (31 km²) area; if drawdowns of this magnitude were actually to occur, some dewatering of the Aquia would result at PNATS-Lexington Park.

During the predictive runs no limits were placed on the head gradient across the confining bed. This condition assumes that no drawdown occurs in the overlying aquifer during the simulation and, consequently, the maximum possible leakage is calculated; water-

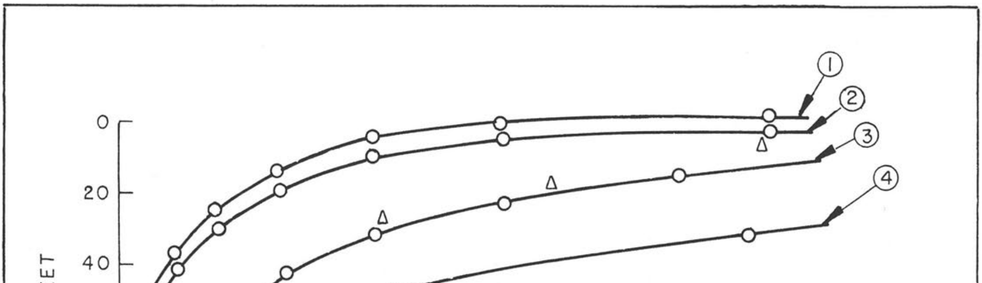


Figure 13.—Graph showing calculated and observed drawdowns in the Aquia aquifer. Distances are measured from the center of pumping at PNATS.

level declines in the Aquia are therefore minimized. An additional set of runs were made with the head gradient across the confining bed limited to 40 feet (12.2 m). This condition assumes that considerable drawdown will occur in the overlying aquifer (as a result of pumpage from the aquifer or leakage into the Aquia). In these runs, leakage through the confining bed was reduced and water-level declines in the vicinity of the Aquia pumping centers were approximately 20 percent greater than shown in figures 16, 17, and 18. Although the 40-foot head gradient doubtless is extreme, it provides some insight into the relative effect that drawdowns in the adjacent aquifer have on the predicted water-level declines in the Aquia.

Large head declines have caused serious land subsidence problems in many areas. Data are needed on the compressibility of the confining beds overlying the Aquia aquifer in order to evaluate

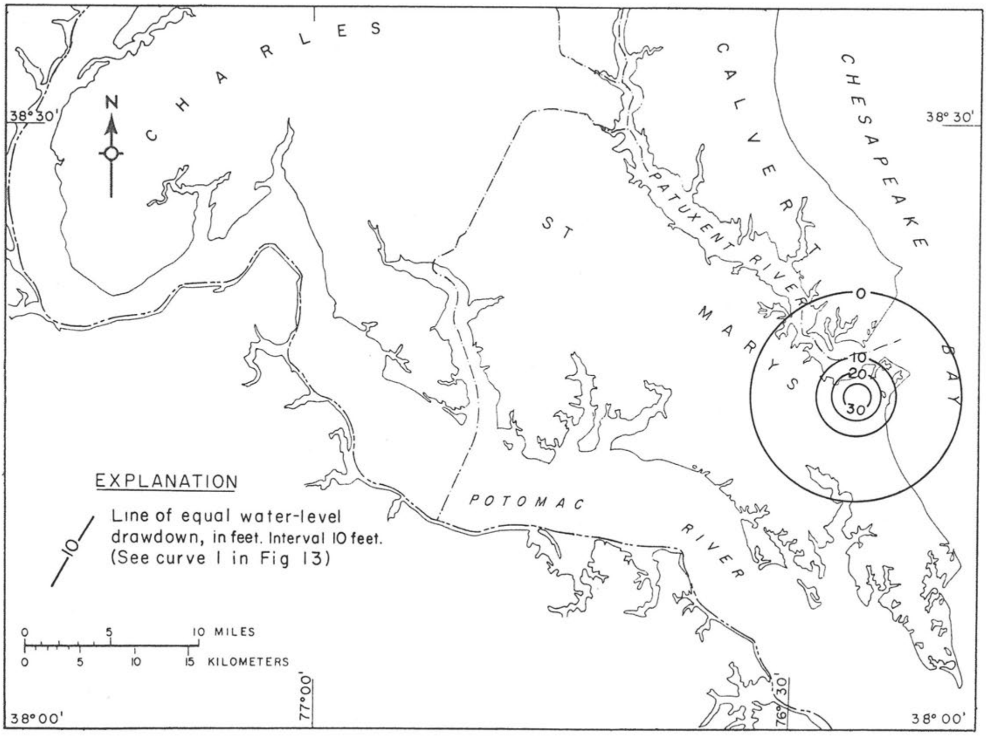


Figure 14. — Map showing drawdown in the Aquia aquifer calculated from the first simulation run (curve 1 in fig. 13).

the potential for subsidence and also to estimate the reduction of hydraulic conductivity and specific storage of each confining bed that may be produced by compaction (Poland, 1972).

RECOMMENDATIONS FOR FURTHER STUDIES

Improvements could be made in the calculations of sources and quantities of recharge waters by modifying the model to include two confining beds and, possibly, multiple aquifers. The present model with a single confining bed, calculated only a total recharge quantity via vertical leakage. A model with two confining layers could be used to separate vertical leakage quantities and a multi-aquifer model would allow the evaluation of effects on adjacent aquifers. Modifications to the program to accommodate a second confining bed could be reasonably made; a multi-layer aquifer model has been described by Trescott (1975).

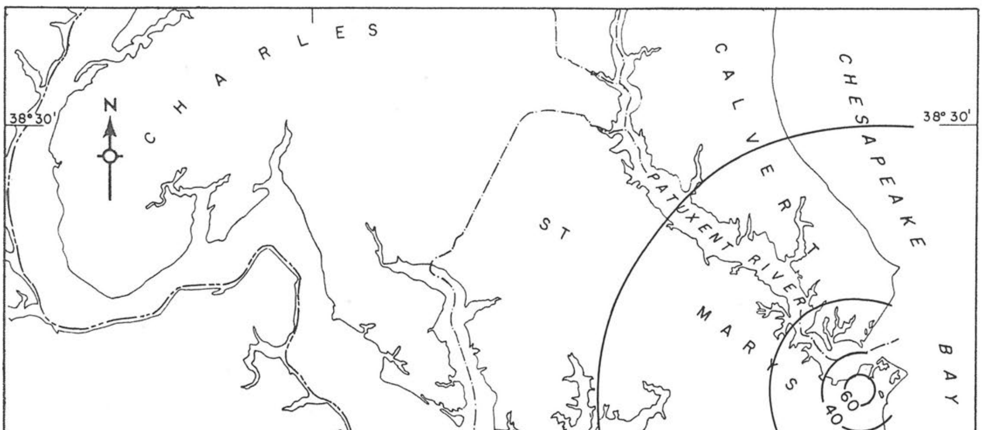


Figure 15.—Map showing drawdown in the Aquia aquifer calculated from the third simulation run (curve 3 in fig. 13).

In future studies, emphasis should be placed on water-level and confining-bed data. Water-level data will become more important for calibration as additional pumping stress is imposed on the Aquia. For a multi-layer aquifer model, water-level data will be needed for all the aquifers in the system. Both areal evaluation methods and selected aquifer-test methods, in addition to laboratory analyses of cores, should be used to determine confining-bed parameters wherever possible. Because model calibration will generally involve adjustment of confining-bed parameters, care must be taken so that the adjusted parameters remain consistent with the known depth, thickness, lithology, and areal distribution of these units (Hansen, 1971).

SUMMARY AND CONCLUSIONS

A finite difference digital model was constructed to simulate the hydrology of the Aquia aquifer in about 3,800 square miles (9,840 km^2) of southern Maryland. A sensitivity analysis showed the

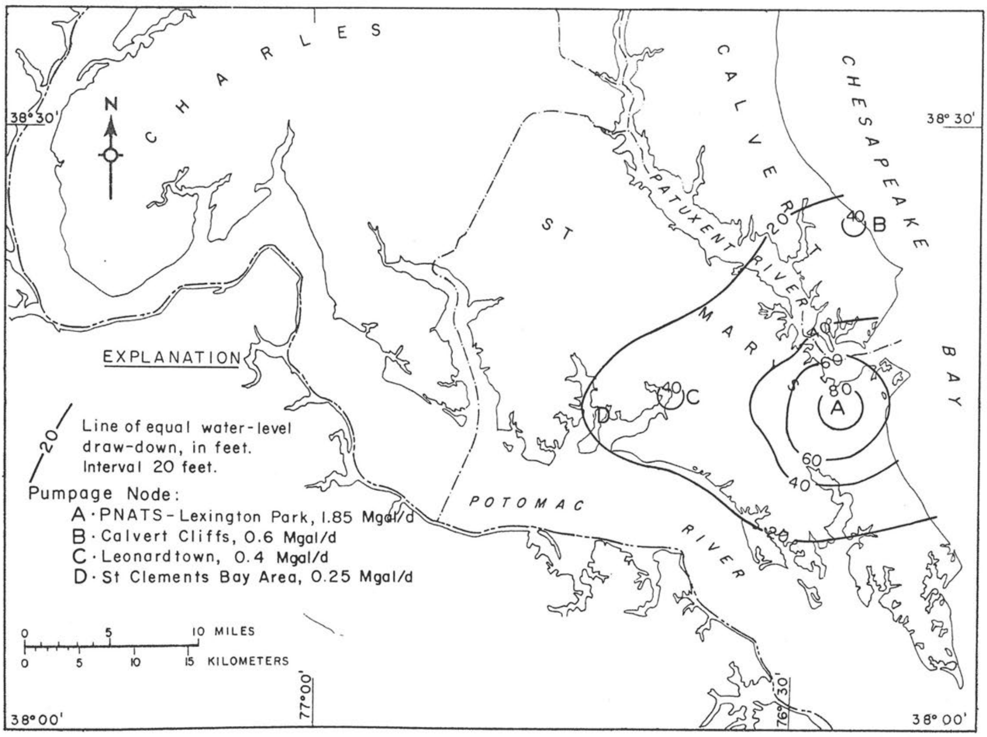


Figure 16.—Map showing predicted water-level declines in the Aquia aquifer based on pumpage of 3.1 M gal/d (11,730 m^3/d) for 10 years.

hydraulic conductivity (K) of the confining bed to be the most important hydrologic parameter controlling recharge. Because of difficulties in determining representative values of K by laboratory analysis, the value of this parameter was adjusted in the model to obtain the best match of observed and calculated drawdown data. The model was calibrated for the area of the Patuxent Naval Air Training Station (PNATS) as this was the only part of the project area in which pumpage has been large enough to produce a sizeable cone of depression. During calibration, the laboratory value of K was decreased by a factor of ten.

After calibration, the model was used to predict future water-level declines based on hypothetical withdrawals from several pumping centers in the proximity of the PNATS. For the final run, using a total pumpage of 21 million gallons per day (79,490 m^3 /d) for 10 years, drawdowns of over 400 feet (122 m) were predicted which would result in partial dewatering of the aquifer over a 12-square mile (31 km^2) area of the PNATS.

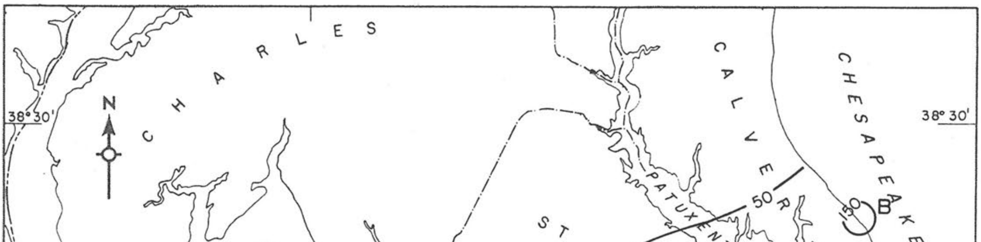


Figure 17.—Map showing predicted water-level declines in the Aquia aquifer based on pumpage of 10 M gal/d (37,850 m^3/d) for 10 years.

Limitations on the use of the present model stem principally from the fact that only a single aquifer and confining bed are included. Thus, the effects of pumpage on adjacent aquifers cannot be determined. Also, the usage of the model is restricted because it was calibrated only for the PNATS area.

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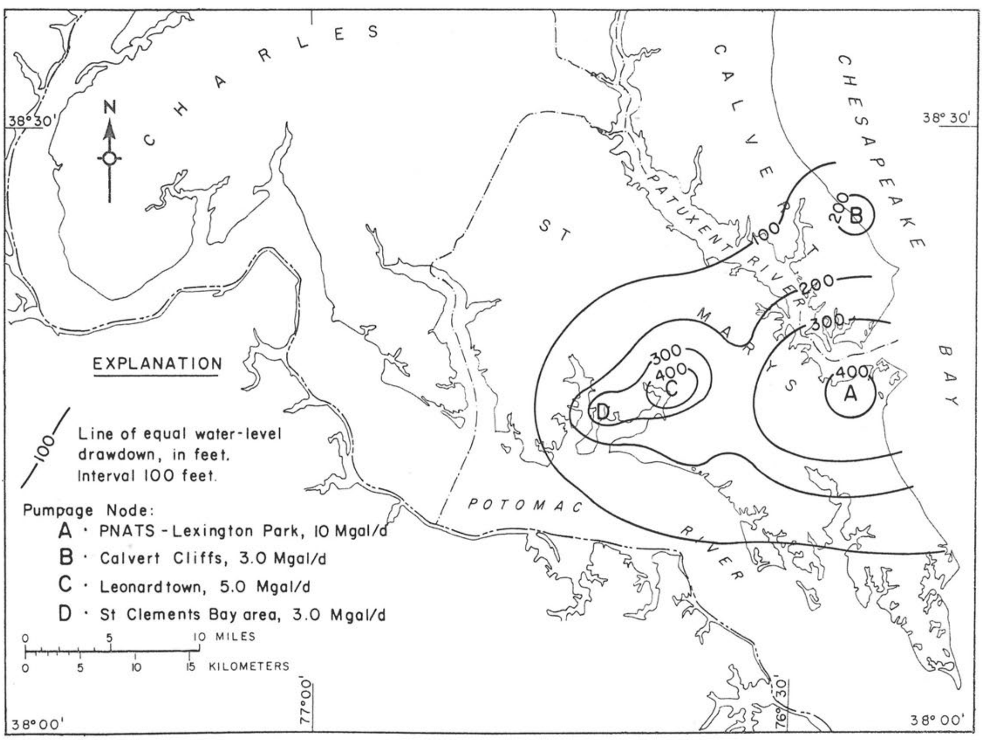

Figure 18.—Map showing predicted water-level declines in the Aquia aquifer based on pumpage of 21 M gal/d (79,490 m^3/d) for 10 years.

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[1] The name of this agency was changed to the Maryland Geological Survey in June, 1964.

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