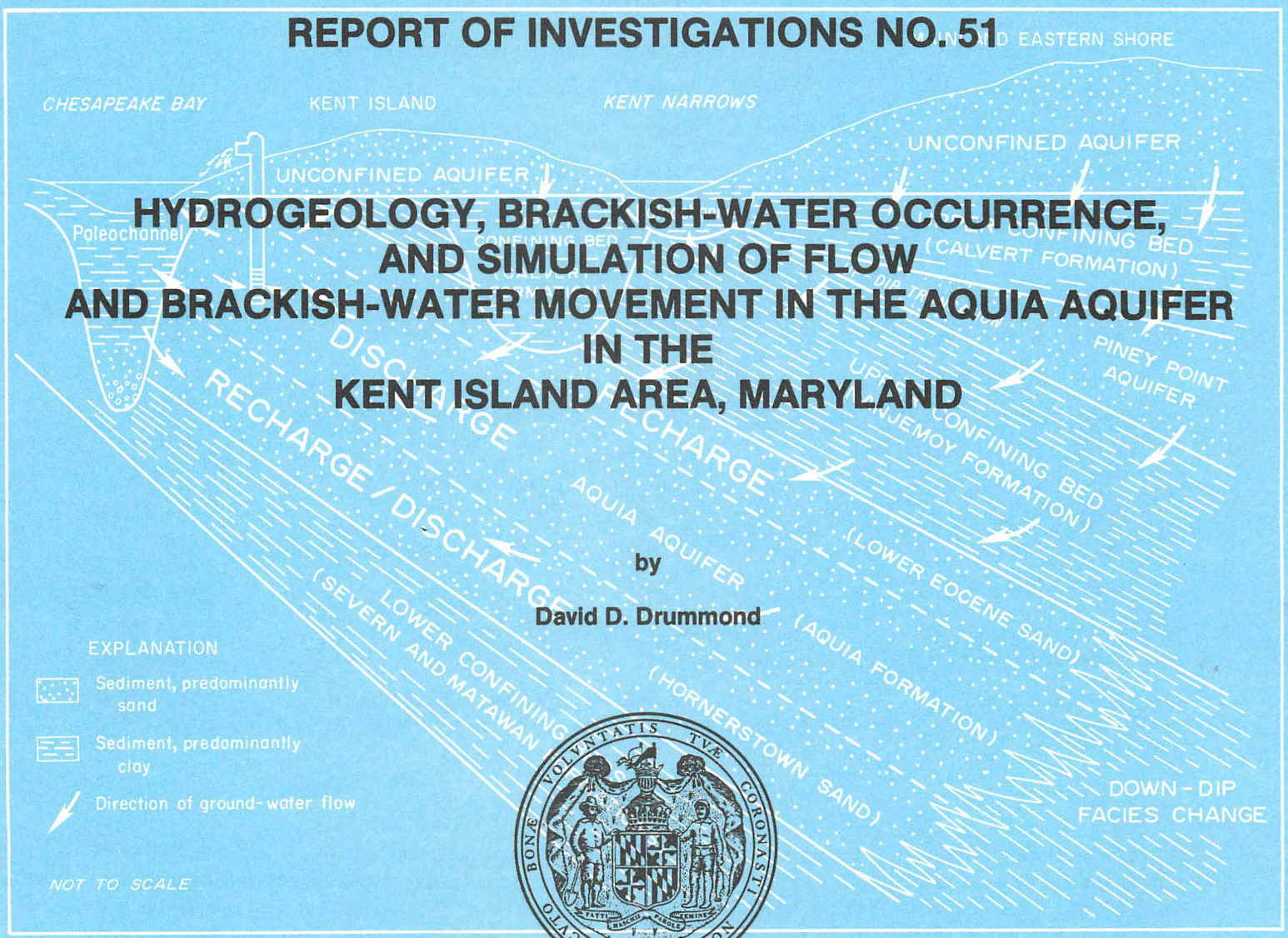
Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 51

HYDROGEOLOGY, BRACKISH-WATER OCCURRENCE, AND SIMULATION OF FLOW AND BRACKISH-WATER MOVEMENT IN THE AQUIA AQUIFER IN THE KENT ISLAND AREA, MARYLAND

by

David D. Drummond



Prepared in cooperation with the
United States Department of the Interior
Geological Survey
The County Commissioners of Queen Anne's County
and
The Maryland Water Resources Administration

1988

CONVERSION FACTORS AND ABBREVIATIONS

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

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
gallon per day per foot [(gal/d)/ft]	0.01242	square meter per second (m^2/s)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
pound per square inch	6.895	kilopascal (kPa)
pound per second per square foot [$(lb_m/s)/ft^2$]	1488	centipoise (cP)
pound per cubic foot (lb_m/ft^3)	0.01602	gram per cubic centimeter (gm/cm^3)

Chemical concentration, water temperature, specific conductance, resistivity, and electrical potential are given in metric units. Chemical concentration is expressed in milligrams per liter (mg/L) or micrograms per liter (μg/L). Water temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8\ (°C) + 32$$

Specific conductance is expressed in microsiemens per centimeter (μS/cm) at 25° Celsius. Resistivity is expressed in ohm-meters. Electric potential is expressed in millivolts (mV).

Mass is expressed in pounds, with the "m" subscript designating mass as opposed to pounds of force.

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

A study was conducted to investigate the hydrogeology of the Aquia aquifer in the Kent Island area, Maryland. The problem of brackish-water occurrence in the Aquia aquifer was specifically addressed.

The Aquia aquifer contains sediments of Paleocene and Eocene age. The aquifer is a fine- to medium-grained glauconitic sand, containing layers of clayey sand, layers indurated by calcite cement, and abundant shell material. The upper confining bed overlies the Aquia aquifer and contains sediments of the Nanjemoy and Calvert Formations. It is chiefly a silty clay and clayey sand and forms a leaky confining bed. The lower confining bed underlies the Aquia aquifer and contains sediments of the Matawan and Severn Formations. It is chiefly a silty, sandy clay and forms a relatively tight confining bed. The unconfined aquifer overlies the upper confining bed and contains sediments of the Kent Island and Talbot Formations. It is chiefly a clayey silt with pockets of sand and gravel, and supplies recharge to the aquifer system below.

Brackish water is present in the Aquia aquifer along the Chesapeake Bay shore from the northernmost tip of the island (Love Point) to at least as far south as Prices Creek. In the northern part of the brackish-water zone, the entire vertical section of the Aquia aquifer contains brackish water. In the southern part of the brackish-water zone, the bottom of the Aquia contains brackish water, but the top contains freshwater. Five major hydrogeologic controls were identified that influence the distribution and movement of brackish water in the Aquia aquifer: density-dependent flow, water pressures, the presence of calcite-cemented layers, the presence of paleochannel sediments, and the confining-bed permeability.

A quasi three-dimensional, finite-difference two-layer areal flow model was developed to simulate the response of water levels to projected pumpage in the Aquia aquifer. The flow-model area includes Kent Island and a large part of the Eastern Shore to simulate pumping centers at the towns of Easton, Oxford, St. Michaels, and Centreville. A simulation based on the best estimate of future pumpage indicates an additional 5 feet of drawdown from the 1984 potentiometric surface by the year 2005 on parts of Kent Island. The greatest declines occur on the eastern part of the island near Grasonville. Simulations based on pumpage amounts 20 percent higher and lower than the best estimate indicate additional drawdowns of 6 to 8 feet and 2 to 4 feet, respectively, from the 1984 potentiometric surface. Other simulations were made to evaluate alternative pumpage conditions such as replacement of domestic pumpage by centralized supply wells and varying pumpage amounts in areas other than Kent Island. A sensitivity analysis was performed on the calibrated flow model to evaluate the effects of uncertainties in the input data on model results. The sensitivity analysis indicates that simulated water levels could be in error by 2 to 4 feet in the Kent Island area because of possible inaccuracies in the input data.

A cross-sectional solute-transport model was developed to estimate the movement of brackish water in response to projected pumpage amounts and to evaluate the importance of the hydrogeologic controls on the distribution and movement of brackish water. Estimated distances and rates of movement should be regarded as general approximations rather than accurate predictions. Model results indicate that the freshwater/brackish-water interface will move about 440 feet inland during the 21-year simulation period (1984-2005) based on the best estimate of future pumpage. Alternative simulations based on pumpage amounts 20 percent higher and lower than the best estimate indicate interface movement of about 490 feet and about 350 feet, respectively, for that same period. Average interface velocities for the three simulations are about 21, 24, and 17 feet per year. A simulation based on continued 1984 pumpage throughout the future simulation period indicates interface movement of about 275 feet at an average velocity of about 13 feet per year. A simulation based on no pumpage in the Aquia throughout the simulation period indicates interface movement of about 40 feet in the opposite direction (bayward) at an average interface velocity of about 2 feet per year. A sensitivity analysis was run on the calibrated transport model to evaluate the effect of uncertainties in input data on model results. The sensitivity analysis indicates that projected interface movement

could be in error by 125 feet for the 21-year simulation period, or about 6 feet per year, because of possible inaccuracies in the input data.

Simulations designed to evaluate the importance of the hydrogeologic controls on brackish-water movement indicate that density-dependent flow, water pressures in the Aquia aquifer, and the permeability of the upper confining bed are the most important factors. Calcite-cemented layers and paleochannel sediments provide minor controls on brackish-water movement in the Aquia aquifer in the Kent Island area.

INTRODUCTION

The Kent Island area has undergone considerable residential and commercial development in the last few decades, which is expected to continue into the future. This development is accompanied by an increasing demand for freshwater. Virtually all of the freshwater is obtained from ground water, and most of that has been supplied by the Aquia aquifer. Although not the sole ground-water source on Kent Island, the Aquia is relatively shallow, dependable, and produces water of drinking water quality throughout most of its extent. However, because it is shallow in the vicinity of the Chesapeake Bay and its tidal tributaries, the Aquia is vulnerable to brackish-water intrusion. Water levels in the Aquia dropped from several feet above sea level in the mid-1950's to several feet below sea level in 1984. In addition, numerous wells screened in the Aquia near the Chesapeake Bay were reported to produce water of high chloride concentrations, ranging up to 800 mg/L (milligrams per liter). These factors led to concern by State and county officials that brackish water was entering the Aquia aquifer and that it was in danger of becoming irrevocably contaminated. A study was undertaken between April 1983 and June 1986 to provide a better understanding of the hydrogeologic system, the response of ground-water levels to pumpage, and the occurrence and movement of brackish water in the Aquia aquifer.

PURPOSE AND SCOPE

The purpose of this report is to present the results of a 3-year study investigating the Aquia aquifer at Kent Island, Maryland. The results are presented in four parts: hydrogeology, brackish-water occurrence, simulation of ground-water flow, and simulation of brackish-water movement. The report is intended to provide planning officials with a better understanding of the hydrogeologic system and the potential effects of projected pumpage on the availability and quality of water in the Aquia aquifer.

To define the hydrogeology, about 150 existing wells were inventoried in the study area from which data were collected on water levels and lithology. In addition, 15 test holes were drilled, 14 of which were completed as observation wells, and data collected for water levels, lithology, stratigraphy, and aquifer characteristics. The occurrence of brackish water was determined by sampling about 75 wells for chloride and other chemical constituents, by analyzing electrical-resistivity geophysical logs, and by comparing historical data with present chemical data. Ground-water flow was simulated using a quasi three-dimensional finite-difference areal flow model. The movement of brackish water through the Aquia aquifer was simulated using a two-dimensional finite-element cross-sectional solute-transport model. The effects of projected pumpage on freshwater flow and brackish-water movement were evaluated using these models.

Supplemental data referred to throughout the report are included at the end of the report in tables 8 through 11. This includes well-construction data (table 8), water-chemistry analyses (tables 9a and 9b), biostratigraphic analyses (tables 10a and 10b), and lithologic descriptions (table 11).

LOCATION OF STUDY AREA

The Kent Island study area is located in Queen Anne's County on the Eastern Shore of Maryland (fig. 1). The island is bounded on the west by the Chesapeake Bay, on the southeast by the Eastern Bay, on the northeast by the Chester River, and is separated from the mainland to the east by Kent Narrows. The island has a total land area of 31.6 mi^2 (square miles). The main study area includes Kent Island and surrounding regions with a total area of 203 mi^2. The flow-model area includes a large portion of the Maryland Eastern Shore in order to establish the regional flow regime and to include the major pumping centers at the towns of Easton, St. Michaels, Oxford, and Cambridge. The model covers a total area of 1,311 mi^2.

METHODS OF INVESTIGATION

An extensive well inventory was taken of selected domestic, commercial, industrial, and public-supply wells. The purpose of the inventory was to gather data to formulate a preliminary picture of ground-water flow systems, water chemistry, and lithologies. Data collected at selected wells (150) included water levels (90), water samples (75) for analysis of chemical parameters (chloride, conductivity, dissolved oxygen, and pH), locations and altitudes. A driller's completion report was then procured from the State files to access information on lithologies.

From the well inventory, wells were selected for a synoptic water-level measurement. This measurement was carried out at the beginning of October in 1983, 1984, and 1985 to determine the potentiometric surface at the same time each year. Because of the low relief in the potentiometric surface (less than 10 ft) throughout much of the study area, many wells on the network were surveyed for precise altitudes and increased vertical control. The results of the yearly measurements were then plotted on maps and compared to determine yearly trends and regional shifts in water levels.

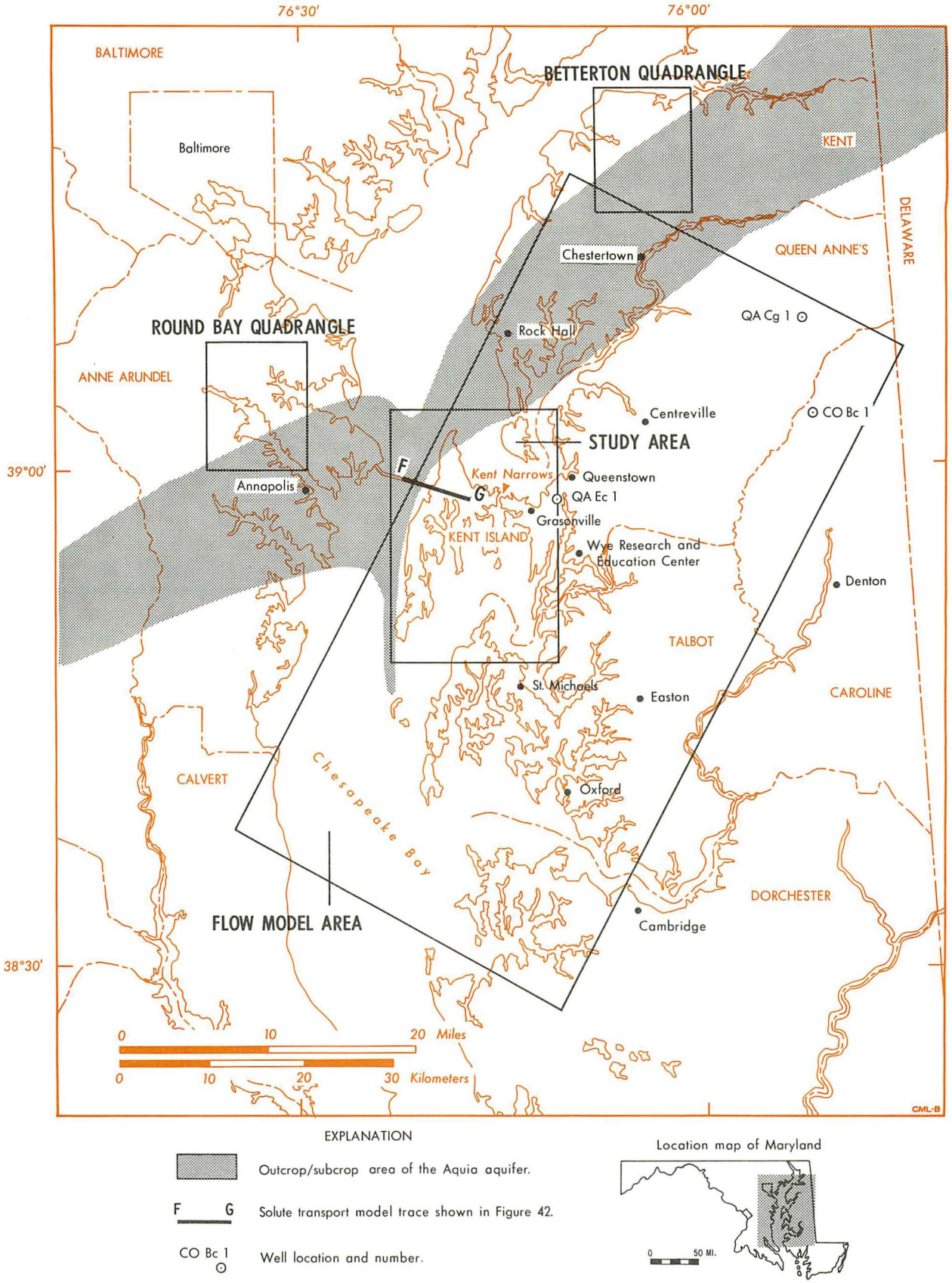

Figure 1. — Locations of study area, flow-model area, solute-transport model trace, and outcrop/subcrop area of the Aquia aquifer.

A total of 48 wells also were selected from the inventory for chemical-analysis sampling. The purpose of the chemical sampling was twofold—first, it was to determine the natural or regional ground-water chemistry pattern, and second, to determine the nature and source of any contaminating influences such as brackish-water intrusion. Water was sampled and analyzed in accordance with techniques outlined in Skougstad and others (1979). The samples were analyzed for major constituents plus some minor constituents such as iron and strontium.

Geophysical logs were obtained from numerous newly drilled wells. The majority of these were gamma logs (14) because they can be run on cased wells, but a few electric-resistivity logs (5) also were obtained from uncased holes. The network of geophysical logs provides a three-dimensional framework on which to base stratigraphic correlations and vertical water-chemistry zonation.

An extensive test-drilling program was undertaken to obtain data in areas and at depths unavailable from existing well sites. Fourteen wells and one test boring were drilled at eight sites, with each well in a cluster screened at a different depth. Drill-cutting samples were obtained at 10- and 20-ft intervals and described in detail. Drill cuttings are useful in determining gross lithologies, but because of up-hole contamination and time lag between cutting and actual sampling, they need to be supplemented by core samples for precise lithologic control. Sample colors were determined by comparison with the Geological Society of America Rock-Color chart, and color designations were based on the Munsell system (Goddard, 1948). Core samples were taken at selected intervals to determine various hydraulic properties (permeability, porosity, and grain density) and to obtain lithologic samples at precise intervals. Core subsamples and five drill-cutting subsamples were taken for micropaleontological age determination and stratigraphic correlation. The pollen were analyzed by G. J. Brenner of the State University of New York at New Paltz and the foraminifera were analyzed by R. K. Olsson of Rutgers University, New Brunswick, N. J.

After drilling the deepest hole in each cluster, a suite of geophysical logs was run on the uncased hole. Logs run at all sites include natural gamma, single-point resistivity, multi-point resistivity, and caliper. Logs run at selected sites include gamma-gamma (porosity), neutron (density), and acoustic velocity.

Each test hole was completed as a well with a PVC screen 10 ft long and 4 in. (inches) in diameter, 4-in. PVC casing and a 6-in. protective steel casing with locking cap. The wells were then gravel packed and grouted with a cement/bentonite mixture and developed with compressed air.

Aquifer tests were completed at five of the seven test sites. Each test included a 24-hour pumping period followed by a 24-hour recovery period. Water levels were measured and recorded in all wells at the site. Water samples for chemical analysis were taken from pumping wells during the test, and from nonpumping wells at a previous time using a submersible pump.

A ground-water flow model was developed to simulate water levels in response to historic, present, and future pumpage. The U.S. Geological Survey modular three-dimensional finite-difference model (McDonald and Harbaugh, 1984) was used for the simulations. Hydraulic input parameters were obtained from published and file sources as well as from data collected during the course of the project. Water-level data were selected from published sources, from the northern Atlantic Coastal Plain Regional Aquifer Systems Analysis (RASA) conducted by the U.S. Geological Survey, project files, and measurements taken during the project. The flow model was used to simulate the response of water levels to best-estimate projected pumpage and to alternative pumpage conditions.

A solute-transport model was developed to simulate the distribution and movement of brackish water in the Aquia aquifer. The U.S. Geological Survey Saturated-Unsaturated Transport model (SUTRA) (Voss, 1984) was used in cross-sectional form for these simulations. The model was first calibrated, then used to simulate the movement of brackish water in response to projected and alternative pumpage conditions. It was also used to evaluate the importance of hydrogeologic controls in determining the occurrence of brackish water in the Aquia aquifer.

PREVIOUS INVESTIGATIONS

The geology of the Coastal Plain aquifers of Maryland was first described by Darton (1896). Clark and Martin (1901) further described the Eocene formations which, at that time, were undifferentiated from Paleocene formations. Clark, Mathews, and Berry (1918) provide descriptions of Coastal Plain sediments and tabulate useful well data such as depth, water levels, yield, and water "character." Anderson (1948) provided a detailed account of petrology and paleontology of the Tertiary and Cretaceous beds of three deep oil test wells on the Eastern Shore. Rasmussen and Slaughter (1957) and Overbeck and Slaughter (1958) published extensive well records and other data concerning the geohydrology of the Eastern Shore counties. Back (1966) investigated the regional geochemistry of the Aquia and Nanjemoy aquifers.

WELL-NUMBERING SYSTEM

Well locations are shown on the well-location maps in figure 63, also at the end of the report. Well numbers are designated in the following manner. Each county in Maryland is divided into quadrangles of 5 minutes of latitude and longitude (fig. 63). Each quadrangle is assigned a two-letter

code, the first of which is determined by the latitude section, the second by the longitude section. The first group of letters in the well number indicates the county code (CO for Caroline, KE for Kent, QA for Queen Anne's, and TA for Talbot); the second group indicates the 5-minute quadrangle in which the well is located; and the third group is a sequential number generally assigned according to the order in which the well was inventoried. Thus, QA Db 22 is assigned to the 22nd well inventoried in quadrangle Db in Queen Anne's County.

ACKNOWLEDGMENTS

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The author would like to express thanks to Mr. Wilbur Garret, Dr. Charles Mylander, the Langenfelder Corporation, and the Cloverfields Improvement Association for allowing test wells to be drilled on their property. Thanks also go to the Colliers Well Drillers and the Delmarva Well Drilling Company for their cooperation in geophysical logging of wells. Palynological analysis was performed by Gilbert J. Brenner of the State University of New York at New Paltz, and foraminiferal analysis was performed by Richard K. Olsson of Rutgers University. The manuscript was typed by Donajean M. Appel of the Maryland Geological Survey. Cynthia Lang-Bachur of the Maryland Geological Survey and Patrice Gernhardt and Raymond G. Davis of the U.S. Geological Survey assisted in the production of illustrations and tables. A portion of this report was submitted to the Department of Geology, the George Washington University, as a Master's thesis. The assistance of the Department is gratefully acknowledged.

HYDROGEOLOGY

Kent Island is underlain by sediments of Quaternary, Tertiary, and Cretaceous age, which form the clastic wedge of the Atlantic Coastal Plain. These sediments dip and thicken to the southeast and generally crop out or subcrop beneath surficial sediments in northeast-southwest trending bands which define their northwesternmost extent. The sediments are underlain by bedrock of variable type, the surface of which also deepens to the southeast. Bedrock was reached at 2,504 ft below sea level at test well QA Eb 110 near the town of Chester (Mack, 1983).

The Aquia aquifer supplies most of the freshwater needs for Kent Island, and therefore is the focus of this report. However, there are alternative water sources in the deeper aquifers of the Potomac Group and the Magothy Formation. Useful hydrogeologic data for these deeper aquifers, including depth, thickness, lithologic descriptions, transmissivity, water levels and water chemistry, is provided by Mack (1983). The Matawan Formation contains sandy beds in the Easton area which supply limited quantities of water (Mack, Webb, and Gardner, 1971). Because of the difficulty of distinguishing these beds from beds in the underlying Magothy Formation, they are included in the Magothy aquifer, as in Mack, Webb, and Gardner (1971). Limited quantities of freshwater are also supplied by the unconfined aquifer which is the surficial sandy bed. The Aquia aquifer is bounded on the top and bottom by the upper and lower confining beds, as referred to in this report. The generalized hydrogeology and stratigraphy of the Kent Island area are shown in table 1. Cross-sections AB, CD, and ED are shown in figures 3, 4, and 5, and their locations in figure 2. These sections are based on gamma logs and test borings and show the areal and vertical relations of the important hydrogeologic units.

As shown in figures 3 through 5, the Aquia aquifer ranges in thickness from about 135 ft at well QA Db 33, where it is partially incised by the Calvert Formation, to about 275 ft at well QA Fa 73 in the southern part of the island. The upper confining bed ranges in thickness from 0 ft at well QA Db 35 in the northern part of the island to about 185 ft at well QA Fa 72 in the southern part. The unconfined aquifer ranges in thickness from about 20 ft at well QA Eb 154 to about 75 ft at well QA Ec 85. The paleochannel sediments obtain a maximum thickness of about 120 ft along the axis of the paleochannel. The hydrogeologic units below the unconfined aquifer dip and thicken to the southeast. The hydrogeology of all these units will be discussed in detail in order of ascending occurrence.

LOWER CONFINING BED

The lower confining bed, as referred to in this report, is the sandy clay unit which occurs below the sandy Aquia aquifer. It contains shallow marine sediments of Late Cretaceous and Early Paleocene age, as determined by analysis

(Text continues on p. 12)

Table 1. — Generalized hydrogeology and stratigraphy of the Kent Island area

SYSTEM	SERIES	HYDROGEOLOGIC UNIT	STRATIGRAPHIC UNIT	THICKNESS (FEET)	DOMINANT LITHOLOGIC CHARACTER	WATER-BEARING PROPERTIES
QUATERNARY	PLEISTOCENE and HOLOCENE	UNCONFINED AQUIFER	TALBOT and KENT ISLAND FORMATIONS (Undifferentiated)	20 - 80	Silt, sand, clay, some pockets of coarse sand and gravel; tan, gray, orange.	Yields small amounts of water for domestic supplies. Functions as a water supply for recharge to the Aquia aquifer.
		PALEOCHANNEL	PALEOCHANNEL	0 - 115	Sand, silt, clay, gravel; extremely variable.	Functions as a conduit where confining bed has been eroded and replaced by high-permeability sediments. Functions as a confining bed where an aquifer has been eroded and replaced by low-permeability sediments.
TERTIARY	MIOCENE	UPPER CONFINING BED	CALVERT FORMATION	0 - 135	Clay, silty, with some lenses of sand; gray.	Functions as a leaky confining bed.
	EOCENE	UPPER PINEY POINT AQUIFER	PINEY POINT FORMATION	---	Sand, fine to very coarse; green to gray; quartz with abundant glauconite; interbedded layers of shell, very fine sand, silt, clay.	Supplies water for parts of Talbot, Caroline and Dorchester Counties; truncated just southeast of Kent Island; not present beneath Kent Island.
			NANJEMOY FORMATION	0 - 185	Sand, silt, clay; green to gray; glauconitic.	Generally functions as a leaky confining bed. Yields small amounts of water in places for domestic supplies.
		AQUIA AQUIFER	UNNAMED LOWER EOCENE SAND	0 - 90	Sand, fine to medium, green to gray; quartz with abundant glauconite; layers of calcite-cemented sand; abundant shell material.	The primary source of water in the Kent Island area; brackish in some areas. The three formational units generally act as a single aquifer, although there may be local hydraulic separation.
	PALEOCENE		AQUIA FORMATION	0 - 110	Sand, fine to medium, green to gray; quartz with abundant glauconite; layers of calcite-cemented sand; abundant shell material.	
			HORNERSTOWN SAND	55 - 90	Sand, fine to medium, with clay matrix; dark gray to green; quartz with abundant glauconite.	
		LOWER CONFINING BED	BRIGHTSEAT FORMATION	15 - 30	Clay, sandy; dark gray and yellow; glauconitic.	Functions as a confining bed in the Kent Island area.
CRETACEOUS	UPPER CRETACEOUS		SEVERN and MATAWAN FORMATIONS (Undifferentiated)	60 - 85	Clay, sandy; dark gray and dark green; abundant glauconite.	Functions as a nonleaky confining bed in the Kent Island area. Elsewhere on the Eastern Shore, it functions as an aquifer.
		MAGOTHY AQUIFER	MAGOTHY FORMATION	120	Sand, medium to coarse, clay; white to gray, non-glauconitic.	A potential major source of water. High iron content.
	LOWER CRETACEOUS	POTOMAC GROUP AQUIFERS and CONFINING BEDS	POTOMAC GROUP (Includes Patapsco, Arundel and Patuxent Fms.)	2000	Sand, silt and clay, interbedded; red, white, gray.	A potential major source of water. High iron content in upper sands.
PALEOZOIC and PRECAMBRIAN			CRYSTALLINE ROCKS (Basement)	---	Variable types of crystalline rock.	Not considered a source of water.

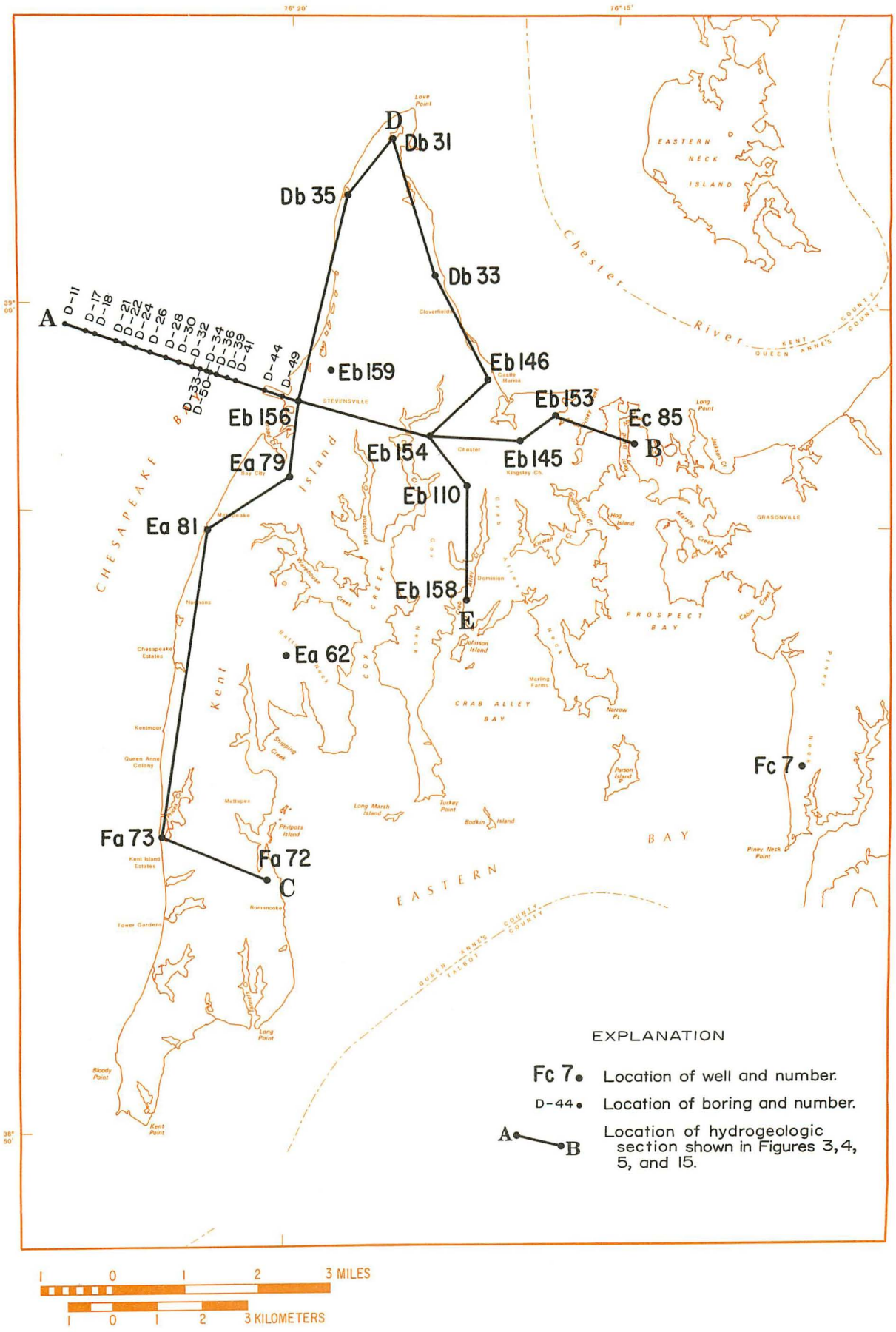


Figure 2. — Locations of hydrogeologic sections.

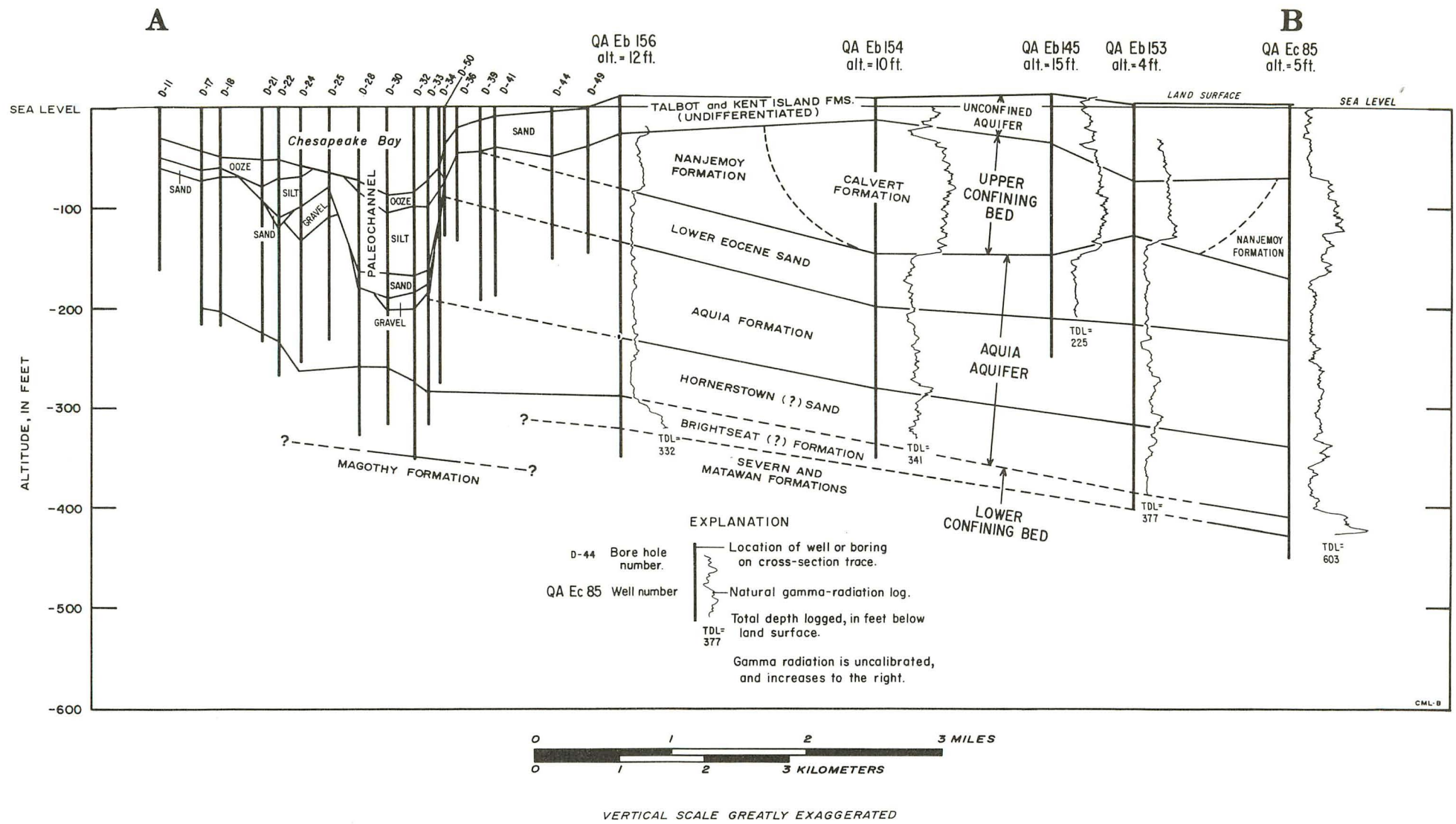


Figure 3. — Hydrogeologic section A-B showing major hydrogeologic units in the Kent Island area based on gamma logs and test borings.

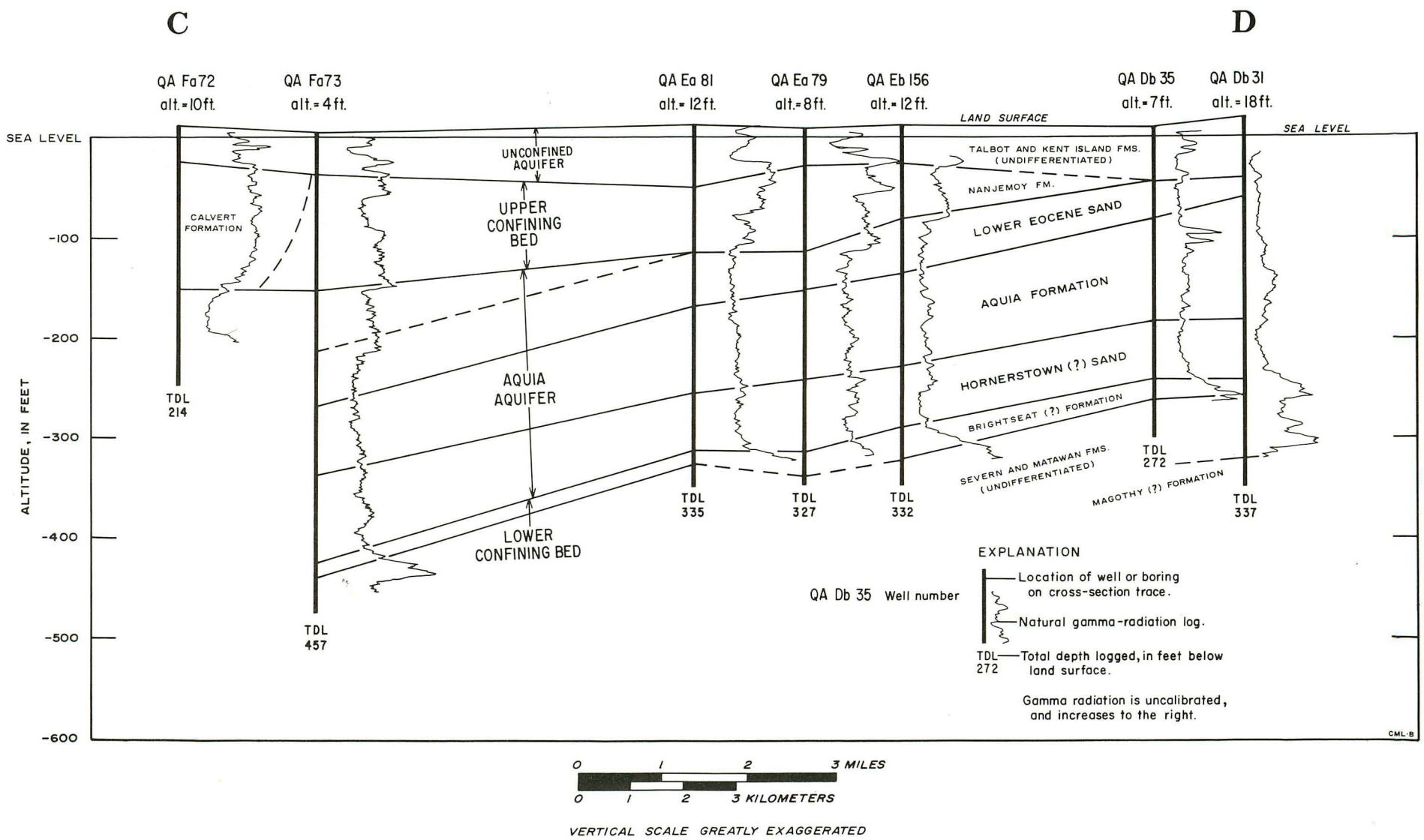


Figure 4. — Hydrogeologic section C-D showing major hydrogeologic units in the Kent Island area based on gamma logs.

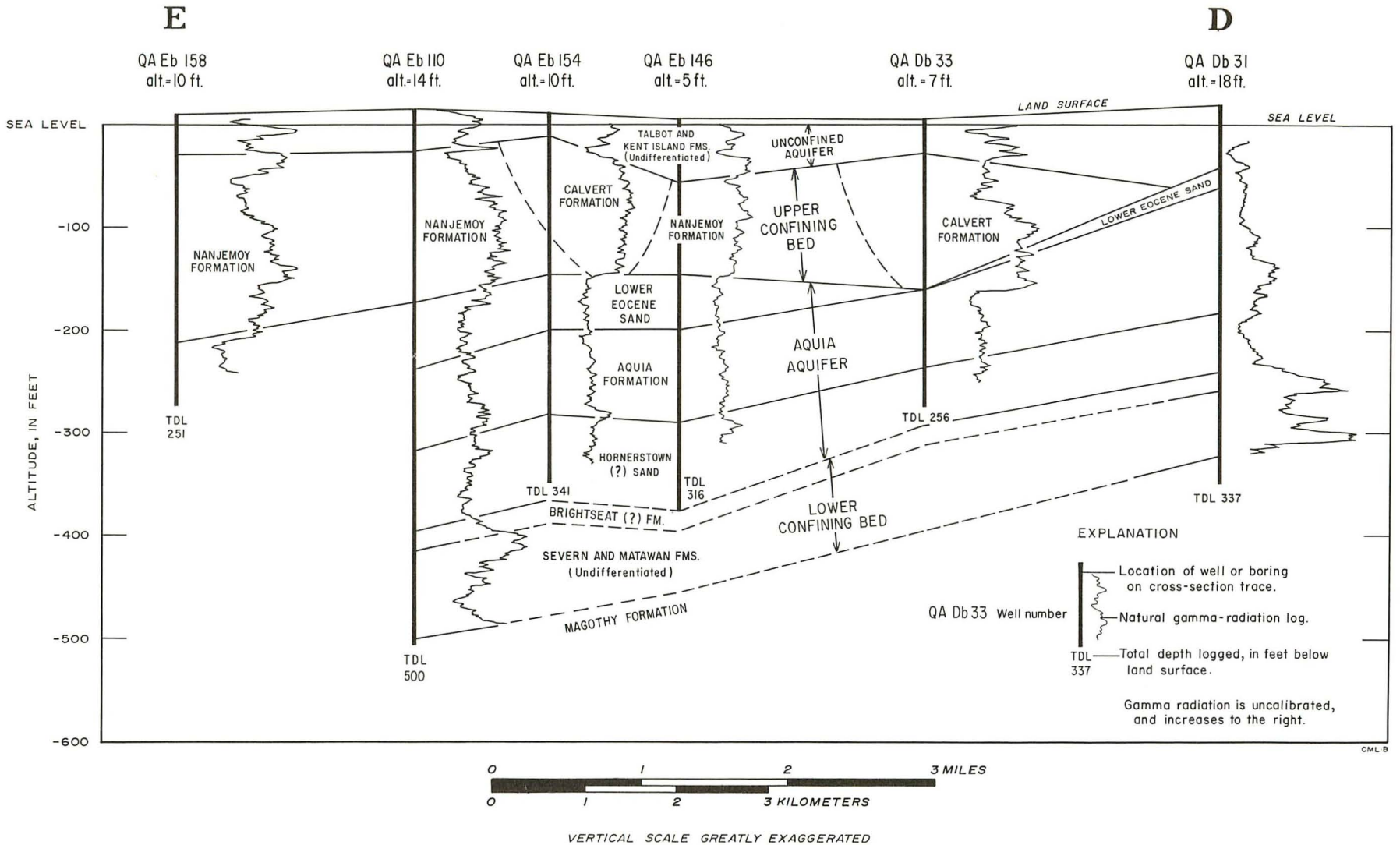


Figure 5. — Hydrogeologic section E-D showing major hydrogeologic units in the Kent Island area based on gamma logs.

of pollen and foraminifera from core samples. The Late Cretaceous age is indicative of the Matawan and Severn Formations or the clayey portions of the Magothy Formation. The Early Paleocene age is indicative of the Brightseat Formation. Because of their similar lithology, the individual formations are generally difficult to differentiate in drill cuttings and geophysical logs, and therefore have been grouped together as the lower confining bed.

The lower confining bed is typically a dark gray (5Y 5/1)[1] sandy clay, commonly mottled with light yellowish-brown (2.5Y 6/4) sandy clay. The sand is fine- to medium-grained quartz, generally clear and colorless, but commonly iron-stained, subangular to subrounded. It contains fine-grained muscovite and rare pyrite. Glauconite is common as fine to medium, greenish-brown to black, botryoidal grains; it is absent in the deeper part of the bed.

There are no data available on the hydraulic properties of the lower confining bed. Coring attempts yielded no suitable samples for laboratory testing. However, visual inspection of core samples indicates that the sediments are relatively impermeable and provide an effective confining bed.

AQUIA AQUIFER

Stratigraphic Relations

For the purpose of this report, the term "Aquia aquifer" is defined as the sandy hydrogeologic unit above the lower confining bed and below the upper confining bed. This designation assigns three stratigraphic units to the Aquia aquifer (in ascending order): the Hornerstown Sand, the Aquia Formation, and the Lower Eocene sand. Although these sands have different ages, they are assumed to act as a single hydraulic unit, at least on a regional scale, and are thus designated a single aquifer.

The Hornerstown Sand is the sandy unit directly overlying the lower confining bed which is distinguishable throughout the study area on geophysical logs. Core material analyzed for pollen and foraminifera yielded an Early Paleocene (Danian) age of the P1B biochronozone[2], consistent with the Hornerstown Sand and Brightseat Formation. Minard (1974) traced the Hornerstown from New Jersey to the Betterton quadrangle in Kent County (fig. 1) in outcrop and determined that it was the approximate age equivalent of the Brightseat Formation in the Round Bay quadrangle in Anne Arundel County (fig. 1) (Minard, 1980). Sediments assigned to the Brightseat Formation may also be present in this unit, possibly at the separation of the Hornerstown Sand and lower confining bed visible on gamma logs.

The Aquia Formation is the middle unit in the Aquia aquifer. It is of Late Paleocene age (Thanetian) of the P4 biochronozone as confirmed by pollen and foraminifera samples taken from cores. Minard (1974) traced the Vincentown Formation from New Jersey to the Betterton quadrangle, and apparently determined that it is equivalent to the Aquia Formation in the Round Bay quadrangle (Minard, 1980). The traditional use of the Aquia Formation designation in Maryland is retained here.

The sediments designated Lower Eocene sand in this report directly overlie the Aquia Formation, and are generally overlain by the Nanjemoy Formation. These sediments were formerly included in the Aquia Formation because of their lithologic similarity and lack of a marker bed separating the two units. However, two cores analyzed for foraminifera assemblages yielded an Early Eocene (Ypresian) age of the P9 biochronozone, equivalent to the Nanjemoy Formation. The Nanjemoy, however, is not reported to contain clean, coarse sands of this nature so the stratigraphic relations remain unclear. For the purposes of this report, the name "Lower Eocene sand" is used when distinguishing it from other sands in the Aquia aquifer.

Extent

The Aquia aquifer subcrops and crops out in a northeast-trending band which goes through Annapolis, Rock Hall, and Chestertown (fig. 1). On the Eastern Shore of Maryland, the Aquia generally subcrops beneath a thin veneer of Pleistocene sediments, but actually crops out as bluffs along the banks of rivers and creeks. It also subcrops beneath the Chesapeake Bay and the mouth of the Chester River. The subcrop area forms a proboscidiform pattern trending southward down the bay where a paleochannel truncates the Aquia either partially or wholly. The Aquia undergoes a facies change from a predominantly sandy unit to a silt-clay unit between Easton and Cambridge, (Hansen, 1974) in a line approximately parallel to the subcrop/outcrop band. This facies change defines the southeastern extent of the Aquia aquifer. The Aquia Formation extends northeast of the study area through Delaware and into New Jersey where it is designated the Vincentown Formation of the Rancocas Group. It extends southwest of the study area through southern Maryland and into Virginia.

Structure-contour maps showing the altitudes of the top and bottom of the Aquia aquifer in the Kent Island area are shown in figures 6 and 7. The top of the Aquia aquifer dips to the southeast at about 25 ft/mi (feet per mile), and the bottom dips to the southeast at about 35 ft/mi. This produces a thickening to the southeast of about 10 ft/mi. The Aquia subcrops beneath the unconfined aquifer at Love Point, and subcrops beneath the Chesapeake Bay along the entire extent of Kent Island.

1/ Color designations are based on the Munsell system (Goddard, 1948) and were made on washed, dry samples.

2/ Designation refers to planktonic foraminiferal biochronozones (see Haq, Hardenbol, and Vail, 1987).

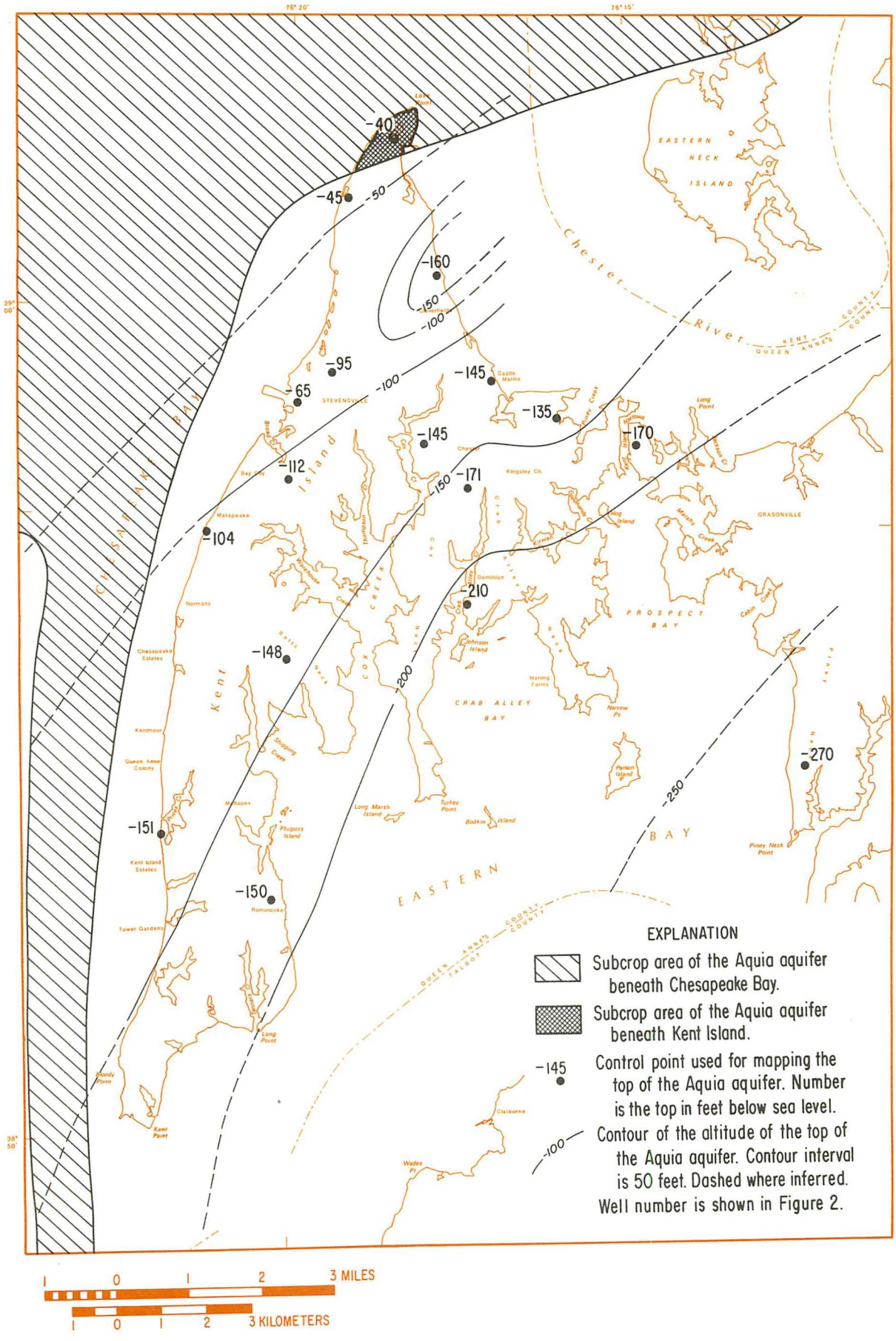


Figure 6. — Altitude of the top and subcrop area of the Aquia aquifer.

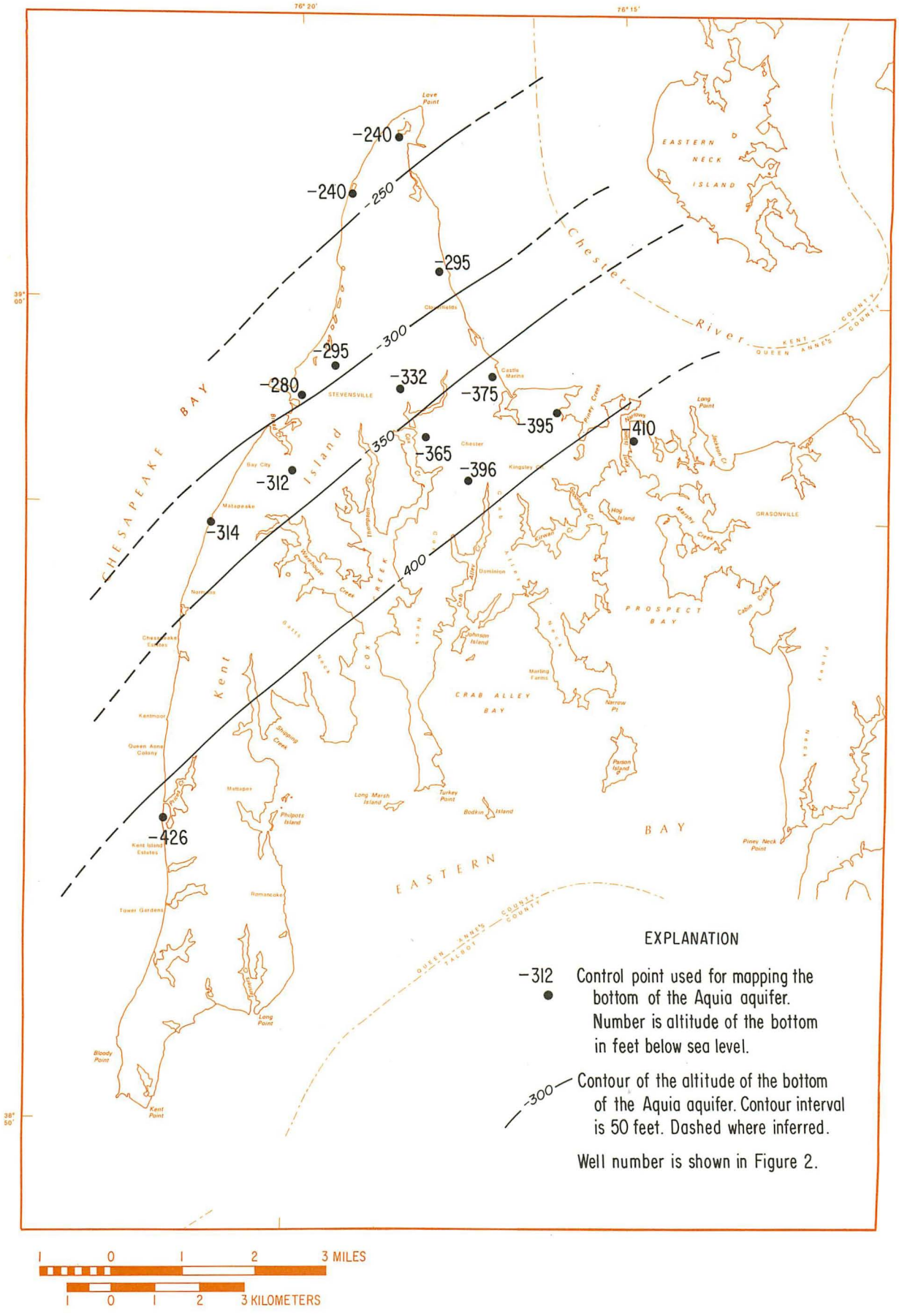


Figure 7. — Altitude of the bottom of the Aquia aquifer.

Lithology

The Aquia aquifer is a fine to coarse glauconitic quartz sand with varying amounts of clay matrix. The unit is generally olive gray (5Y 4/2), but ranges from dark gray (5Y 4/1) where interstitial gray clay is present to a dark yellowish brown (10YR 4/5) where highly weathered.

Glauconite generally constitutes 20 to 30 percent of the sand with some beds containing up to 60 percent. The glauconite occurs as smooth botryoidal grains and rare accordion-shaped grains. It is mostly greenish-black, but ranges in color from pale yellowish-green to yellowish-brown to black.

Shell material is common throughout the Aquia aquifer, generally occurring as fragments less than 0.5 in. across. Clamshell fragments are most common, usually white and commonly partially dissolved. The Hornerstown Sand contains well-rounded light-green and light-gray translucent fragments of calcareous material, possibly punctate brachiopod shell fragments. These fragments, when dissolved with dilute hydrochloric acid, leave insoluble bright green hair-like residues, perpendicular to the shell surface, giving a brush-like appearance. The hairs are probably finely disseminated glauconite infillings of the brachiopod punctae. Foraminifera are sparse throughout the Aquia aquifer, but a bed 20 to 40 ft thick containing abundant foraminifera occurs near the top of the Aquia Formation throughout the study area. This foraminifera assemblage was determined to have a Late Paleocene age of the P4 biochronozone. An assemblage of fossils is present in the Lower Eocene sand, containing bryozoan fragments, echinoid spines, and elongate foraminifera.

Beds of calcite-cemented sand occur throughout the Aquia aquifer. They range from thin (0.1 in.), soft, chalky layers to thick (greater than 15 ft), very hard beds of sandstone which are difficult to drill through. The cement is white in the chalky layers to light brown, gray, and green in the more indurated beds. The beds do not seem to occupy particular stratigraphic positions. Rather, the thick, hard beds generally are present at the top of the aquifer, and the thinner, softer beds are present at various stratigraphic positions deeper in the section indicating the beds are post-depositional features. The beds become harder and more abundant to the southeast. The interstitial cement reduces the porosity and permeability of the sediments, creating local confining beds. These beds may affect the local hydrogeology by allowing the development of vertical-head gradients and by preventing the movement of brackish water.

Hydraulic Properties

The hydraulic properties of the Aquia aquifer are known to differing degrees of accuracy. The properties considered important in this report include transmissivity (or alternatively permeability), storativity (or alternatively matrix compressibility), and porosity. They are discussed briefly here, and more thoroughly in the sections "Simulation of Ground-Water Flow" and "Simulation of Brackish-Water Movement."

Transmissivity is a measure of an aquifer's ability to transmit water. It is an important input for the flow model. Transmissivity distribution of the Aquia aquifer was mapped by Hansen (1972), and scattered values were given by Overbeck and Slaughter (1958). Aquifer tests were run at five test-well sites during this project for which water levels were measured in the pumping well and observation wells. Transmissivities were calculated using the modified Theis nonequilibrium formula, and the results are shown in table 2. The calculated transmissivities show a great deal of variation, even between pumping and recovery tests on the same well. Values range from 200 to 7,800 ft^2/d (feet squared per day) but define no lateral or vertical trend. The variability in test results is perhaps due to partial penetration effects, local aquifer inhomogeneity, tidal fluctuations during aquifer tests, or improper well-construction techniques, such as the inadvertent partial cementation of the screens.

Permeability is related to transmissivity by the equation (Freeze and Cherry, 1979)

$$k = \frac{K\rho g}{\mu} = \frac{T/b\rho g}{\mu} \qquad (1)$$

where

k = permeability $[L^2]$,
K = hydraulic conductivity $[L/T]$,
ρ = fluid density $[M/L^3]$,
g = gravitational constant $[L/T^2]$,
μ = fluid viscosity $[M/L\ T]$,
T = transmissivity $[L^2/T]$, and
b = aquifer thickness $[L]$.

Permeability is a measure of the ability of the aquifer material to transmit a fluid, and is independent of aquifer thickness and fluid properties. Permeability is an important input for the cross-sectional, solute-transport model, and is calculated from equation 1 by entering values for transmissivity and thickness of the aquifer at a particular site.

Storativity is a measure of the amount of water released by an aquifer given a change in head. It is an input to the flow model, but the value used is not critical because the model is not particularly sensitive to this input (see flow model sensitivity analysis). Values for the Aquia aquifer are given by Hansen (1972) and Overbeck and Slaughter (1958) and range from 0.0001 to 0.0004. A value of 0.0002 was chosen to represent the Aquia throughout the study area. Storativity is related to specific storage and matrix compressibility by the equation (Freeze and Cherry, 1979)

Table 2. — Transmissivity values determined from aquifer tests

[ft^2/d = feet squared per day; -- = data not available]

Well number	Transmissivity (ft^2/d)				
	Pumped well		Observation wells		Average
	Pumping	Recovery	Pumping	Recovery	
Sewage Plant Eb 156 Eb 157	2,900	2,700	2,900	2,400	2,700
Matapeake Ea 77 Ea 78 Ea 81	200	600	1,900	--	900
Piney Creek Eb 153 Eb 155	1,300	5,000	3,100	3,200	3,200
Cloverfields Db 34 Db 37	3,200	7,800	2,500	5,700	4,800
Love Point Db 30 Db 32 Db 36	400	1,300	1,900	--	1,200

$$S = S_s b = \rho g b (\alpha + n\beta) \qquad (2)$$

where

S = storativity [unitless],
S_s = specific storage [L^{-1}],
b = aquifer thickness [L],
ρ = matrix density [M/L^3],
g = gravitational constant [L/T^2],
α = matrix compressibility [$L\,T^2/M$],
n = porosity [unitless], and
β = fluid compressibility [$L\,T^2/M$].

Matrix compressibility is an input for the solute-transport model and may be calculated from equation 2.

The effective porosity of a sediment is the ratio of interconnected void volume divided by the total volume. It is a measure of the relative aquifer volume available for storage of interstitial water, and is an input for the solute-transport model. Porosity was calculated from three types of geophysical logs—the neutron, gamma-gamma, and acoustic-velocity logs. Values calculated from neutron logs showed the best agreement with laboratory tests performed on Calvert and Nanjemoy material, and are considered the most reliable. Porosity values obtained in this manner range from 0.25 to 0.35, and a value of 0.30 was chosen for use in the transport model. This value is consistent with the range of values given by Freeze and Cherry (1979) for clayey sands.

Water Levels

Water-level changes over time show the response of an aquifer system to various stresses on the system. Hydrographs are shown in figures 8 and 9 for wells at two different sites. Well QA Eb 113 is located near Chester (fig. 2), about a mile from any large pumping wells or major tidal bodies of water. (All well locations are shown on maps at the end of

the report.) It is screened in the Lower Eocene sand of the Aquia aquifer. Wells QA Ea 77, QA Ea 78, and QA Ea 81 are located near Matapeake (fig. 2) in a cluster about 300 ft from the Chesapeake Bay and about 100 ft from the supply well (QA Ea 4) for the Maryland Natural Resources Police Training Center. Well QA Ea 77 is screened in the Aquia Formation, Ea 81 is in the Hornerstown Sand, and Ea 78, in the Lower Eocene sand. The supply well, QA Ea 4, also is screened in the Lower Eocene sand.

The data in figure 8 span a time interval from May 1980 through June 1986, and show the maximum and minimum water levels for each month taken from continuous water-level recorder charts. Precipitation data from the Wye Research and Education Center (fig. 1) are also shown. Several important trends are displayed. Water levels at well QA Eb 113 show a general decline of about 2 ft during the 7-year interval, or 0.3 ft/yr. The three wells at Matapeake show very slight water-level declines of about 0.2 ft during their 3-year record, or 0.07 ft/yr. Local pumpage is not greater in the vicinity of well QA Eb 113 than the Matapeake cluster, and cannot explain the greater decline at that site. Large pumping centers on the mainland Eastern Shore are somewhat closer to QA Eb 113, but the difference is probably not enough to cause the disparity. The difference in water-level declines is most likely due to the effect of the Chesapeake Bay, which regulates water levels and keeps them near sea level at the Matapeake site. This indicates the bay is a recharge/discharge boundary for the Aquia aquifer.

An annual cyclic trend also is displayed by water levels for well QA Eb 113, which reach a maximum in the spring and a minimum in late summer. This trend is not apparent in the water levels of the Matapeake wells, possibly because their record does not extend back to the years (1982 and 1983) when this trend was strongest. Seasonal water-level trends are sometimes caused by seasonal variations in water use (Weigle and Achmad, 1982), but pumpage on Kent Island is fairly constant throughout the year. The seasonal trend is more likely caused by seasonal fluctuations in evapotranspiration and precipitation. The timing of the water-level peaks correlates generally with lows in the evapotranspiration cycle, and the heights of the water-level peaks correlate generally with the amount of yearly precipitation. The correlation of water levels with evapotranspiration and precipitation suggests that the Aquia aquifer is recharged locally, at least in part, and that there is a hydraulic connection with the unconfined aquifer.

Figure 9 shows hydrographs from observation wells at Chester and Matapeake for December 2-30, 1985. A semidiurnal tidal fluctuation is displayed by the hydrographs, as well as a longer-term barometric fluctuation. The spikes in the data of well QA Ea 78 are caused by the periodic pumping of nearby well QA Ea 4. The amplitude of water-level fluctuations in the wells at Matapeake can be used to qualitatively determine the relative average permeabilities of the sands in which the wells are screened, using the method described by Ferris and others (1962). The tidal efficiency of a well is controlled by the average permeability of the screened sands along with aquifer thickness, storativity, and distance to the tidal water body. Wells QA Ea 77 (screened in the Aquia Formation) and QA Ea 78 (Lower Eocene sand) show equal tidal efficiencies, whereas well QA EA 81 (Hornerstown Sand) shows a tidal efficiency somewhat less, indicating that the Lower Eocene sand and Aquia Formation have about equal permeability, and the Hornerstown Sand has a lower permeability.

The spikes in the water-level data of well QA Ea 78 indicate that water levels are responding to the pumpage stress in well QA Ea 4, and that there is a good lateral hydraulic connection between these wells screened in the Lower Eocene sand. However, these fluctuations are not present in the two wells screened in the deeper units, indicating that the Lower Eocene sand is hydraulically separated from the deeper units, at least locally. The separation could be caused by calcite-cemented layers separating the Lower Eocene sand from the Aquia Formation at that site, or by vertical anisotropy throughout the aquifer. During the 24-hour aquifer test of well QA Ea 77, there was about 1 ft of drawdown in well QA Ea 78, and 0.5 ft of drawdown in well QA Ea 81 (there was 15 ft of drawdown in pumping well QA Ea 77) indicating some vertical hydraulic connection between the individual sands of the Aquia aquifer at this location.

The potentiometric surface of the Aquia aquifer was measured in October 1984 and is shown in figure 10. Heads in the study area range from about 1 ft above sea level on northern Kent Island to about 8 ft below sea level on the mainland Eastern Shore. The low heads are a result of heavy pumpage from the Easton area southeast of the study area, and of distributed domestic pumpage throughout Kent Island. The direction of ground-water flow is perpendicular to the potentiometric contours, generally from northwest to southeast.

UPPER CONFINING BED

The upper confining bed is defined here as the clayey unit above the Aquia aquifer which hydraulically separates the Aquia from the overlying aquifer or water body. It includes the Nanjemoy and Calvert Formations which generally separate the Aquia from the overlying unconfined aquifer and, in places, separate the Aquia from the Piney Point aquifer. The upper confining bed also includes the bay-bottom sediments which, in places, separate the Aquia from the Chesapeake Bay. The upper confining bed does not occur where the Aquia aquifer subareally crops out or subcrops and there is direct contact between the Aquia and the unconfined aquifer (fig. 6).

The Calvert Formation was deposited on an erosional surface which cuts down into the Nanjemoy Formation. All of the Nanjemoy is removed in places and the Calvert

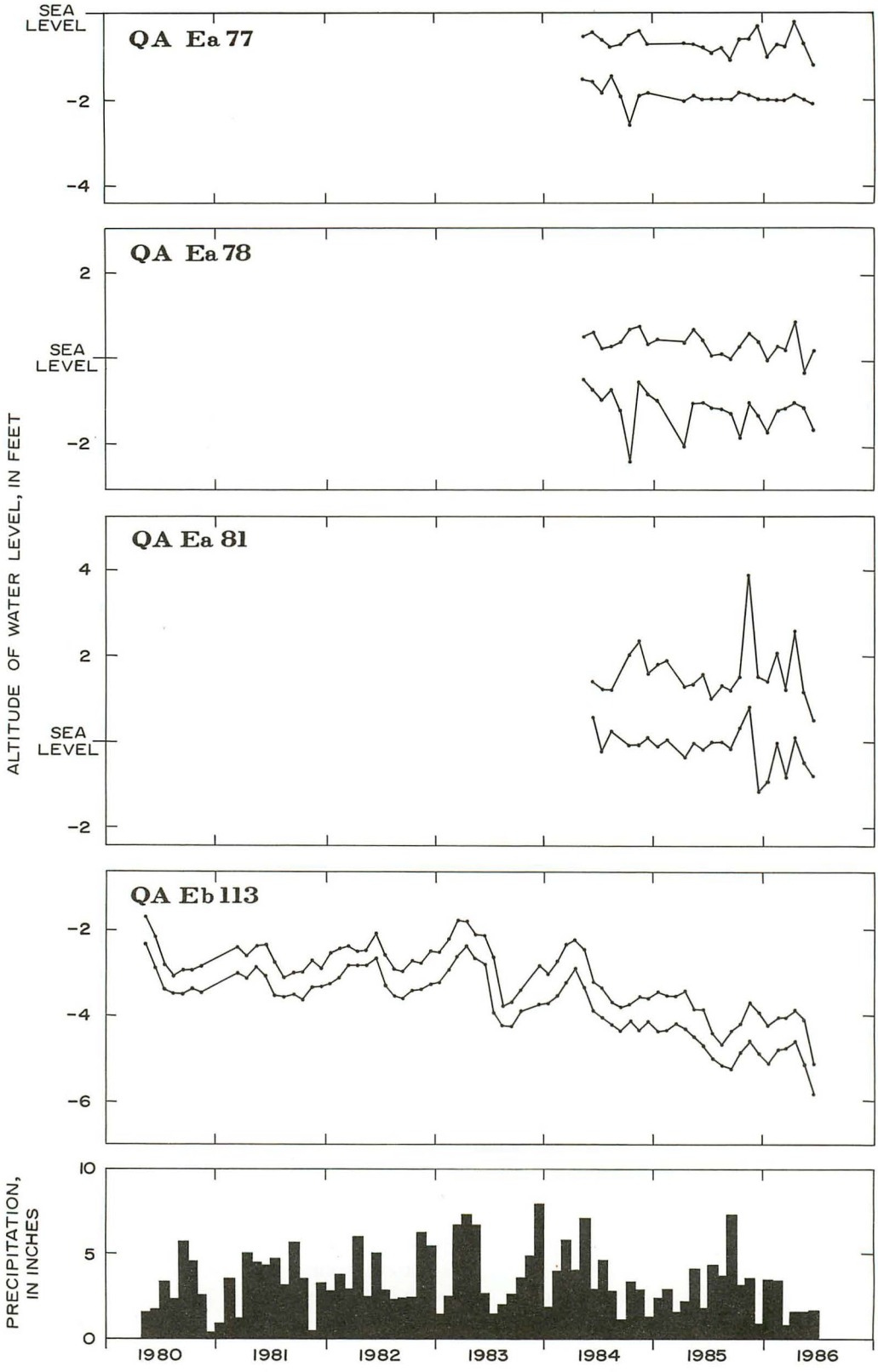


Figure 8. — Monthly maximum and minimum water levels from wells screened in the Aquia aquifer, and precipitation at Wye Research and Education Center.

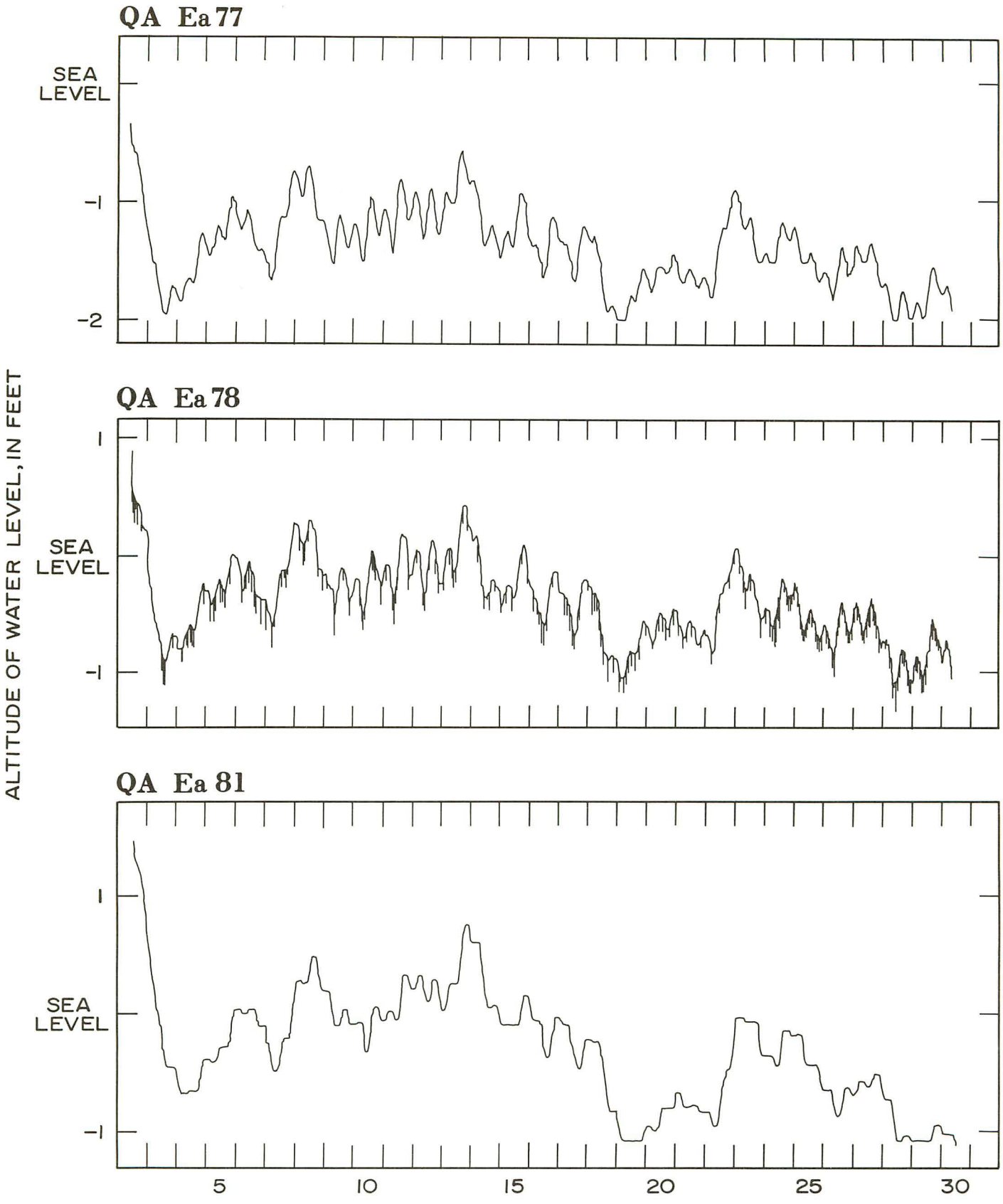


Figure 9. — Water levels in wells screened in the Aquia aquifer, December 2-30, 1985.

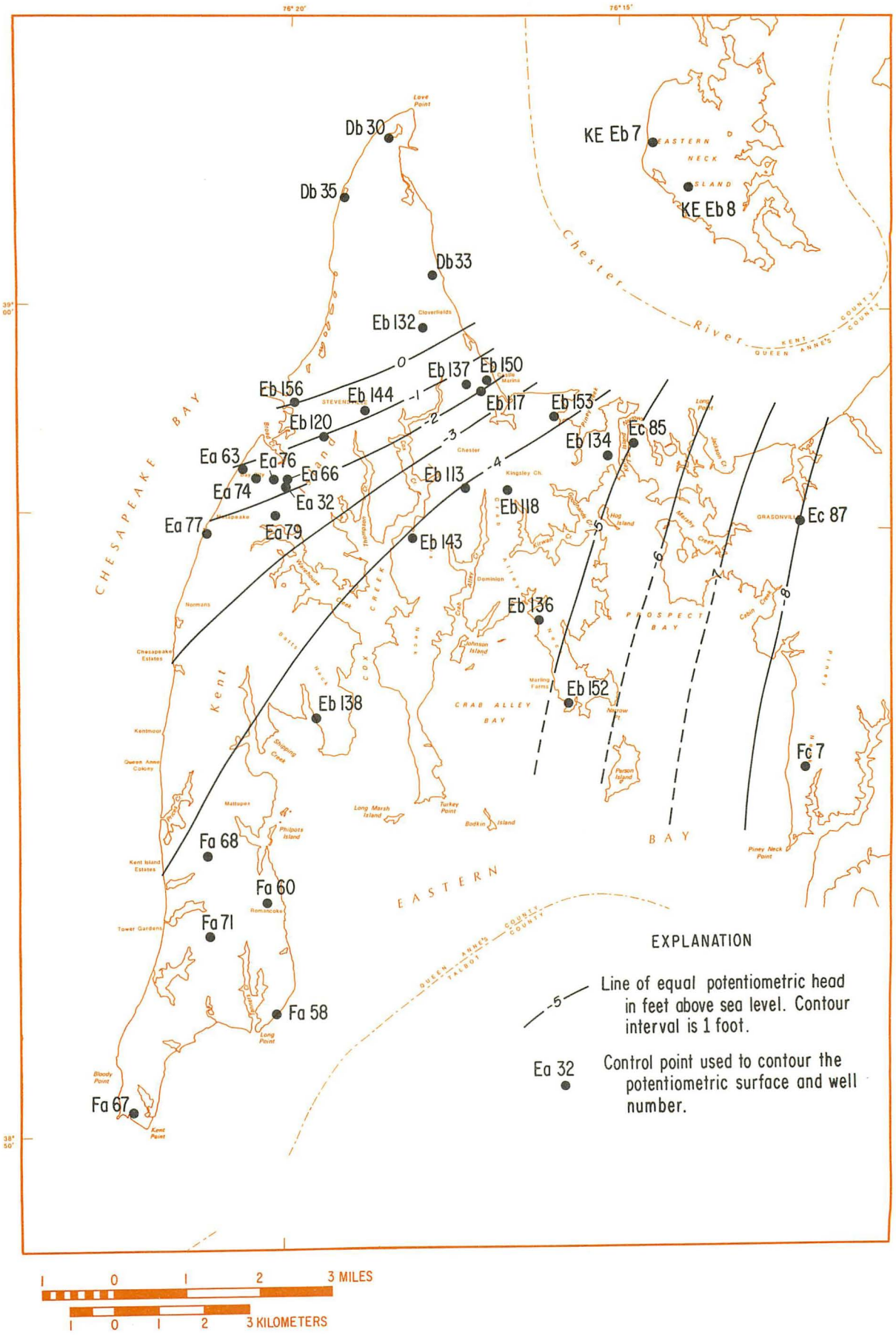


Figure 10. — Potentiometric surface of the Aquia aquifer, October 1984.

directly overlies the Aquia. The erosional surface has a relief of at least 100 ft. It is often difficult to distinguish between sediments of the Calvert and Nanjemoy Formations in drill cuttings because of their similar lithology. This is perhaps due to the reworking of Nanjemoy sediments into the Calvert Formation during deposition.

The Nanjemoy Formation is of Early Eocene age (Ypresian) and shallow marine origin (inner to middle shelf). It is a clayey, glauconitic, fine- to medium-grained quartz sand. It contains varying amounts of interstitial clay which ranges from dark gray to bright green. Beds within the Nanjemoy contain abundant shell fragments, mostly clams, and partially calcite-cemented beds occur near the bottom. Glauconite is abundant (up to 60 percent), and occurs as fine- to medium-grained, medium green to black botryoidal sand grains, and as a finely disseminated constituent of the clay matrix imparting to it a bright green hue.

The Calvert Formation is of Miocene age and generally of estuarine to shallow marine origin. It is a silty, medium-gray clay, and contains sparse grains of quartz sand and gravel, sparse fine glauconite, common muscovite, lignite, and vivianite, and abundant shell material, mostly clams. The base of the Calvert contains a fining-upward series of sediments including coarse gravel to sand to typical Calvert silty clay. This sequence indicates a fluviatile environment early in the deposition of the Calvert.

Laboratory tests were performed on three Shelby-tube core samples from the upper confining bed to determine hydraulic properties, and the results are shown in table 3. Samples from wells QA Eb 153 and QA Db 34 are from the Calvert Formation, and the sample from well QA Ea 78 is from the Nanjemoy Formation. Two subsamples were taken from each core—one oriented horizontally and one oriented vertically—and hydraulic tests were performed on each subsample. The hydraulic properties that were determined include permeability to air, porosity using the Boyles law method with helium, and grain density. Hydraulic conductivity was calculated from permeability. The porosity and density values thus obtained are typical for sediments of this type (Freeze and Cherry, 1979). The permeabilities are considered maximum values because damage may have occurred during coring and handling of the material. Comparison of the horizontal permeability to vertical permeability of each sample indicates they are approximately equal, and that the sediments are fairly isotropic.

PINEY POINT AQUIFER

The Piney Point aquifer does not occur in the Kent Island study area. It pinches out between the Nanjemoy and Calvert Formations just southeast of Kent Island, and extends to the southeast beneath Talbot, Caroline, and Dorchester Counties. In these counties, it is an important aquifer and supplies freshwater for residential and commercial use and for the town of Cambridge. The Piney Point aquifer is a glauconitic quartz sand with abundant shell material and beds of calcite-cemented sand, very fine sand, silt, and clay. A cone of depression has developed in the Piney Point aquifer centered at Cambridge, and was 90 ft below sea level in 1976 (Williams, 1979). This deep cone of depression has established a significant head gradient across

Table 3. — Results of laboratory tests of hydraulic properties for selected cores

[ft = feet; ft^2 = square feet; ft/d = feet per day; lb_m/ft^3 = pound (mass) per cubic foot]

Well number	Depth (ft)	Formation	Orientation	Permeability (ft^2)	Hydraulic conductivity (ft/d)	Porosity (fraction)	Density (lb_m/ft^3)
QA Ea 78	90.6- 91.0	Nanjemoy	Horizontal	3.99×10^{-5}	10.3	0.35	170
QA Ea 78	90.6- 91.0	Nanjemoy	Vertical	3.23×10^{-5}	8.33	.35	169
QA Eb 153	130.6-131.0	Calvert	Horizontal	4.36×10^{-8}	1.12×10^{-2}	.58	164
QA Eb 153	130.6-131.0	Calvert	Vertical	9.14×10^{-9}	2.30×10^{-3}	.59	163
QA Db 34	156.1-156.6	Calvert	Horizontal	5.84×10^{-8}	1.5×10^{-2}	.53	165
QA Db 34	156.1-156.6	Calvert	Vertical	7.54×10^{-8}	2.0×10^{-2}	.51	165

the upper confining bed which separates the Piney Point and Aquia aquifers. Induced leakage from the Aquia to the Piney Point is a significant possibility, and therefore the hydrogeology of the Piney Point must be considered in the analysis of the Aquia. The hydrogeology of the Piney Point aquifer has been discussed in detail by Williams (1979).

PALEOCHANNELS

During the Pleistocene Epoch (about 2,000,000 to 10,000 years before present), there were several periods of worldwide glaciation during which much of the water in the world was frozen in vast ice sheets. This caused a cyclic worldwide fluctuation of sea level. During periods of low sea-level stand, rivers cut deep channels into the existing Coastal Plain sediments in an attempt to reestablish equilibrium with the lowered base level. During the periods between glaciations, the ice melted, sea level rose, and the channels were filled with sediments. These paleochannels influence the hydrogeology of the Coastal Plain aquifer systems, such as the Aquia aquifer in southern Maryland (Chapelle and Drummond, 1983) and the aquifer system in the Potomac Group near Baltimore, Md. (Chapelle, 1985).

The distribution of paleochannels in the Kent Island area has been studied by several workers. Ryan (1953) and Hack (1957) identified a major paleochannel near the shore of Kent Island (fig. 11), approximately following the present course of the Chesapeake Bay. Overbeck and Slaughter (1958) identified a paleochannel in the Chester River near Chestertown from bridge borings. The thickness of channel-fill sediments is reported to be 73 ft, which would place the bottom of the channel at about 80 ft below sea level. Schubel and Zabawa (1972), using marine seismics, identified an older, shallower paleochannel diverging from the present bay channel, going east of Kent Island into the mouth of the Chester River, and crossing into Eastern Bay just west of Kent Narrows (fig. 11). Test well QA Eb 153 was drilled to intercept this channel, but the results were inconclusive. About 120 ft of silty gray clay was encountered above the Aquia, which lithologically could be either the Calvert Formation or Pleistocene channel fill (fig. 3). Core material from 126 ft below sea level at this site yielded a Miocene age (Calvert), and core material from 66 ft below sea level yielded a questionable Pleistocene age. This would presumably put the base of the channel somewhere between 66 and 126 ft below sea level. No sand or gravel sediments were encountered which would confirm the channel-base depth. Drillers' logs and geophysical logs from wells south of site QA Eb 153 do not indicate the presence of this paleochannel. Kerhin, Halka, and Conkwright (1980) used marine seismic techniques to locate the southern extension of the Chester River paleochannel in Eastern Bay, southeast of Kent Island (fig. 11). The paleochannel depth determined by this method is much greater than those reported for other channels (Halka, Maryland Geological Survey, oral commun., 1986). They may have detected deeper Miocene erosional channels.

Because of the fluvial depositional environment of the Pleistocene channel-fill deposits, their lithology is highly variable. A generalized sequence, given by Hack (1957), consists of a fining-upward series of fluvial and estuarine deposits. Coarse fluvial lag gravel occurs at the base of this channel, grading upward into sand, silt, clay, and bay-bottom ooze at the top. This simplified version is complicated at particular locations by portions of the series being repeated or absent.

The hydraulic properties of the channel-fill sediments are not well known because no laboratory or field hydraulic test results are available. Permeability of these sediments can be estimated from lithologic descriptions to within perhaps several orders of magnitude (Freeze and Cherry, 1979). The extremely variable nature of channel-fill sediments makes it difficult to estimate hydraulic properties beyond the area of lithologic control.

UNCONFINED AQUIFER

Kent Island and most of the Eastern Shore are blanketed by deposits of Quaternary age which act as an unconfined or water-table aquifer. The division of these Quaternary deposits into formational units and the theories regarding their depositional environments have changed significantly in the recent past and continue to be debated. A recent study by Owens and Denny (1979) designated the Kent Island Formation as the sand and silt-clay unit, up to 40 ft thick, which covers Kent Island as well as much of the lowland along the western edge of the Chesapeake Bay. Unnamed Quaternary deposits of variable thickness lie below the Kent Island Formation, but above the Tertiary deposits.

The Kent Island Formation consists of a loose, light-colored sand overlying dark clay-silt with gravel scattered throughout. The sand is predominantly quartz with some feldspar and an immature heavy mineral assemblage including pyroxene. The clay fraction is a mixture of many clay types, including kaolinite, illite, illite/smectite, smectite, chlorite, and vermiculite. The unnamed Quaternary deposits below the Kent Island Formation contain beds of silt, clay, sand, local deposits of coarse gravel, and peat.

The unconfined aquifer has historically been used for domestic and small commercial supplies. However, because of its vulnerability to surface contamination and dewatering during droughts, recently constructed wells are seldom completed in these deposits. The Love Point area is one exception, where the Aquia aquifer is brackish throughout its section and the unconfined aquifer is the only freshwater source above the deep Cretaceous aquifers. The hydraulic

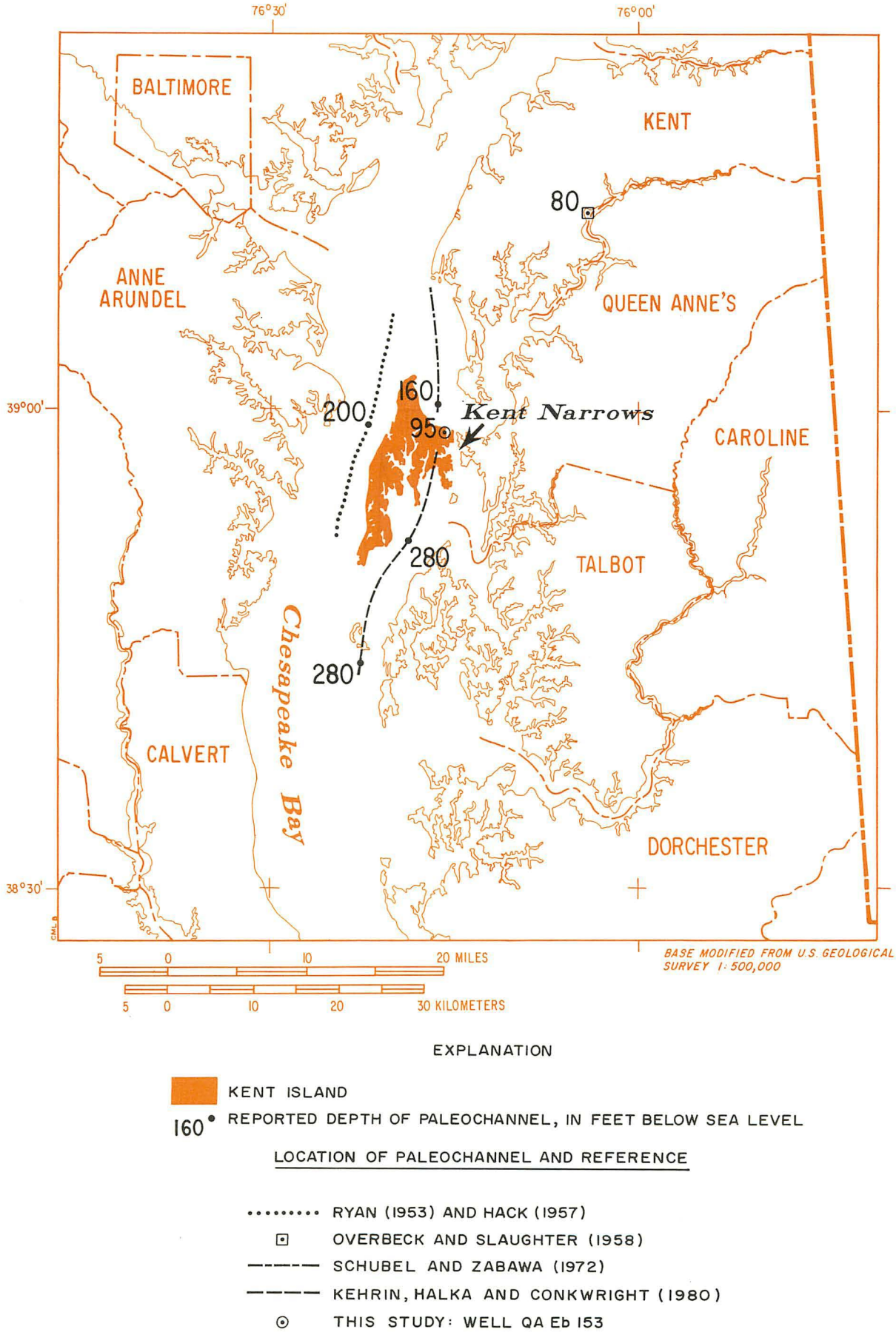


Figure 11. — Locations and reported depths of paleochannels.

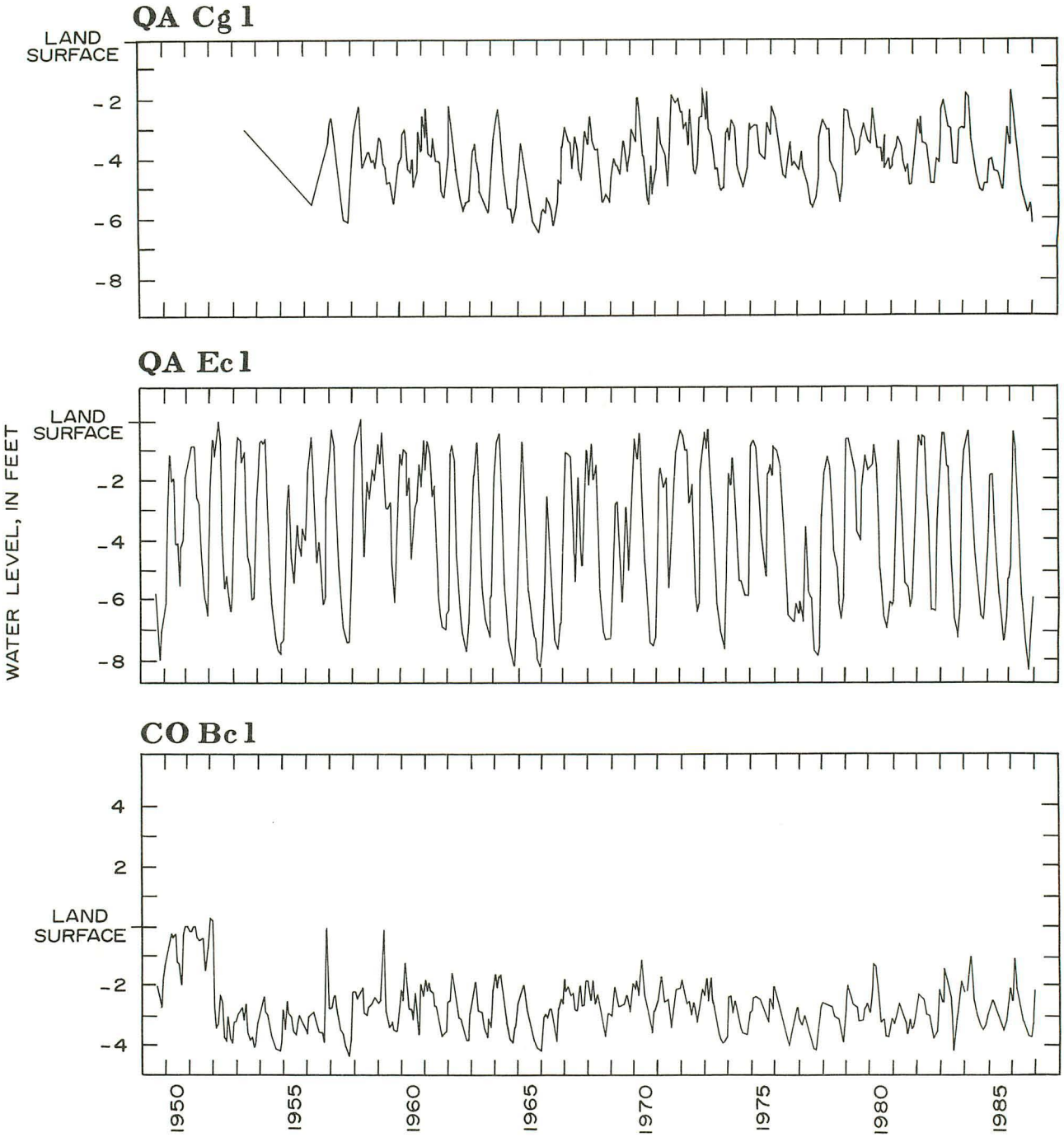


Figure 12. — Water levels in wells screened in the unconfined aquifer.

properties of the unconfined aquifer are not well known in the Kent Island area. Overbeck and Slaughter (1958) report transmissivity values of 800, 900, and 1,700 (gal/d)/ft from pumping tests of wells completed in the Talbot Formation in Cecil County. Although they assign the sediments of the unconfined aquifer in Kent Island to the Talbot Formation, the transferability of these values to the Kent Island area is questionable because of the variability in lithology. There are no hydrographs available for wells in the unconfined aquifer on Kent Island. Water levels in the unconfined aquifer from elsewhere in Queen Anne's and Caroline Counties remain reasonably constant over the long term. Figure 12 shows hydrographs from observation wells QA Cg 1, QA Ec 1, and CO Bc 1 located on the Eastern Shore

(fig. 1). Although there is a distinctive annual cyclic fluctuation in water levels caused by precipitation and evapotranspiration fluctuations, average yearly water levels in the unconfined aquifer have remained fairly constant during the period of available record. A similar trend probably exists throughout most of the Kent Island study area. A possible exception is the Love Point area where the unconfined aquifer is rather heavily pumped and where it is in direct contact with the Aquia aquifer. At this location, some water-level declines can be expected.

REGIONAL FLOW SYSTEM IN THE AQUIA AQUIFER

The Aquia aquifer forms a flow system in which it gains water at its recharge zones, transmits water throughout its extent, and loses water at its discharge zones (fig. 13). Potential recharge and discharge zones include the subareal outcrop/subcrop area, leakage through the upper and lower confining beds, and the subcrop area beneath the Chesapeake Bay. Whether one of these sites acts as a recharge or discharge zone depends on the relative water pressures in the Aquia and the zone at that point. If the water pressure is greater in the zone than in the Aquia, the site will act as a recharge zone, and vice versa. Pumpage from the Aquia also is considered a form of discharge.

Subareal Outcrop/Subcrop Area

The Aquia aquifer probably receives some recharge through the subareal outcrop/subcrop area. Water can enter the Aquia directly where its sands are exposed, or through the overlying sediments where the Aquia is overlain by the unconfined aquifer. However, the subareal outcrop/subcrop area probably acts primarily as a discharge zone. The Aquia is exposed only along the steep banks of tidal creeks and the Chester River. The low elevation of these exposures relative to the local water table most likely causes them to be discharge areas.

Leakage

Leakage through the upper confining bed is considered the major source of recharge to the Aquia aquifer. The high elevation of the water table relative to water levels in the Aquia creates a head gradient downward into the Aquia of as much as 40 ft in the northern part of Queen Anne's County. The Calvert and Nanjemoy Formations, which comprise the upper confining bed, are considered leaky confining beds and will transmit water under a sufficient pressure gradient. The large surface area over which downward leakage occurs makes this the major source of recharge to the Aquia.

Discharge from the Aquia upward through the upper confining bed occurs where water pressure is lower in the directly overlying aquifer. This occurs in the Cambridge area where the Piney Point aquifer, which directly overlies the upper confining bed there, is heavily pumped and a cone of depression 90 ft below sea level developed by 1976 (Williams, 1979). However, upward leakage during prepumping conditions was probably minimal due to the lack of an upward head gradient.

Leakage through the lower confining bed is not considered a major source of recharge or discharge for the Aquia aquifer. The low permeability of the lower confining bed and lack of substantial pressure gradient throughout most of the study area make it unlikely to transmit much water; the exception is the Easton area where substantial pumpage from the aquifers underlying the lower confining bed has created a cone of depression in those aquifers and a consequent pressure gradient across the confining bed. Therefore, this area is one of discharge for the Aquia during pumping conditions.

Subcrop Beneath the Chesapeake Bay

The subcrop of the Aquia aquifer beneath the Chesapeake Bay is an important zone for recharge and discharge. In bay subcrop areas where the freshwater head in the Aquia exceeds the equivalent freshwater head of brackish bay water, freshwater will discharge into the bay. In bay subcrop areas where the freshwater head in the Aquia is less than the equivalent freshwater head of the bay water, brackish water will enter the Aquia as recharge. Before substantial pumpage from the Aquia began, water pressures in the Aquia probably exceeded those in the bay everywhere, and the entire Aquia subcrop beneath the bay was a discharge zone. However, since major Aquia pumpage began, Aquia heads have dropped below the equivalent freshwater head of the bay water in some areas of the bay subcrop (fig. 10), and these areas have become recharge zones for brackish water.

Pumpage

Pumpage from the Aquia aquifer is a form of discharge. It is estimated that in 1980, Aquia domestic pumpage on Kent Island was about 103,000 ft^3/d (cubic feet per day) (Troxell, 1983) and Aquia commercial and industrial pumpage throughout the Eastern Shore was about 147,000 ft^3/d (Wheeler and Wilde, U.S. Geological Survey, written commun., 1987). A major cone of depression has formed in the Easton area which extends northwest to the Kent Island area; the center of the cone was about 50 ft below sea level in 1984. Pumpage on Kent Island, which is predominantly domestic and somewhat evenly distributed, has contributed to the regional lowering of water levels in the Aquia.

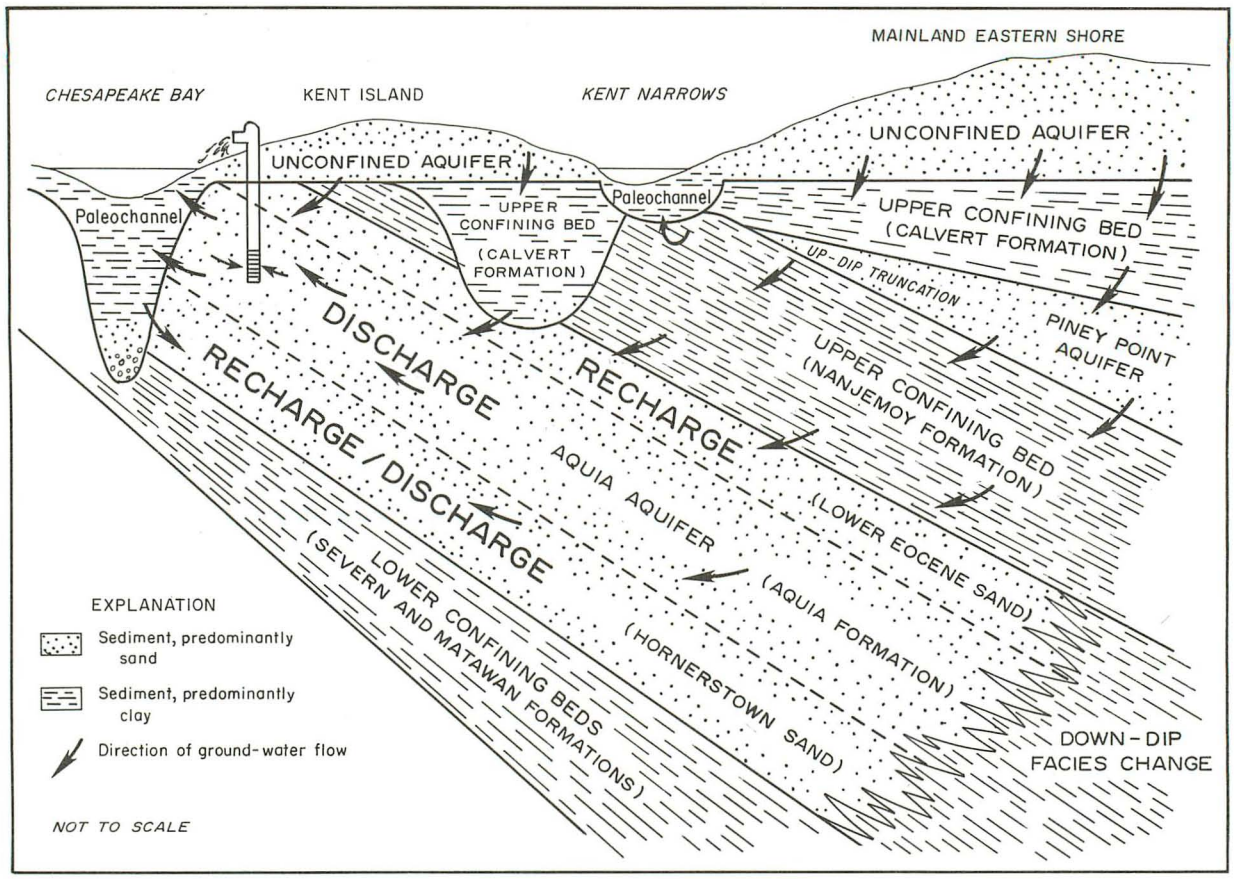


Figure 13. — Conceptual model of the flow system in the Aquia aquifer.

Flow Reversal

A major change of flow direction has occurred in the Aquia aquifer since major pumpage from the Aquia began. During prepumping conditions, water entered the Aquia mainly through the upper confining bed in the areas of high elevation, flowed southward and westward toward the bay, and discharged into the bay through the subcrop area. During present pumping conditions, the Aquia is still being recharged primarily through the upper confining layer, but flow is now predominantly southward and eastward toward the major pumping centers on the mainland Eastern Shore. The Aquia subcrop beneath the bay has become a recharge zone for brackish water.

BRACKISH-WATER OCCURRENCE

DISTRIBUTION

The distribution of brackish water in the Aquia aquifer was determined by sampling about 75 domestic, commercial, and test wells and analyzing the water for chloride concentration and specific conductance, and by obtaining borehole resistivity logs from uncased test wells. The areal distribution of chloride in 1983-84 is shown in figure 14. Due to vertical variations in chloride concentrations, there are several values available at some sites, and only the highest value at each site was used to determine chloride zones. Thus, the zones show the approximate maximum landward extent of those chloride concentrations. In general, brackish water occurs along the entire shore of the Chesapeake Bay. The 10-mg/L zone swings inland at both the northern and southern tips of the island. The 1,000-mg/L zone hugs the bay shore, staying within 0.25 mi of the shore at all locations and extending north to Love Point and south to at least as far as Prices Creek. Although no water samples were collected with chloride concentrations above

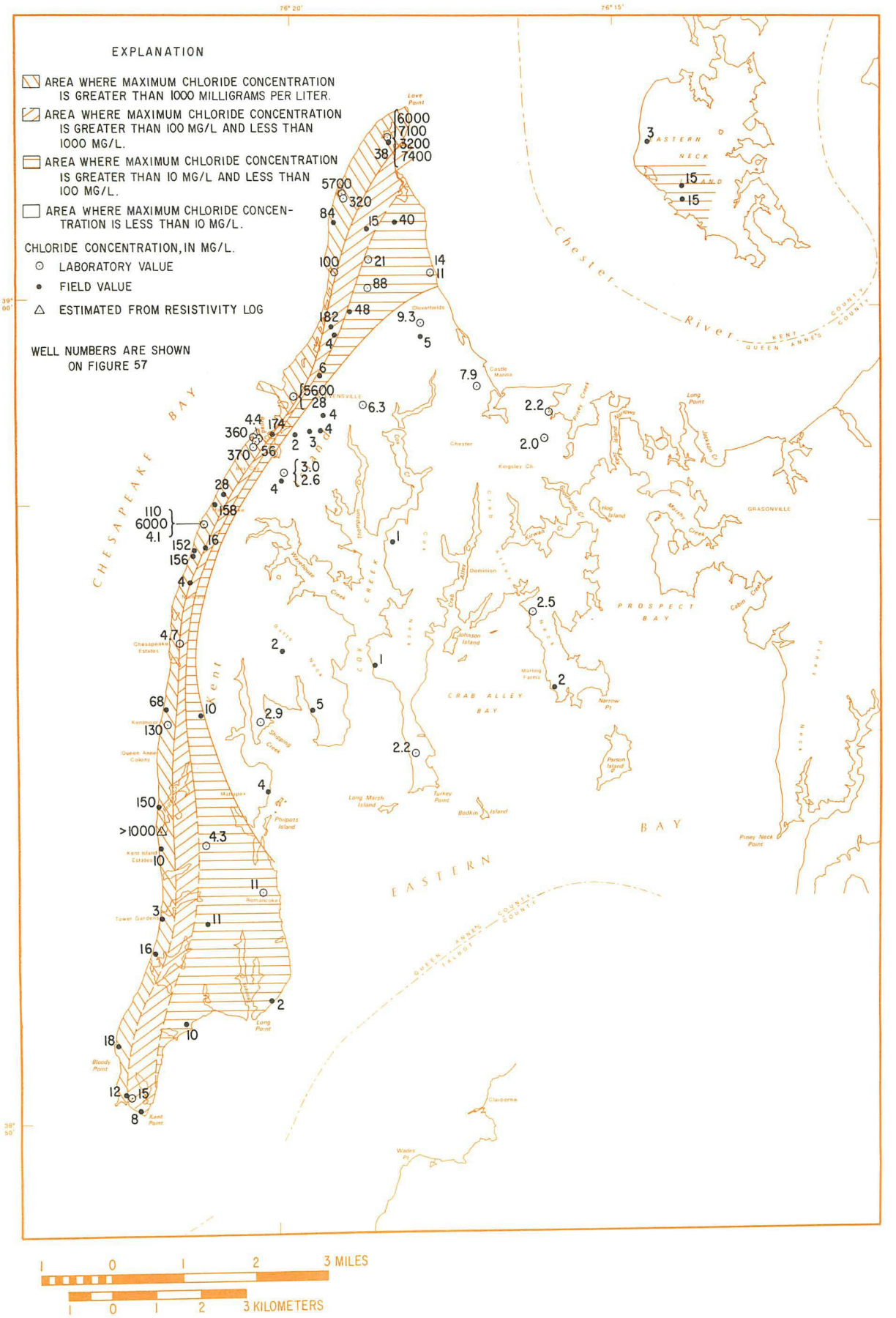


Figure 14. — Areal distribution of chloride in the Aquia aquifer, 1983-84.

1,000 mg/L south of Matapeake, the low resistivity recorded on the electrical-resistivity log from the test boring from well QA Fa 73 at Prices Creek indicates chloride concentrations in this range in the deeper part of the aquifer.

The vertical distribution of brackish water in the Aquia aquifer is shown in the cross section in figure 15. Brackish water can be identified in the resistivity logs by low formation resistivity in sandy sections. The high ionic concentrations of brackish water makes it more electrically conductive than freshwater, and less resistive. Sandy sections containing brackish interstitial water, therefore, produce resistivity responses near zero, as opposed to high resistivity responses of fresh sandy sections. In all wells within 0.25 mi of the Chesapeake Bay shore, water in the lower part of the Aquia is brackish, whereas the upper part is freshwater. In well QA Ea 79 (fig. 2), farther from the bay shore, the entire section of the Aquia contains freshwater. At the Matapeake test-well site (QA Ea 81), the bottom of the Aquia is only slightly brackish, with a measured chloride concentration of 110 mg/L.

CHANGES WITH TIME

Historical data on chloride concentration in the Aquia aquifer are scarce, making it difficult to determine movement of brackish water through the aquifer. Three wells were sampled in 1954 (Overbeck and Slaughter, 1958), two of which were located and resampled in 1983 (QA Db 10 and QA Ea 10). These wells had chloride concentrations of 80 and 3.1 mg/L in 1954 (table 9a). Although both of these wells are located near the freshwater/brackish-water interface and might be expected to contain higher chloride concentrations after the 29-year interval, neither well showed a significant increase. Another well, QA Ea 4, supplied water for the ferry at Matapeake during the early 1940's and was periodically sampled for chloride. As shown in figure 16, chloride concentration increased during the first 2 years of pumping, reaching a maximum chloride concentration of 150 mg/L in early 1942. Chloride concentration then decreased through 1942, and increased through 1943-45 when sampling was discontinued in May 1945. This well was resampled in 1983 and was found to have a chloride concentration of 136 mg/L, approximately the concentration of the mid-1940's. No pumpage data are available for this well.

A resampling program was undertaken to determine if chloride concentrations are changing with time. A total of 32 wells sampled in 1982 and 1983 were resampled in late 1985 and early 1986. Chloride concentrations and specific conductance values for the wells are shown in table 4. The chloride concentrations of some wells increased while others decreased, and the mean value increased from 101.35 to 104.54 mg/L. A statistical analysis was run on the data in which a T-test for paired data was calculated. The test showed that within the area sampled, chloride values increased during the time interval with an 85-percent confidence level. Statistically, this is not a very high confidence level and a clear trend is not demonstrated. The lack of a clear trend may be attributable to the relatively short time interval between samples, or to short-term variations caused by upconing and localized pumpage changes. It should also be noted that only domestic and commercial wells which had relatively low chloride concentrations (less than 600 mg/L) were resampled. No wells in the high range of chloride values were available for this test.

SOURCE

The source of brackish water in the Aquia aquifer is indicated by its distribution. The proximity of brackish water in the Aquia to the Chesapeake Bay and its limited landward extent strongly suggest that it has infiltrated into the Aquia from the bay. Other possible sources such as road salt and landfill leachate would create contamination plumes localized to those sources and would not develop the vertical zonation present in the Aquia.

In the analysis of occurrence and movement of brackish water in the Aquia, a value of chloride concentration was chosen to represent infiltrating bay water. Although concentrations vary areally and vertically throughout the bay and through time, they average out to a fairly constant value over the long term at a specific location. Webb and Heidel (1970) reported specific conductance values near the Chesapeake Bay Bridge from 1950 to 1969 to be between 9,000 and 30,000 μS/cm (microsiemens per centimeter at 25 degrees Celsius), which convert to 3,000 and 15,000 mg/L (milligrams per liter) chloride and average about 9,000 mg/L. Dispersion processes mix water parcels of different concentrations, which produces a final infiltrating water of fairly constant chloride concentration. Bricker, Matisoff, and Holdren (1977) analyzed the interstitial water from bay sediment cores collected near Kent Island. Figure 17 shows the chloride concentrations as a function of depth for four of those cores. Chloride concentrations differ widely in the top foot below the sediment surface, but consistently approach a value of about 10,500 mg/L below that. A value of 10,500 mg/L was chosen to represent infiltrating bay water.

HYDROGEOLOGIC CONTROLS

The distribution and movement of brackish water in the aquifer system are determined by hydrogeologic controls, the importance of which vary with location and time. The potentially important controls that have been identified are density-dependent flow, water pressures in the Aquia aquifer, and permeability variations, including calcite-

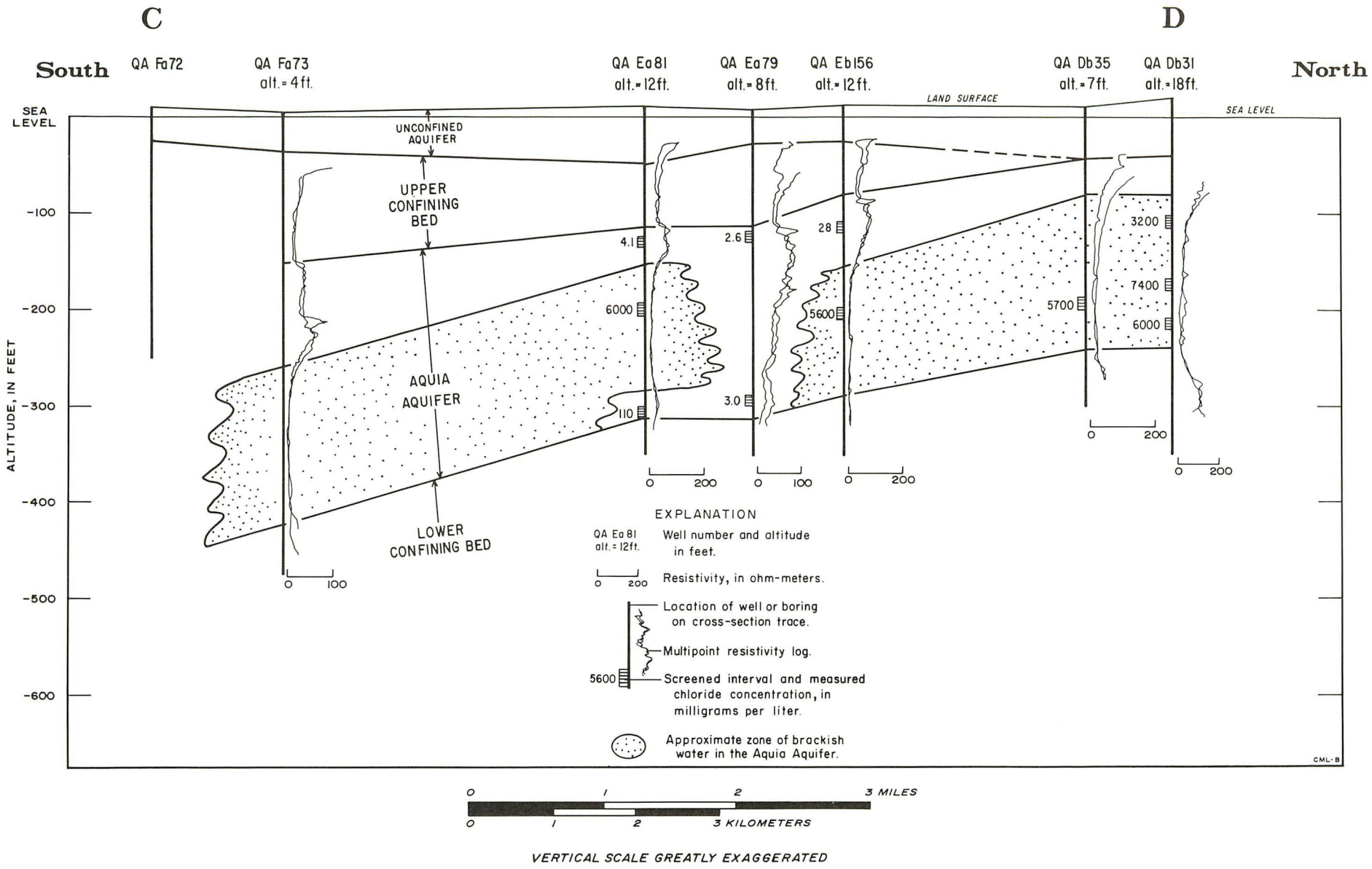


Figure 15. — Hydrogeologic section C-D showing multipoint resistivity logs, chloride concentrations, and zone of brackish water.

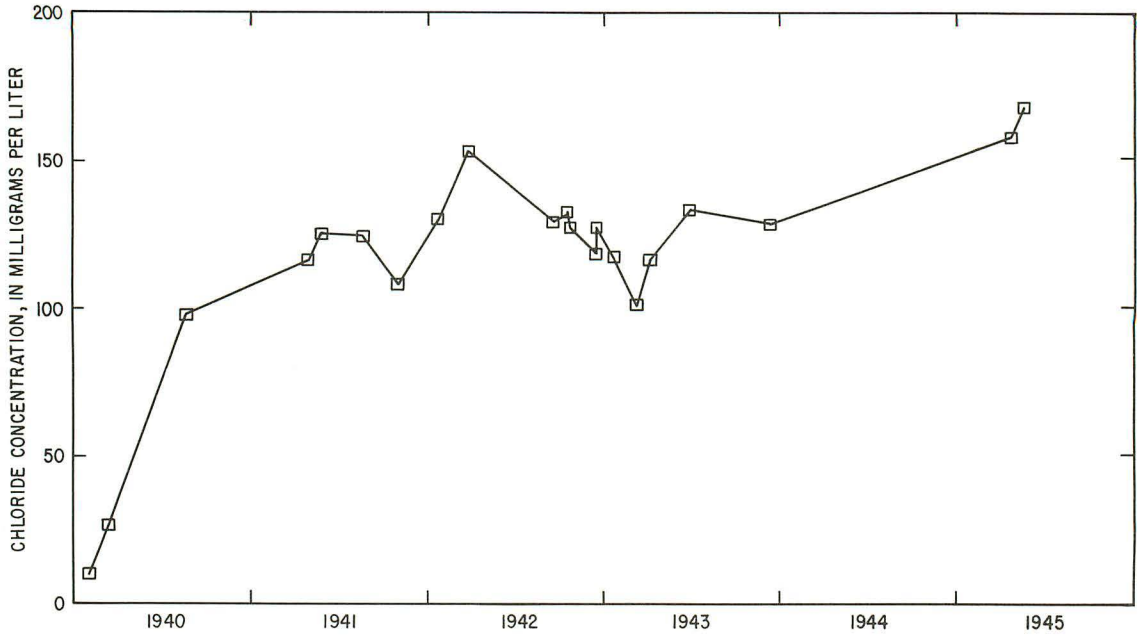


Figure 16. — Chloride concentrations at well QA Ea 4.

cemented layers, paleochannel sediments, and the type of upper confining bed. In order to understand the distribution and evaluate potential movement of brackish water in the Aquia, it is necessary to first understand the hydrogeologic controls and their relative importance in the aquifer system. Figure 18 is a schematic cross section of the Aquia aquifer, showing the relevant geologic units and the hydrogeologic controls. These controls are described in this section of the report and are examined quantitatively in the section titled "Simulation of Brackish-Water Movement."

Density-Dependent Flow

Water with high dissolved-solids content is denser than freshwater and will tend to sink below the freshwater, commonly forming a wedge-shaped interface (fig. 18). This is a common occurrence along oceanic coastlines where saltwater wedges typically occur in deep coastal aquifers. Brackish water in the Chesapeake Bay does not have as high a dissolved-solids content as that of sea water (it is about half that of sea water at Kent Island), but is significantly higher than fresh ground water in the Aquia aquifer. For this reason, brackish water underlies freshwater even though its source is near the surface.

The position of the interface between fresh and brackish water can be estimated using the Ghyben-Herzberg relation (Freeze and Cherry, 1979),

$$Z_s = \frac{\rho_f}{\rho_b - \rho_f} Z_w, \qquad (3)$$

where

Z_s = depth to interface below sea level [L],
Z_w = height of water table above sea level [L],
ρ_f = density of freshwater [M/L^3], and
ρ_b = density of brackish water [M/L^3].

Assuming $\rho_f = 1.000$ and $\rho_b = 1.0125$,

$$Z_s = 80\ Z_w \qquad (4)$$

For instance, if the bottom of the Aquia aquifer is 300 ft below sea level, then the landward extent of the interface would occur at the bottom of the aquifer where the water table is 3.75 ft above sea level.

This approach is severely limited by several assumptions. The first assumption is that water pressures in the aquifer are identical to those in the water table. This is not generally valid in the Kent Island area where the upper confining bed separates the Aquia aquifer from the unconfined aquifer and water pressures in the Aquia can vary independently of those in the water table. The second assumption is that there is no mixing (dispersion) of brackish and freshwater at the interface. This is not valid in the Aquia, where a wide range of chloride concentrations occur. The third assumption is that the aquifer system is homogeneous and isotropic. Although there is no evidence of anisotropy in the Aquia aquifer, there are permeability variations of about seven orders of magnitude. These per-

Table 4. — Chloride concentrations and specific conductance values for resampled wells

[mg/L as Cl = milligrams per liter as chloride; μS/cm = microsiemens per centimeter at 25 degrees Celsius]

Well number	Date	Chloride, dissolved (mg/L as Cl)	Specific conductance (μS/cm)	Date	Chloride, dissolved (mg/L as Cl)	Specific conductance (μS/cm)
QA Db 10	08-16-83	88	1,060	02-12-86	16	513
QA Db 13	01-25-82	40	385	02-18-86	47	455
QA Db 14	01-25-82	14	241	02-12-86	14	460
QA Db 17	04-27-83	72	431	01-12-86	63	626
QA Db 19	04-27-83	374	1,550	02-12-86	350	1,470
QA Db 23	07-06-83	21	457	02-12-86	18	459
QA Db 25	07-06-83	66	352	02-12-86	110	535
QA Db 27	07-14-83	320	1,430	02-12-86	310	1,420
QA Ea 10	09-06-83	5.3	308	08-19-85	4.9	312
QA Ea 36	07-05-83	560	2,090	08-19-85	570	2,010
QA Ea 37	07-05-83	4.4	312	08-19-85	4.3	290
QA Ea 39	06-14-83	11	370	08-19-85	16	386
QA Ea 42	04-06-83	35	376	08-19-85	34	443
QA Ea 43	04-29-83	16	375	10-15-85	18	379
QA Ea 45	08-17-83	4.7	353	10-15-85	4.5	350
QA Ea 48	05-19-83	174	890	10-15-85	190	892
QA Ea 50	05-19-83	1.2	360	10-15-85	3.8	352
QA Ea 52	05-25-83	115	680	10-15-85	140	712
QA Ea 53	05-25-83	7	326	02-18-86	14	331
QA Ea 55	06-14-83	7.8	340	10-15-85	11	344
QA Ea 57	06-14-83	152	780	10-15-85	170	853
QA Ea 59	06-15-83	68	548	10-15-85	68	523
QA Ea 60	08-18-83	190	870	10-15-85	200	928
QA Ea 61	09-06-83	370	1,530	10-15-85	430	1,640
QA Ea 71	08-03-83	40	377	10-15-85	35	447
QA Eb 121	05-19-83	2.5	375	02-18-86	3.5	373
QA Eb 123	04-26-83	4.4	221	03-04-86	11	379
QA Eb 124	04-27-83	4.3	302	03-04-86	4.0	370
QA Eb 126	04-28-83	200	802	03-06-86	220	1,010
QA Eb 127	04-28-83	4.9	269	03-04-86	4.8	361
QA Fa 49	06-02-83	150	880	02-12-86	120	801
QA Fa 64	07-07-83	130	718	02-18-86	140	736
Mean		101.35			104.54	

meability variations are exhibited by the upper confining bed, calcite-cemented layers in the Aquia aquifer, and paleochannel sediments. Because of these invalid assumptions, a more rigorous method of estimating the behavior of brackish water is required which can accommodate these other controls.

Water Pressure

Water pressures at various points in the Aquia aquifer system will, to a large extent, determine flow direction and velocity of water through the system (fig. 18). Water pressures at the bottom of the bay and at the water table remain fairly constant. Water pressure in the Aquia aquifer at the right boundary of the diagram is variable and is determined by influences external to the diagram, such as pumpage, recharge rate, and deep discharge.

The position of the brackish-water interface is partially determined by water pressure in the Aquia. During prepumping conditions, water pressure in the Aquia was higher than in the bay and freshwater flowed toward the bay, discharging near the shore. The flow system achieved a state

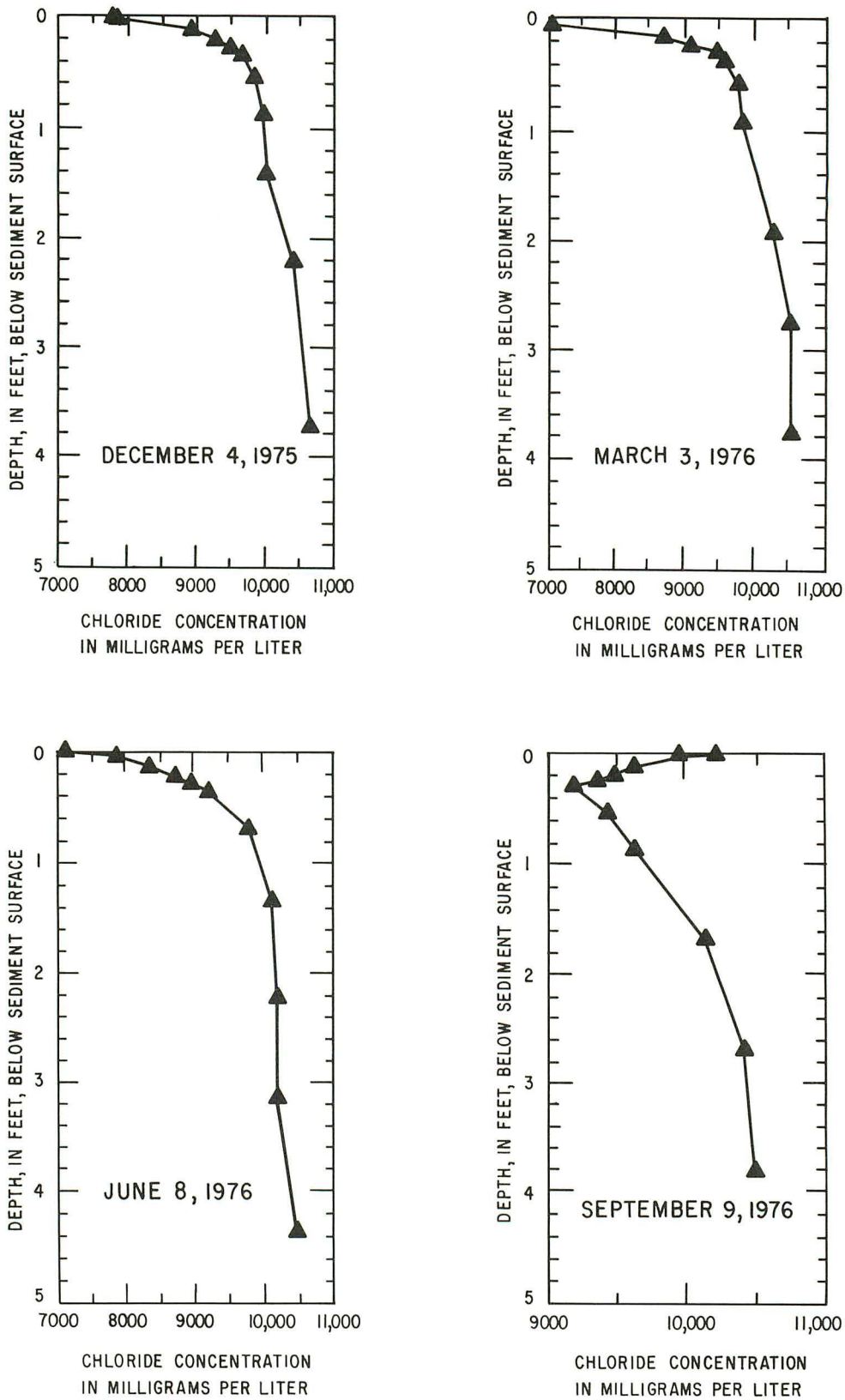


Figure 17. — Vertical distribution of chloride in Chesapeake Bay sediments.

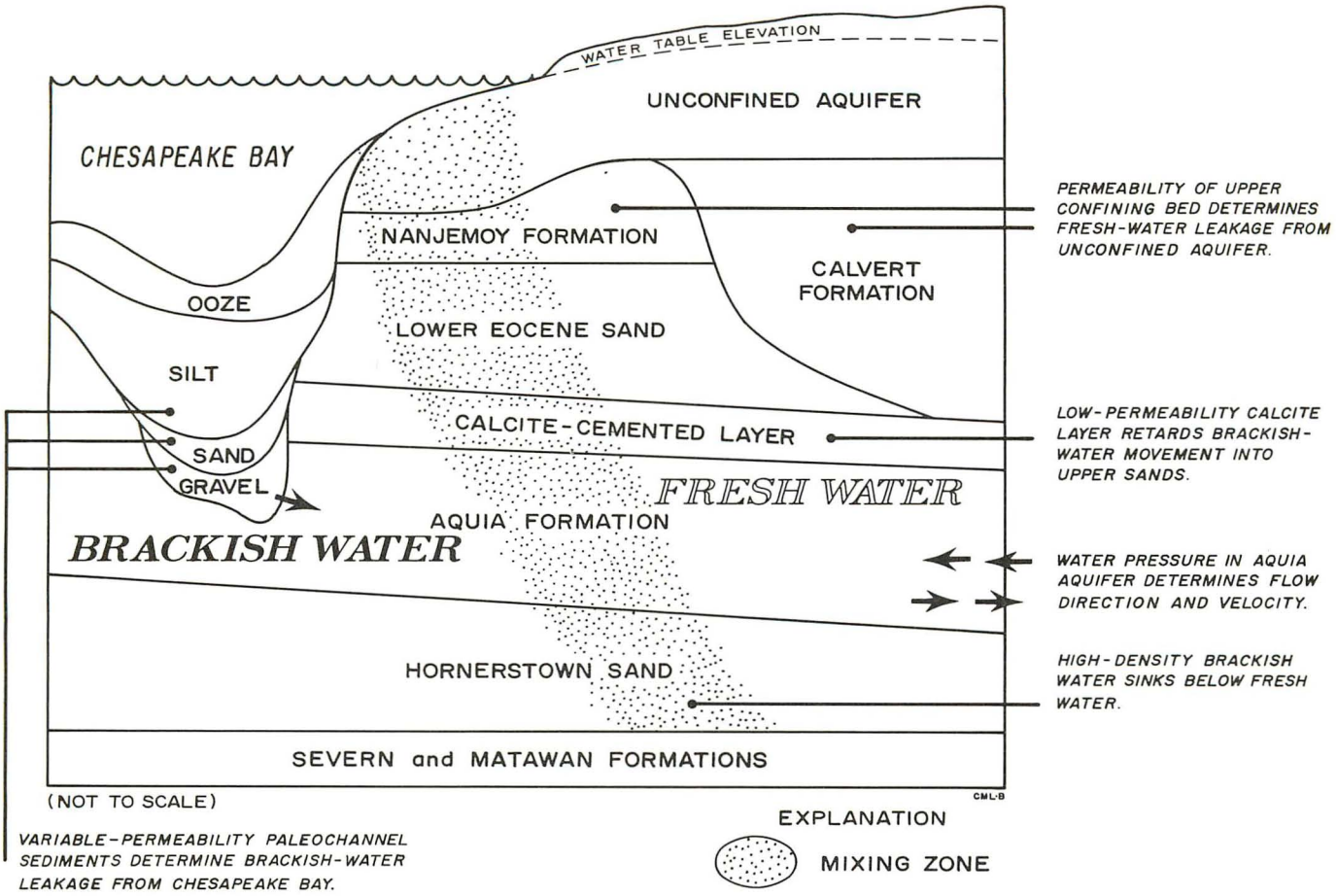


Figure 18. — Hydrogeologic controls on the distribution and movement of brackish water in the Aquia aquifer system.

of dynamic equilibrium in which the position of the brackish-water interface was balanced by the brackish-water pressure of the bay, and the freshwater pressure of the Aquia aquifer and the water table. As heavy pumpage decreased water pressure in the Aquia, equilibrium was upset, the flow direction was reversed, and the interface migrated landward in an attempt to reestablish equilibrium with the new pressure conditions.

Permeability Variations

Calcite-cemented layers

The Aquia aquifer contains numerous layers of calcite-cemented sand of differing depth, thickness, degree of induration, and lateral extent. At several locations, these calcite layers occur between the shallow freshwater zone and the deeper brackish-water zone. Visual inspection of cemented material indicates that it has significantly lower permeability than uncemented Aquia sand. This suggests that cemented calcite layers may locally control the distribution and movement of brackish water in the Aquia aquifer (fig. 18). This could be accomplished in two ways. In the pre-pumping situation, low-permeability calcite layers would affect the flow field, producing a different equilibrium interface position than had there been no calcite layers present. In the pumping situation, the calcite layers would inhibit vertical flow and reduce the migration of brackish water across the layer. This would also inhibit upwelling of brackish water from below the calcite layer to wells above the layer.

Paleochannels

Pleistocene paleochannels have been found to exert an important influence on the hydrogeology of some Coastal Plain aquifer systems. In the Aquia aquifer in southern Maryland (Chapelle and Drummond, 1983), the removal of confining-bed material and subsequent replacement with more permeable channel-fill sediments during the Pleistocene caused heads in the Aquia aquifer to equilibrate with water levels in the Potomac and Patuxent Rivers and the

Chesapeake Bay. Similarly, in the Baltimore Harbor area, replacement of confining-bed material with more permeable channel-fill sediments provided a conduit for brackish harbor water to move into the underlying aquifers in the Potomac Group (Chapelle, 1985). A similar situation exists in the Kent Island vicinity where Pleistocene erosional channels cut as much as 200 ft below sea level, removing the upper portion of the Aquia aquifer and all of the upper confining bed.

Pleistocene paleochannels in the vicinity of Kent Island may partially control the distribution and movement of brackish water in the Aquia aquifer (fig. 18). The removal of aquifer or confining-bed material and subsequent replacement with sediments of different permeability can alter the flow field and boundary conditions, producing a different hydrogeological framework. Paleochannels have the greatest impact where the infilling sediments have the greatest difference in permeability from the replaced sediments.

Although several paleochannels have been postulated in the Kent Island area, only the major one paralleling the present Chesapeake Bay channel has been sufficiently documented to be considered in this analysis. The paleochannel at Piney Creek (fig. 2) was confirmed by drilling, but has minimal impact on local hydrogeology because the infilling sediments are similar to the replaced sediments.

Upper confining bed

The upper confining bed may partially control the distribution and movement of brackish water in the Aquia aquifer. It allows leakage of freshwater from the unconfined aquifer into the Aquia aquifer, which acts to keep the brackish-water interface at bay. The amount of freshwater leakage is determined by the head gradient between the aquifers and the thickness and permeability of the confining bed. Because the thickness and permeability of the upper confining bed vary significantly throughout the study area, the upper confining bed provides a control on brackish-water occurrence which is spatially variable. In areas where the confining bed is thin (or absent altogether) or composed of higher permeability Nanjemoy sediments, the brackish-water interface may be expected to occur farther bayward than in areas where it is thick or composed of lower permeability Calvert sediments. This assumes that heads are higher in the unconfined aquifer than in the Aquia aquifer.

SIMULATION OF GROUND-WATER FLOW

A three-dimensional ground-water flow model was developed to simulate the response of water levels to future pumpage conditions. The physical characteristics of the real hydrogeologic flow system were incorporated into a computerized digital flow model, which was first calibrated to simulate historic and present conditions and then used to simulate projected and alternative pumpage conditions. The U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1984) was used for these simulations.

THEORY

Ground-water flow through a porous medium can be described by the partial differential equation (McDonald and Harbaugh, 1984):

$$\frac{\delta}{\delta x}\left(K_{xx}\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\left(K_{yy}\frac{\delta h}{\delta y}\right)+\frac{\delta}{\delta z}\left(K_{zz}\frac{\delta h}{\delta z}\right)-W=S_s\frac{\delta h}{\delta t} \quad (5)$$

where

x, y, and z (L) = cartesian coordinates aligned along major axes of hydraulic conductivity K_{xx}, K_{yy}, K_{zz} [L/T];

h = potentiometric head [L];

W = volumetric flux per unit volume [T^{-1}];

S_s = specific storage [L^{-1}]; and

t = time [T].

This equation, along with initial head conditions and head or flow conditions at the system boundaries, describes head values continuously throughout space and time.

However, equation 5 is mathematically difficult to solve for complex hydrologic systems and so numerical methods have been developed to solve the equation. The modular model uses the finite-difference method which replaces the partial derivatives in equation 5 with finite-difference approximations. The aquifer system, which is continuous through space and time, is divided into discrete cells with values for hydraulic properties assigned to each cell. Boundary conditions must be specified at the edges of the model, and initial head conditions must be specified at the beginning of the simulation. The model then calculates head values for each cell at specified time intervals.

CONCEPTUALIZATION

The ground-water flow model can be thought of as a part of the real hydrogeologic flow system which is removed from its surroundings and represented in a simplified way by a computer simulation. Figure 19 shows the layering scheme and boundary conditions simulated in the flow model. This can be compared with figure 13 to show how the conceptual model was translated into the digital flow model. Physical characteristics of the flow system such as transmissivity and storativity are entered into the model as input data. Realistic flow conditions must be simulated at the edges of the model by applying either pressures or fluxes. The simulated flow system must then be checked against the real system by comparing model-computed water levels with measured water levels. If they do not agree within a specified error criterion, the model must be adjusted either by changing the input data or by redefining the boundary conditions.

The Kent Island flow system was simulated by two aquifer layers separated by a confining layer (fig. 19). The deeper aquifer layer represents the Aquia aquifer as defined earlier in this report, and is referred to as layer 2. The shallower aquifer layer represents the aquifer immediately above the Aquia, and is referred to as layer 1. Layer 1 represents the Piney Point aquifer where it occurs; tidal bodies of water such as the Chesapeake Bay, Eastern Bay, and the Chester River where they overlie the Aquia; and the unconfined aquifer in areas where the other units do not occur. Layers 1 and 2 are separated by a confining layer, which represents the Calvert Formation, or the Nanjemoy Formation or estuarine bottom sediments, depending on which unit separates the two aquifer layers. In the area where the Aquia aquifer subcrops directly beneath the unconfined aquifer, the confining layer was assigned a very high leakance value to simulate the direct sand-on-sand contact.

Ground-water flow in the Aquia aquifer was simulated by allowing leakage to or from layer 1 through the confining layer (fig. 19). The amount and direction of flow through the confining layer are controlled by the head gradient between the aquifer layers and by the leakance value (hydraulic conductivity of the confining layer [K] divided by its thickness) of the confining layer. Pumpage was simulated in the model by withdrawing appropriate amounts of water from specified cells. All large pumpages (greater than

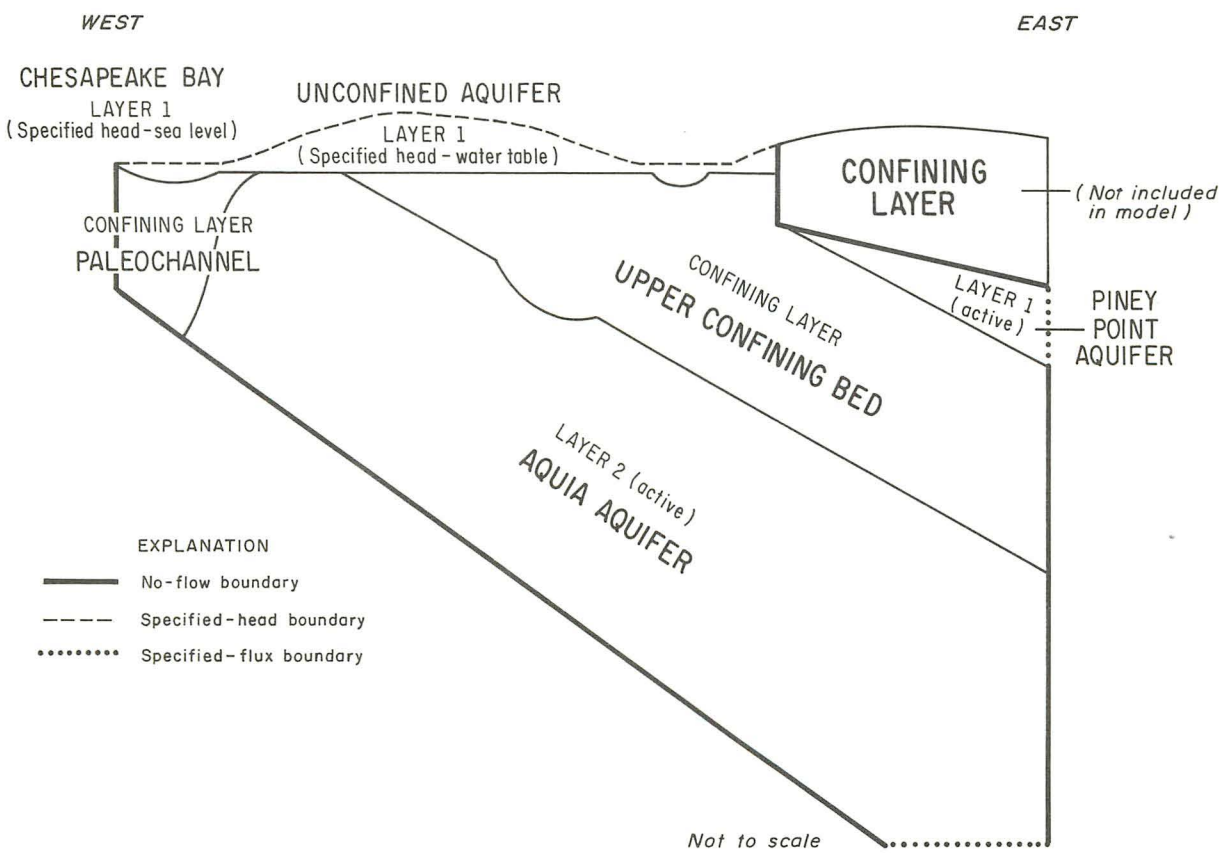


Figure 19. — Layering scheme and boundary conditions used in the flow model.

2,670 ft^3/d) throughout the modeled area were included as well as domestic pumpage in the Kent Island and Grasonville areas.

MODEL DESCRIPTION

Grid Design

The dimensions of the flow-model area are 51.2 mi (miles) by 25.6 mi, with a total area of 1,311 mi^2. The model area was divided into a rectangular grid having 2 layers, 26 rows, and 52 columns (fig. 20). The linear dimensions of the cells vary from 0.5 mi to 5.7 mi, with an increase factor of 1.5 for stability of the numerical solution. Smaller cells were used in the Kent Island area where greater accuracy was desired. The grid was oriented with the long dimension parallel to the downdip facies change of the Aquia so that this natural barrier to flow coincides with the model edge.

Boundary Conditions

Boundary conditions must be specified at the edges of the modeled area that approximate conditions in the aquifer system. The downdip Aquia facies change from a sandy aquifer to a silty-clay aquiclude just east of Easton was specified as a no-flow boundary in layer 2 (figs. 19 and 20). Because there are no natural aquifer boundaries within a reasonable distance along the strike of the Aquia, no-flow boundaries were specified at the northern and southern edges of the model in layers 1 and 2, and were placed far enough from the area of main interest as to have minimal effect on that area. A no-flow boundary was placed beyond the Aquia outcrop area. However, a very high leakance value was assigned to the confining layer at the inner edge of the outcrop, so that constant-head conditions actually prevail. Similarly, a no-flow boundary was placed along the western model edge where the Aquia was entrenched by the Pleistocene erosional channel. High confining-bed leakance values along the inner edge of this no-flow boundary simulate "protected" specified-head conditions. Protected specified-head conditions are created by separating specified-head cells (layer 1) from active cells (layer 2) by a confining layer, and controlling leakage between the layers by adjusting the confining-layer leakance.

The bottom of the Aquia also was modeled as a no-flow boundary throughout most of the model area. The thick sequence of sandy clay of the Severn and Matawan Formations and the low head gradient between the Aquia and Magothy aquifers indicate there is little leakage throughout most of the modeled area. The exception is at Easton, where a specified flux boundary was placed below the Aquia to simulate downward leakage through the lower confining bed. Here, the underlying Magothy aquifer is pumped heavily (111,000 ft^3/d in 1984) for the public water supply. The confining bed between this aquifer and the Aquia is approximately 250 ft thick and of unknown hydraulic conductivity. Records on file at the U.S. Geological Survey show that water levels in a well screened in the Aquia aquifer were lowered when a nearby well screened in the Magothy was pumped, indicating some hydraulic connection between the aquifers. Although no recent water-level data are available for the Magothy aquifer at Easton, records from 1962 show a head of 59 ft below sea level. Heads in the Aquia at that time were about 33 ft below sea level, indicating leakage out of the Aquia and into the Magothy aquifer. The amount of flux specified at this boundary was determined during calibration.

In the areas where layer 1 represents the unconfined aquifer and tidal bodies of water (fig. 21), the layer was modeled as specified-head cells and forms the upper boundary of the model. Although short-term water-level fluctuations do occur in the water table, levels remain constant over the long term (fig. 9). In the portion of the modeled area southeast of the Piney Point truncation line (fig. 20), layer 1 represents the Piney Point aquifer, and was modeled as active cells. In this area, a set of boundary conditions was included for the upper and lateral edges of layer 1. The upper boundary was simulated as no-flow. Williams (1979) simulated all recharge to the Piney Point aquifer as downward leakage from the overlying Cheswold aquifer (a sandy unit in the lower Calvert Formation) and ignored upward leakage from the Aquia aquifer. However, records show that heads in the Cheswold aquifer are at or below those in the Piney Point aquifer (Mack, Webb, and Gardner, 1971) throughout most of the Kent Island model area, and so no downward leakage was simulated for the Piney Point. In the southeastern portion of the modeled area (fig. 20), the lateral boundary of layer 1 was modeled as specified flux cells to simulate the large cone of depression centered at Cambridge, which is outside of the modeled area. A no-flow boundary was simulated in layer 1 at the other lateral edges of the modeled area. The subsurface truncation of the Piney Point aquifer was simulated as specified head, with the head values determined by the specified-head portion of layer 1 to provide recharge to the Piney Point aquifer.

Initial Conditions

Starting heads must be specified for all active and specified-head cells at the beginning of the simulation. At specified-head cells, these values remain constant throughout the simulation. These are the values entered for the water-table altitude. At active cells, the heads are allowed to change throughout the simulation. Starting heads for the Piney Point aquifer were taken from Williams (1979). Starting heads from the Aquia aquifer were entered as 0.0 ft for cells overlain by the estuaries and 8.0 ft for cells overlain by land. Starting head values at active cells are not considered to be critical because equilibrium conditions were achieved during the first stress period.

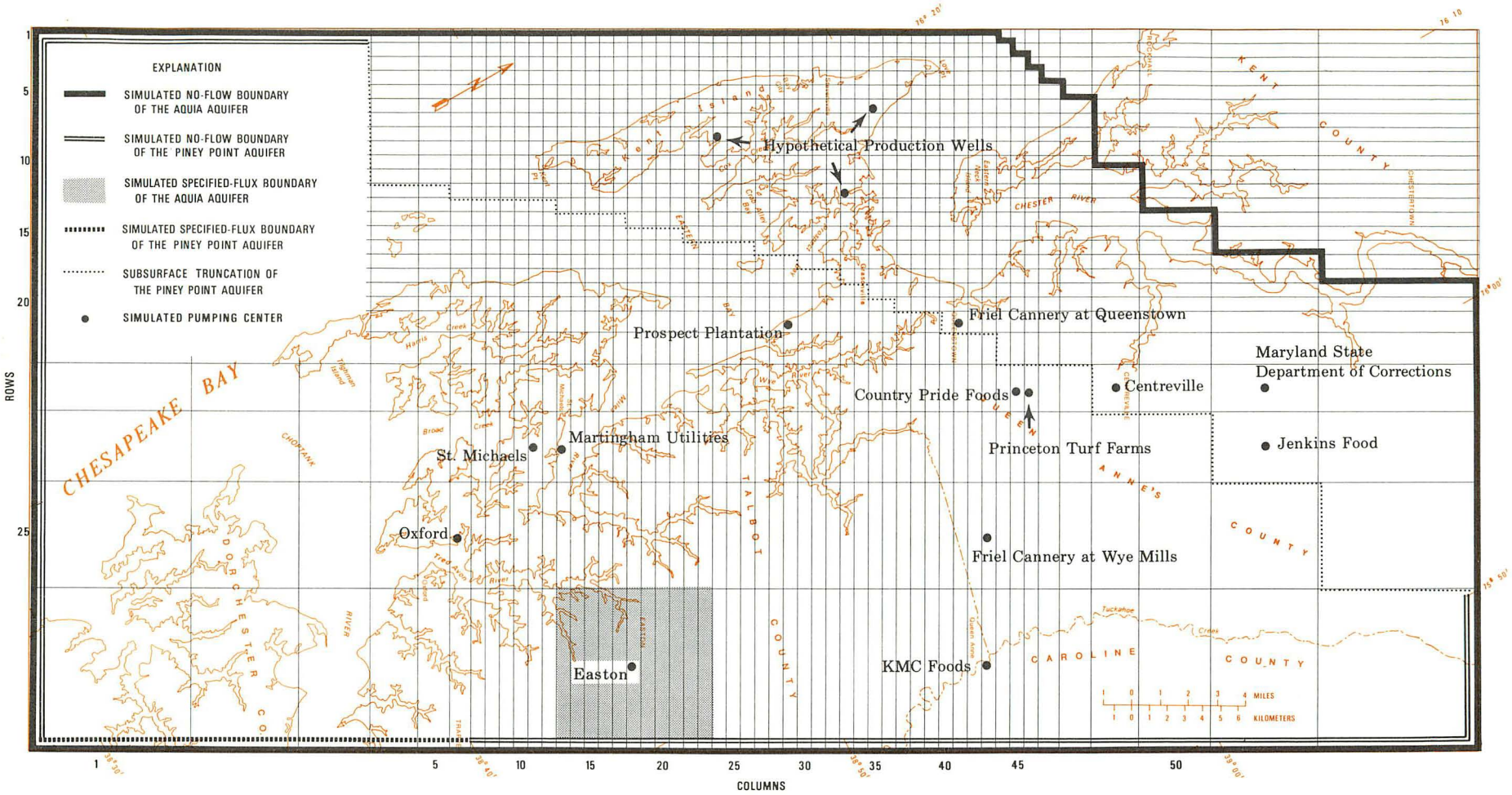


Figure 20. — Finite-difference grid, simulated boundaries, and simulated pumping centers of the flow model.

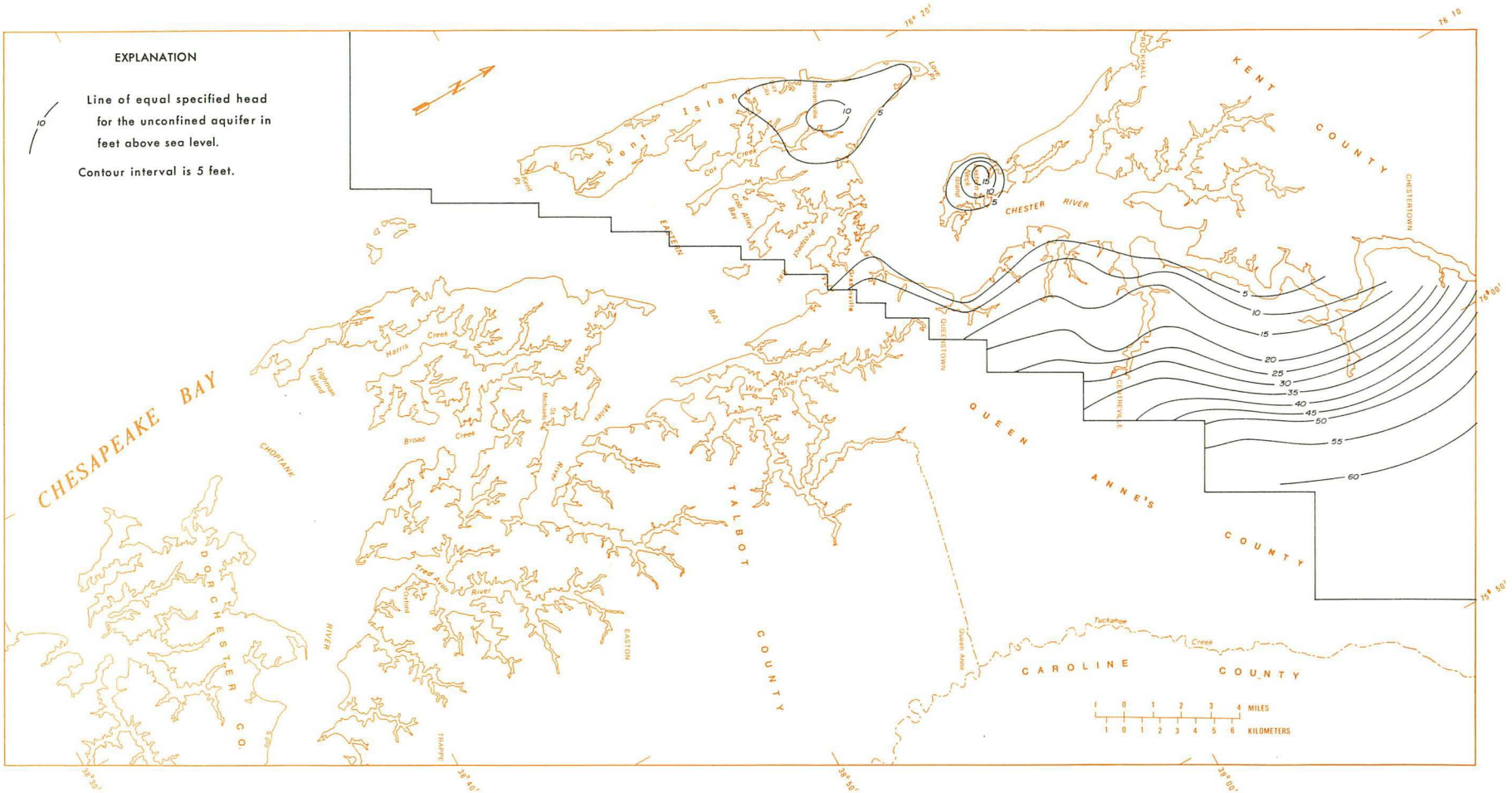


Figure 21. — Specified-head values for the unconfined aquifer.

Input Data

Input data for the flow model include water-table altitude in the unconfined aquifer, leakance of the confining bed, pumpage, transmissivity for each aquifer, and storage coefficient for each aquifer.

Water-table altitude in the unconfined aquifer is an important input for layer 1 because these values become specified head values and largely drive the flow through the Aquia aquifer. These data are contoured in figure 21. The water-table altitude is as high as 60 ft above sea level in the northeastern part of Queen Anne's County where land-surface altitude is highest. It decreases to 0.5 ft at the Chesapeake Bay and its tidal tributaries with water-table highs of 10 and 15 ft on Kent Island and Eastern Neck Island. The value of 0.5 ft was input where layer 1 represents tidal estuaries to approximate the equivalent freshwater head of a layer of brackish water. Water-table altitude was not input to the active layer 1 cells where layer 1 represents the Piney Point aquifer.

A transmissivity value of 500 ft^2/d was used for layer 1 where it represents the Piney Point aquifer. Williams (1979) contoured the transmissivities for the Piney Point aquifer on the Eastern Shore and shows consistent values of about 500 ft^2/d throughout the model area of this project.

Transmissivity values for layer 2 were obtained from Hansen (1972) and a map of these values is shown in figure 22. The contours show a high of 4,500 ft^2/d in the Queenstown area where the Aquia is thickest. They decrease to 1,500 ft^2/d near the outcrop area where the aquifer thins to the north and to 1,000 ft^2/d near the subsurface facies change near Easton to the south. Transmissivities determined from aquifer tests performed for this study at five test well sites on Kent Island are generally consistent with the data from Hansen and are shown in figure 22 with the transmissivity from the Chester test well (Mack, 1983).

A storage coefficient of 0.0002 was used for layers 1 and 2. These are typical values from aquifer tests on the Eastern Shore, taken from Hansen (1972).

Leakance values were assigned to each unit of the confining layer. The distribution of the units and their leakance values are shown in figure 23. Leakance values for the confining layer range from $5 \times 10^{-7}/d$ (per day), where it represents the Nanjemoy Formation separating the Piney Point and Aquia aquifers, to $2 \times 10^{-2}/d$ where there is direct contact between the unconfined and Aquia aquifers.

Pumpage data for the pre-1984 model input were divided into four stress periods (see table 5). Stress period 1 includes 1870 through 1899 and simulates prepumping conditions. Stress period 2 includes 1900 through 1944 and simulates major pumpage centers that were operating in that period, but no domestic pumpage. Stress period 3 includes 1945 through 1964 and simulates pumpage of major users throughout the modeled area and domestic pumpage for the Kent Island area. The domestic pumpage distribution for stress period 3 is shown in figure 24. Because population distribution data for this period are incomplete, the total estimated pumpage of 50,912 ft^3/d was distributed among a few communities such as Stevensville. Stress period 4 includes 1965 through 1984 and simulates pumpage of major users and domestic pumpage in the Kent Island and Grasonville areas. The domestic pumpage distribution for stress period 4 is shown in figure 25. Fairly complete well-density distribution data were available for Kent Island for this period (Troxell, 1983) and were used to estimate domestic pumpage distribution. Pumpage is distributed throughout the entire island, with areas of high pumpage at the communities along the shore. Domestic pumpage from the Grasonville area for stress period 4 (48,000 ft^3/d) was estimated from water use data (Andrews, Miller & Assoc., Inc., 1984). This value may be too high because some wells in this area may be screened in sandy sections of the Severn Formation which may not be hydraulically connected to the Aquia aquifer. Large-user pumpage was compiled from actual records of ground-water withdrawal or was estimated where records were not available (Wheeler and Wilde, U.S. Geological Survey, written commun., 1987). Pumpage from the Piney Point aquifer at Cambridge (outside the study area) and from the Magothy aquifer (below the Aquia) at Easton was simulated indirectly with specified flux boundaries. Flux values at these boundaries were determined in model calibration.

CALIBRATION

Before using the flow model to simulate future hydrologic conditions, it must be calibrated to simulate past and present conditions. The calibration process consisted of adjusting various model inputs within reasonable limits to obtain a good match between measured water levels and model-computed water levels. In general, the inputs that are known with a low degree of accuracy were adjusted more than those that are known with a high degree of accuracy. Pumpage values were obtained from actual records or from relatively accurate estimates and were not adjusted during calibration. Leakance values for the confining layer are not accurately known and were adjusted during calibration. Adjustment of confining-layer leakance values was the primary means of calibrating the flow model. Other inputs which were adjusted to a lesser extent are Aquia transmissivity, the placement of boundaries, and the altitude of the water table.

Calibration of the flow model involved a two-step process. The first step was to run the model under steady-state conditions and simulate prepumping potentiometric surfaces for the Aquia and Piney Point aquifers. Model input data were then adjusted to obtain reasonable simulated

(Text continues on p. 46)

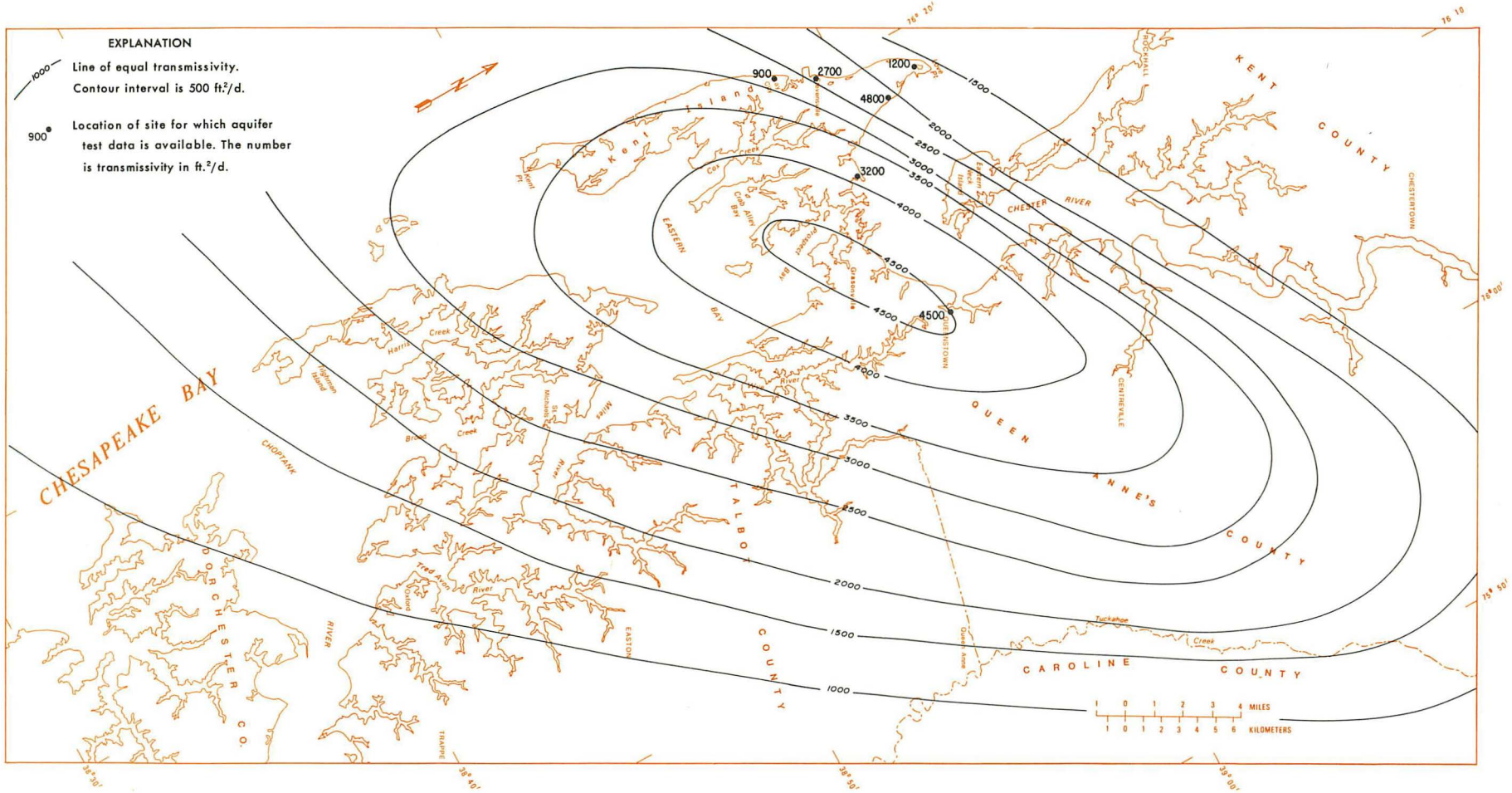


Figure 22. — Transmissivity of the Aquia aquifer (after Hansen, 1972, plate 4).

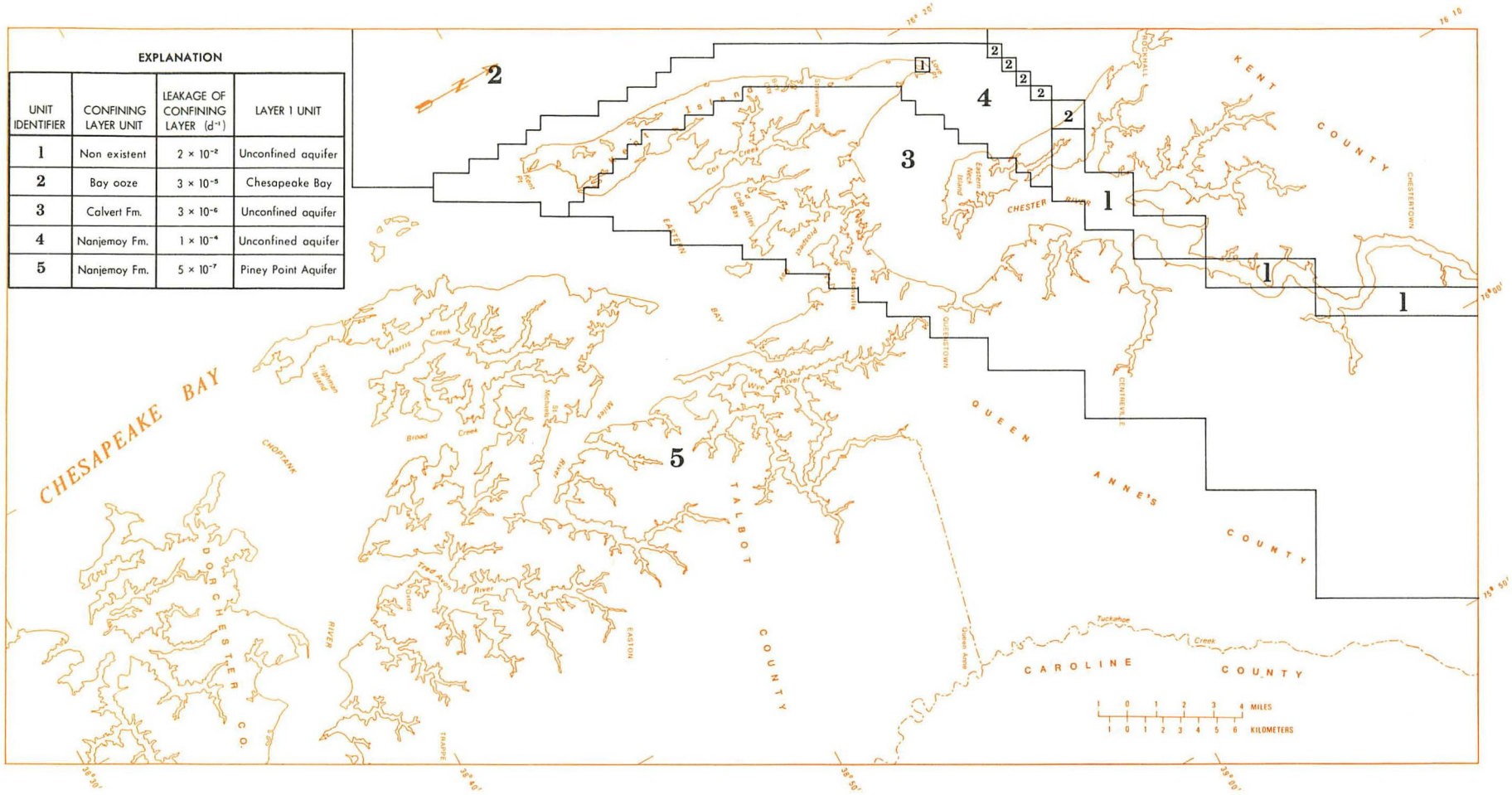


Figure 23. — Upper confining layer leakances for input to the flow model.

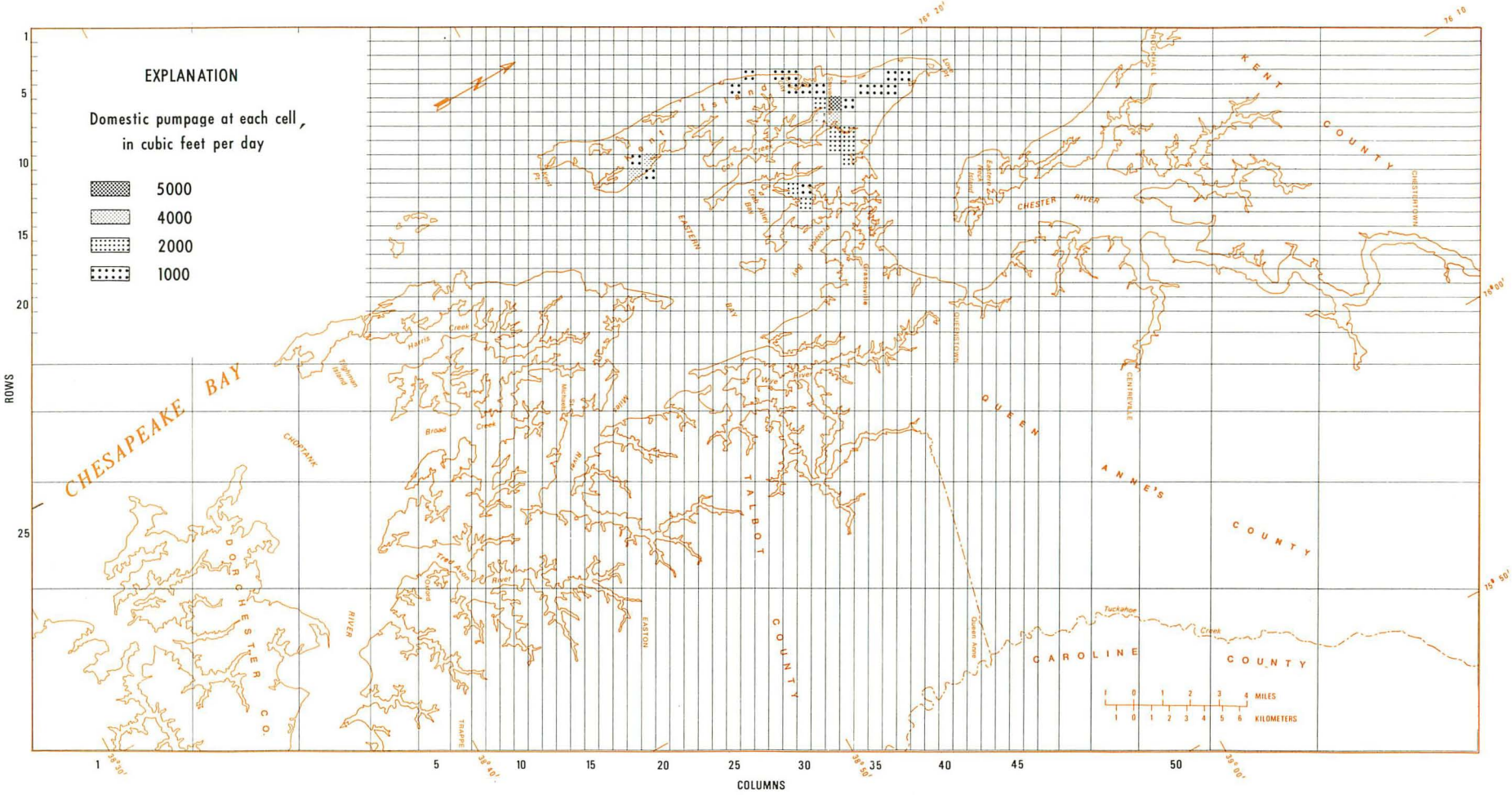


Figure 24. — Simulated pumpage distribution on Kent Island in 1964.

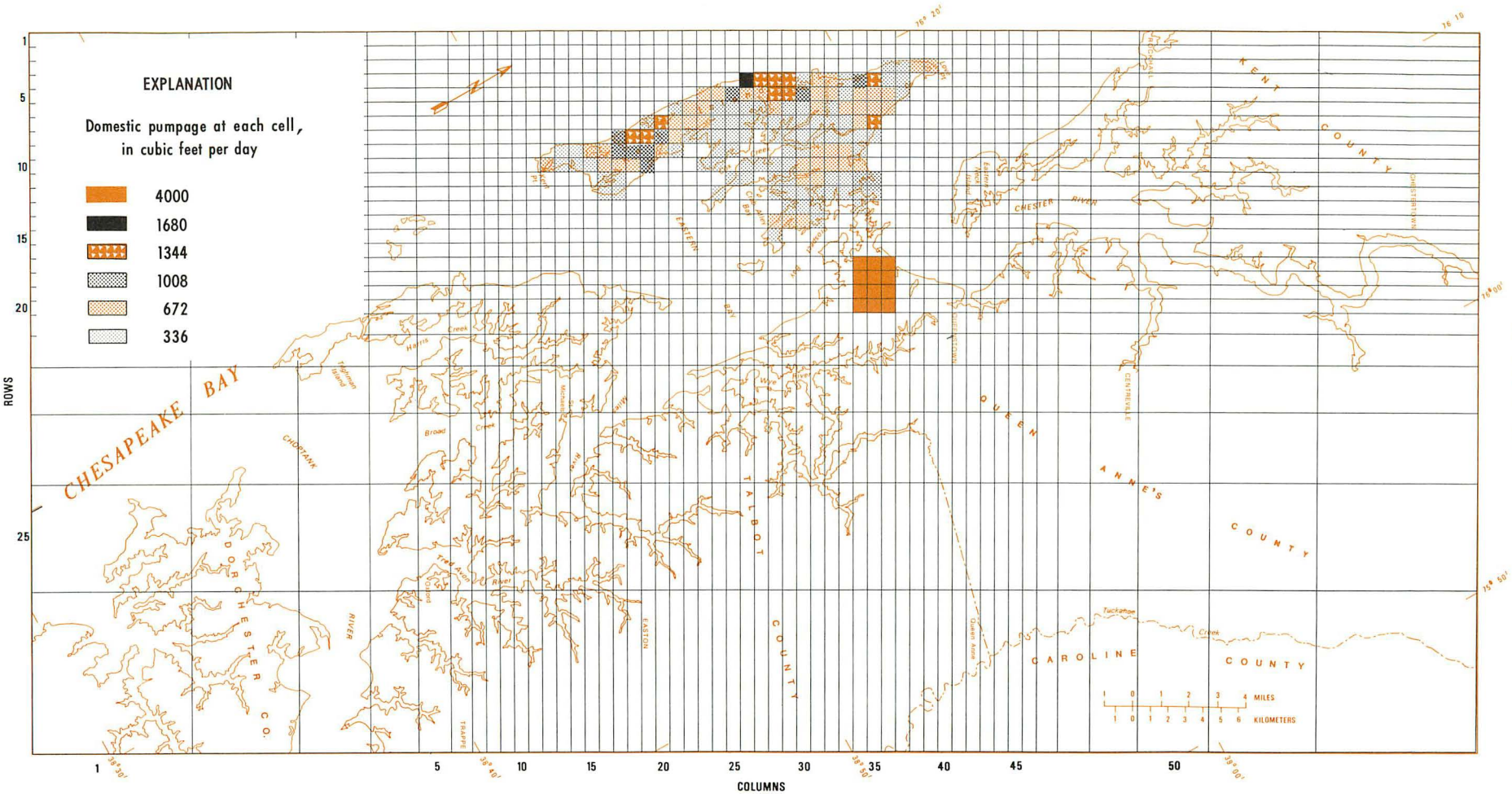


Figure 25. — Simulated pumpage distribution on Kent Island and at Grasonville in 1984.

Table 5. — Pumpage entered in the flow model

[* = same value as in Simulation 1]

Pumping center	Pumpage, in thousand cubic feet per day																	
	Calibration				Simulation 1				Simulation 2				Simulation 3				Simul	
	Stress period				Stress period				Stress period				Stress period				Stress	
	1	2	3	4	5	6	7	8	5	6	7	8	5	6	7	8	5	6
	1870-1899	1900-1944	1945-1964	1965-1984	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995
Kent Island domestic and commercial (total)	0.0	0.0	51.0	103.0	177.0	210.0	246.0	283.0	212.0	252.0	295.0	340.0	141.0	168.0	197.0	227.0	*	*
Grasonville domestic	.0	.0	.0	48.0	63.0	78.0	99.0	120.0	76.0	94.0	119.0	144.0	50.0	62.0	79.0	96.0	*	*
Country Pride Foods	.0	.0	.9	.5	.5	.5	.5	.5	*	*	*	*	*	*	*	*	0.6	0.6
Jenkins Food	.0	.0	.0	2.0	2.0	2.0	2.0	2.0	*	*	*	*	*	*	*	*	2.4	2.4
Maryland State Dept. of Correction	.0	.0	.0	.8	.8	.8	.8	.8	*	*	*	*	*	*	*	*	1.0	1.0
Princeton Turf Farms	.0	.0	.0	.8	.8	.8	.8	.8	*	*	*	*	*	*	*	*	1.0	1.0
Prospect Plantation	.0	.0	.0	.5	.5	.5	.5	.5	*	*	*	*	*	*	*	*	.6	.6
Queenstown	.0	.0	.0	2.0	2.0	2.0	2.0	2.0	*	*	*	*	*	*	*	*	2.4	2.4
Friel Cannery at Queenstown	.0	.5	2.8	3.3	3.3	3.3	3.3	3.3	*	*	*	*	*	*	*	*	3.6	3.6
Friel Cannery at Wye Mills	.0	1.0	7.6	13.9	13.9	13.9	13.9	13.9	*	*	*	*	*	*	*	*	16.8	16.8
Centreville	.0	.0	25.6	38.5	38.5	38.5	38.5	38.5	*	*	*	*	*	*	*	*	46.2	46.2
St. Michaels	.0	4.6	20.7	29.3	29.3	29.3	29.3	29.3	*	*	*	*	*	*	*	*	34.8	34.8
Easton	.0	.0	20.3	37.5	37.5	37.5	37.5	37.5	*	*	*	*	*	*	*	*	45.6	45.6
KMC Foods	.0	.0	5.0	4.5	4.5	4.5	4.5	4.5	*	*	*	*	*	*	*	*	6.0	6.0
Martinham Utilities	.0	.0	.0	.8	.8	.8	.8	.8	*	*	*	*	*	*	*	*	1.0	1.0
Oxford	.0	5.6	8.8	13.0	13.0	13.0	13.0	13.0	*	*	*	*	*	*	*	*	15.6	15.6
Easton flux boundary	.0	18.6	32.6	61.3	61.3	61.3	61.3	61.3	*	*	*	*	*	*	*	*	73.6	73.6
Cambridge flux boundary	.0	26.5	53.1	53.1	53.1	53.1	53.1	53.1	*	*	*	*	*	*	*	*	63.7	63.7
Hypothetical Kent Island production wells (total of 3)	.0	.0	.0	.0	.0	.0	.0	.0	*	*	*	*	*	*	*	*	*	*

Pumpage, in thousand cubic feet per day																					
ation 4		Simulation 5				Simulation 6				Simulation 7				Simulation 8				Simulation 9			
period		Stress period				Stress period				Stress period				Stress period				Stress period			
7	8	5	6	7	8	5	6	7	8	5	6	7	8	5	6	7	8	5	6	7	8
1991-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005	1984-1990	1991-1995	1996-2000	2001-2005
*	*	*	*	*	*	0.0	0.0	0.0	0.0	88.0	105.0	123.0	141.0	*	*	*	*	0.0	0.0	0.0	0.0
*	*	*	*	*	*	*	*	*	*	*	*	*	*	31.5	39.0	49.5	60.0	.0	.0	.0	.0
0.6	0.6	0.4	0.4	0.4	0.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2.4	2.4	1.6	1.6	1.6	1.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1.0	1.0	.6	.6	.6	.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1.0	1.0	.6	.6	.6	.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
.6	.6	.4	.4	.4	.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2.4	2.4	1.6	1.6	1.6	1.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
3.6	3.6	2.4	2.4	2.4	2.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
16.8	16.8	11.2	11.2	11.2	11.2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46.2	46.2	30.8	30.8	30.8	30.8	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34.8	34.8	23.2	23.2	23.2	23.2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
45.6	45.6	30.4	30.4	30.4	30.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6.0	6.0	4.0	4.0	4.0	4.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1.0	1.0	.6	.6	.6	.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
15.6	15.6	10.4	10.4	10.4	10.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
73.6	73.6	49.0	49.0	49.0	49.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
63.7	63.7	42.5	42.5	42.5	42.5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
*	*	*	*	*	*	177.0	210.0	246.0	283.0	88.0	105.0	123.0	141.0	*	*	*	*	*	*	*	*

potentiometric surfaces. As shown in figure 26, the simulated prepumping potentiometric surface of the Aquia aquifer ranges from 25 ft above sea level in the high-altitude portion of northeastern Queen Anne's County to less than 5 ft above sea level near Kent Island and the Chesapeake Bay. The general flow direction is from northeast to southwest.

The second step of calibration was to enter historical pumpage data into the model and simulate stressed potentiometric surfaces at the end of each stress period (figs. 27 and 28). The simulated potentiometric surfaces for 1944 and 1964 shown in figures 27 and 28 display head decreases to 10 and 25 ft below sea level, respectively, in the Easton area. This reflects a change of flow direction in the Kent Island area, caused by the major pumping centers near Easton and domestic pumpage on Kent Island. Whereas the prepumping simulation indicates flow westward across Kent Island toward the bay, the pumping simulations indicate flow southward roughly paralleling the bay shore in 1944, and southeastward from the bay across Kent Island in 1964. The simulated 1984 potentiometric surface was compared to the 1984 synoptic measurement at selected wells and model inputs were adjusted to obtain a good match. This is the most critical step in calibration because it is the only time period for which accurate measured water levels are available, and because the pumpage data are more complete and accurate than for previous time periods. Figure 29 shows the simulated 1984 potentiometric surface and observed data points used to calibrate the model. The match is generally quite close (within 3 ft), although there are some exceptions. In the areas of coarse grid spacing, such as Easton, simulated cones of depression are centered at cell centers rather than the true positions of the pumping centers, causing some lateral shift. Some observation wells may be screened in isolated sands of the Aquia aquifer and not reflect the regional head in the aquifer.

The 1984 potentiometric surface (fig. 29) shows the same general flow pattern as the simulated 1964 surface, but heads have declined to 54 ft below sea level in the Easton area. Heads are below sea level throughout most of the Kent Island area and below the bay, indicating the potential for brackish-water recharge from the bay. Heads in the outcrop/subcrop area are essentially unchanged from the prepumping simulation, but heads elsewhere in eastern Queen Anne's County have declined as much as 15 ft.

Initially, leakance values for the confining layer were calculated from permeability test results of core material (table 3) and average thickness. Given an average thickness of 100 ft, leakance values of 10^{-1}/d and 10^{-4}/d were calculated for the Nanjemoy and Calvert Formations. However, when these values were used in the model, head gradients could not be maintained across the confining layer, and heads in the Aquia aquifer were equilibrating with specified heads in the unconfined aquifer. Leakance values were decreased during calibration. The final calibrated leakance values were 1×10^{-4}/d and 3×10^{-6}/d for the Nanjemoy and Calvert Formations. Because the permeability of sediments of this type may range over several orders of magnitude (Freeze and Cherry, 1979), this adjustment is considered reasonable.

The flux at each of the cells in the specified flux boundary in layer 1 near Cambridge (fig. 20) was calculated to simulate the portion of the cone of depression within the model area. Williams (1979) shows little variation in pumpage and heads in the Piney Point aquifer at Cambridge during the simulation period 1952-76. Accordingly, flux amounts were kept constant for stress periods 3 and 4 (1945-64 and 1965-84) and were adjusted during calibration to simulate the potentiometric surface of 1976 (Williams, 1979). The total flux for the six cells was 53,147 ft^3/d, which is about 18 percent of Cambridge pumpage during that period. Prior to 1944, Cambridge pumpage increased gradually. Thus, for stress period 2 (1895-1944), the total flux entered at the boundary was half the flux entered for stress periods 3 and 4, or 26,573 ft^3/d.

The flux at the specified flux boundary in layer 2 at Easton (fig. 20) was also determined during calibration. Because no data are available for leakance of the intervening confining layer or for 1984 heads in the Magothy aquifer, a flux value could not be calculated directly. The value was adjusted during calibration to simulate the cone of depression in the Aquia aquifer at Easton in 1984 (fig. 29). A total of 61,314 ft^3/d was entered for the 11 cells of the boundary for 1984 (stress period 4), which is 55 percent of the pumpage from the Magothy aquifer. The same percentage was used to determine flux values for stress periods 2 and 3 from actual pumpage amounts.

Head data are available for the Magothy aquifer from the early 1960's (Mack, Webb, and Gardner, 1971) and were used to check the flux value entered for stress period 3 (1944-64). A modified form of the Darcy equation yields the hydraulic conductivity of the intervening confining bed.

$$K_c = \frac{Qb}{(h_a - h_m)A} \qquad (6)$$

where

K_c = hydraulic conductivity of the confining bed [L/T],
Q = volumetric flux at the boundary [L^3/T],
h_a = head in the Aquia aquifer [L],
h_m = head in the Magothy aquifer [L],
b = thickness of the confining bed [L], and
A = area of the boundary [L^2].

Using the model-calibrated $Q = 32{,}648$ ft^3/d and $h_a = -33$ ft; $h_m = -59$ ft and $b = 250$ ft from Mack, Webb, and Gardner (1971); and $A = 8.74 \times 10^8$ ft^2, equation 6 yields K_c of 3.59×10^{-4} ft/d. This hydraulic conductivity value is within the expected range for confining beds (Freeze and Cherry, 1979) and is very close to the value entered in the model for the Calvert Formation (3×10^{-4} ft/d). This indi-

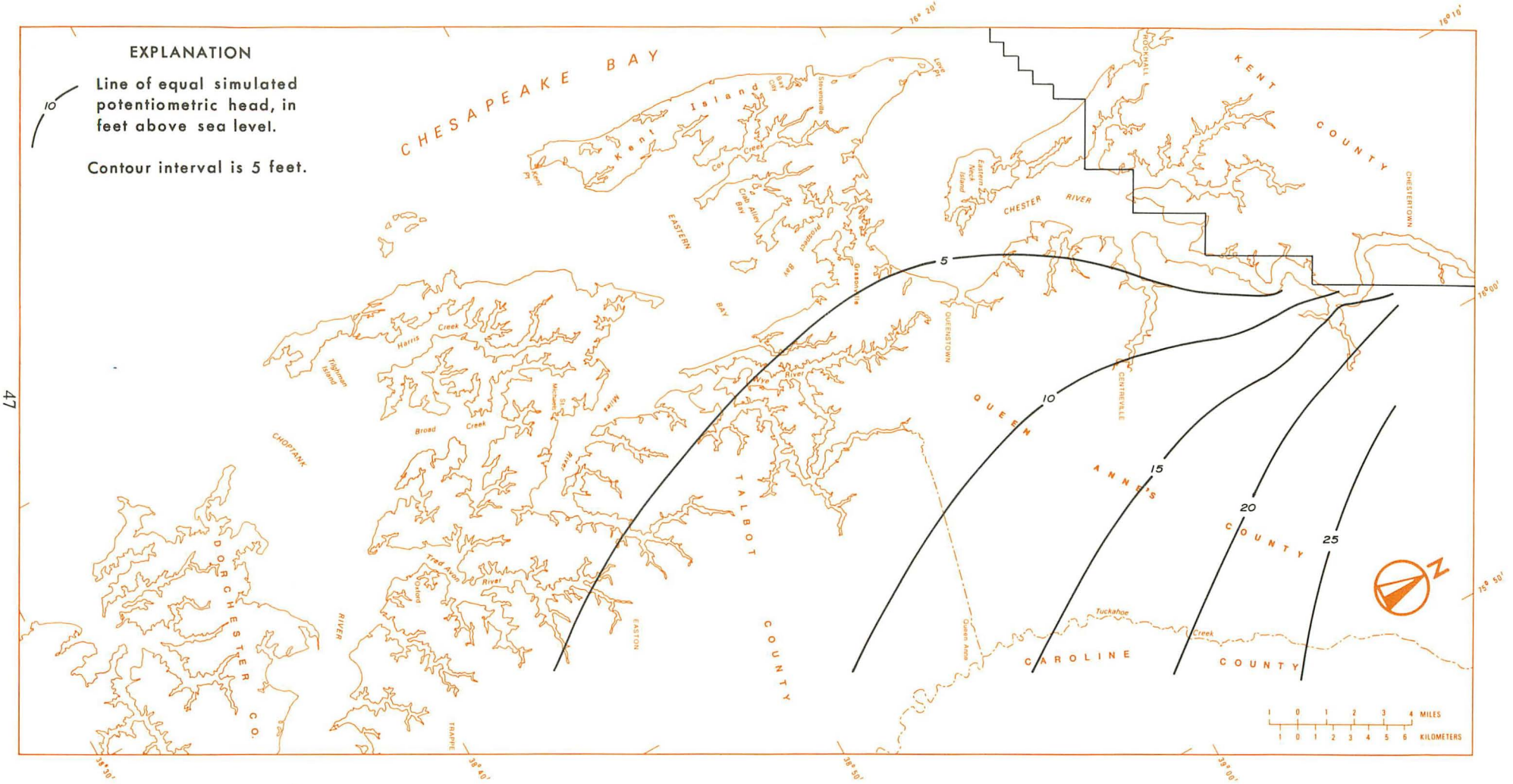


Figure 26. — Simulated potentiometric surface of the Aquia aquifer for prepumping conditions.

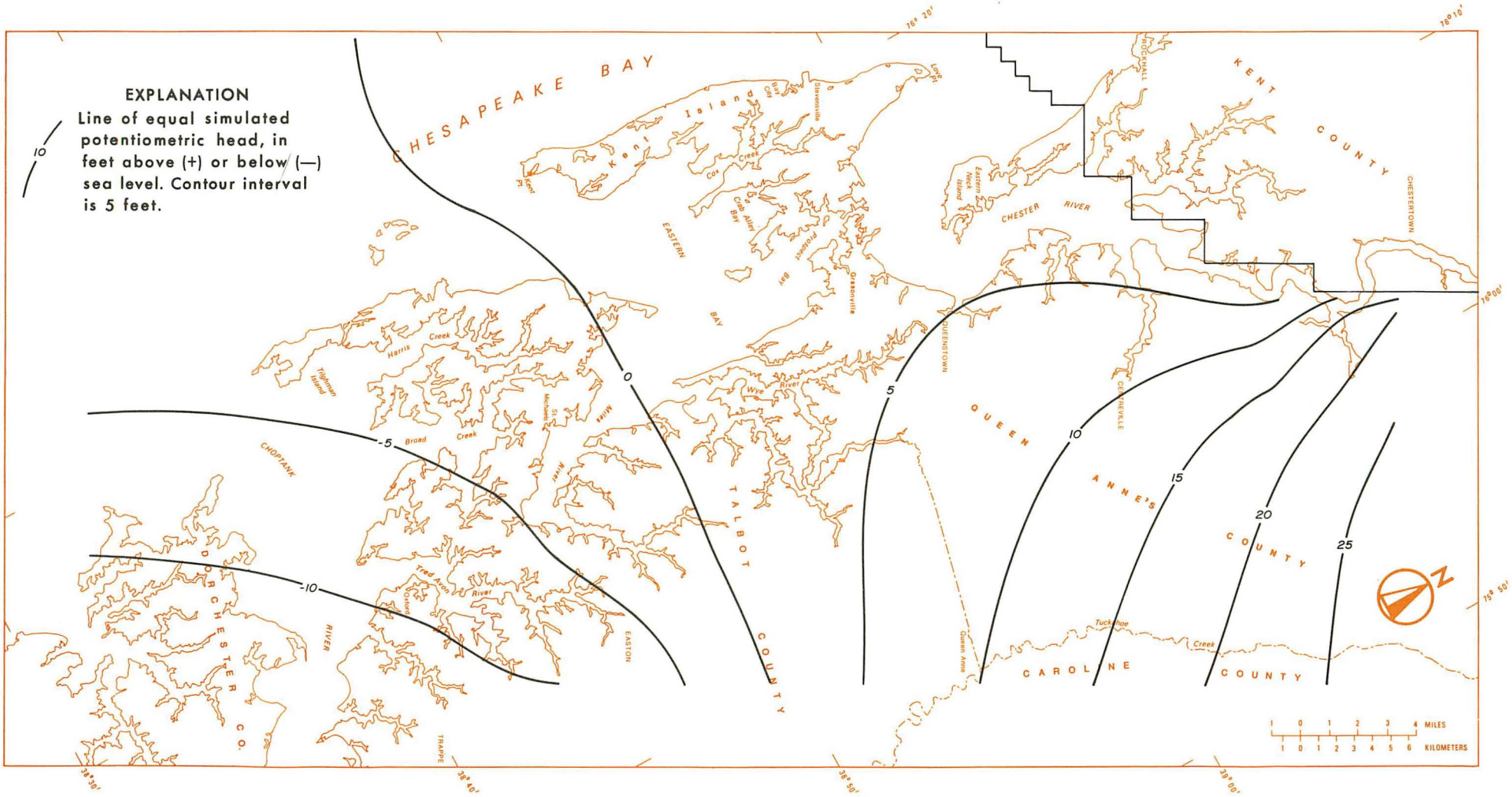


Figure 27. — Simulated potentiometric surface of the Aquia aquifer for 1944.

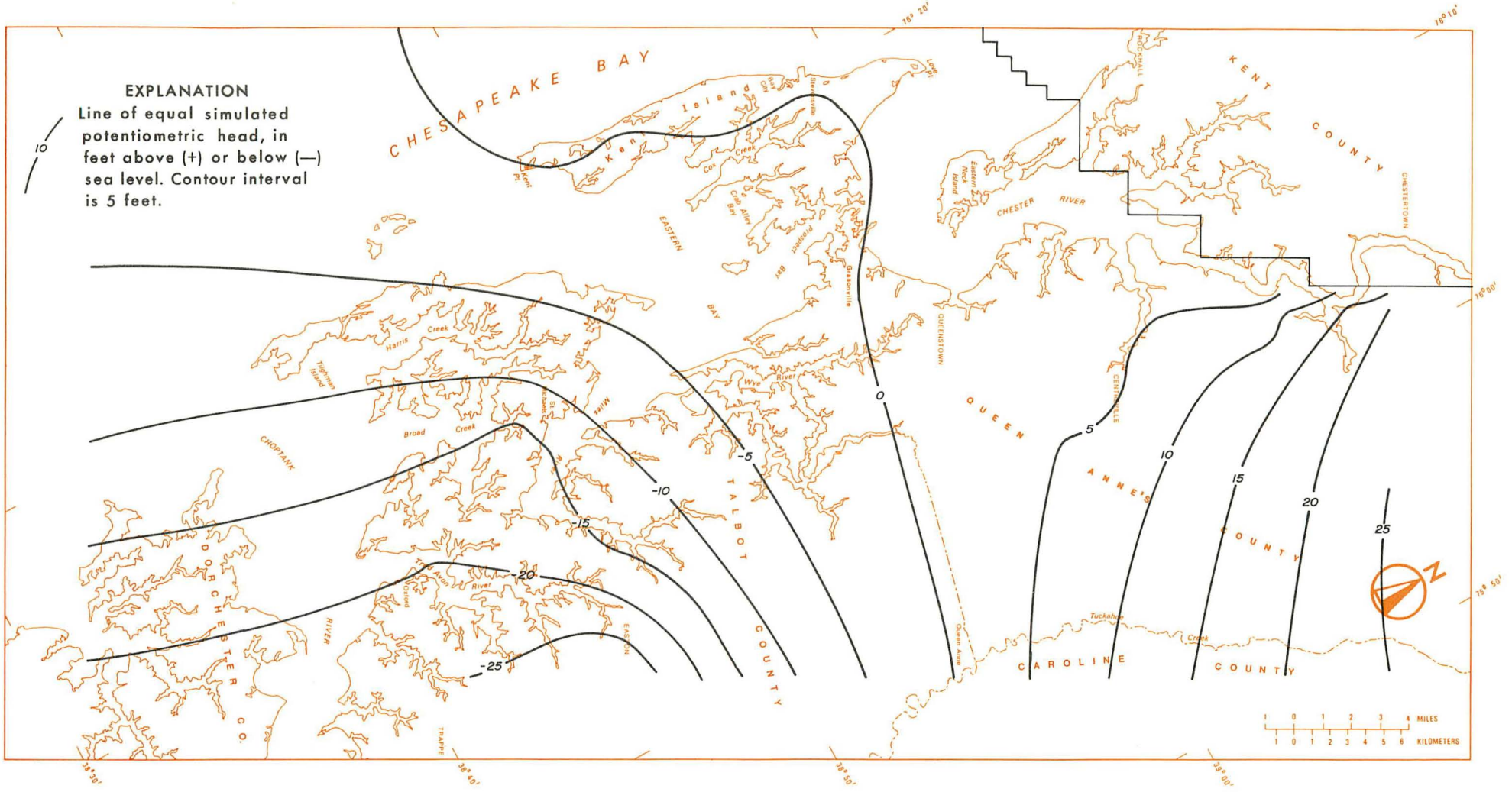


Figure 28. — Simulated potentiometric surface of the Aquia aquifer for 1964.

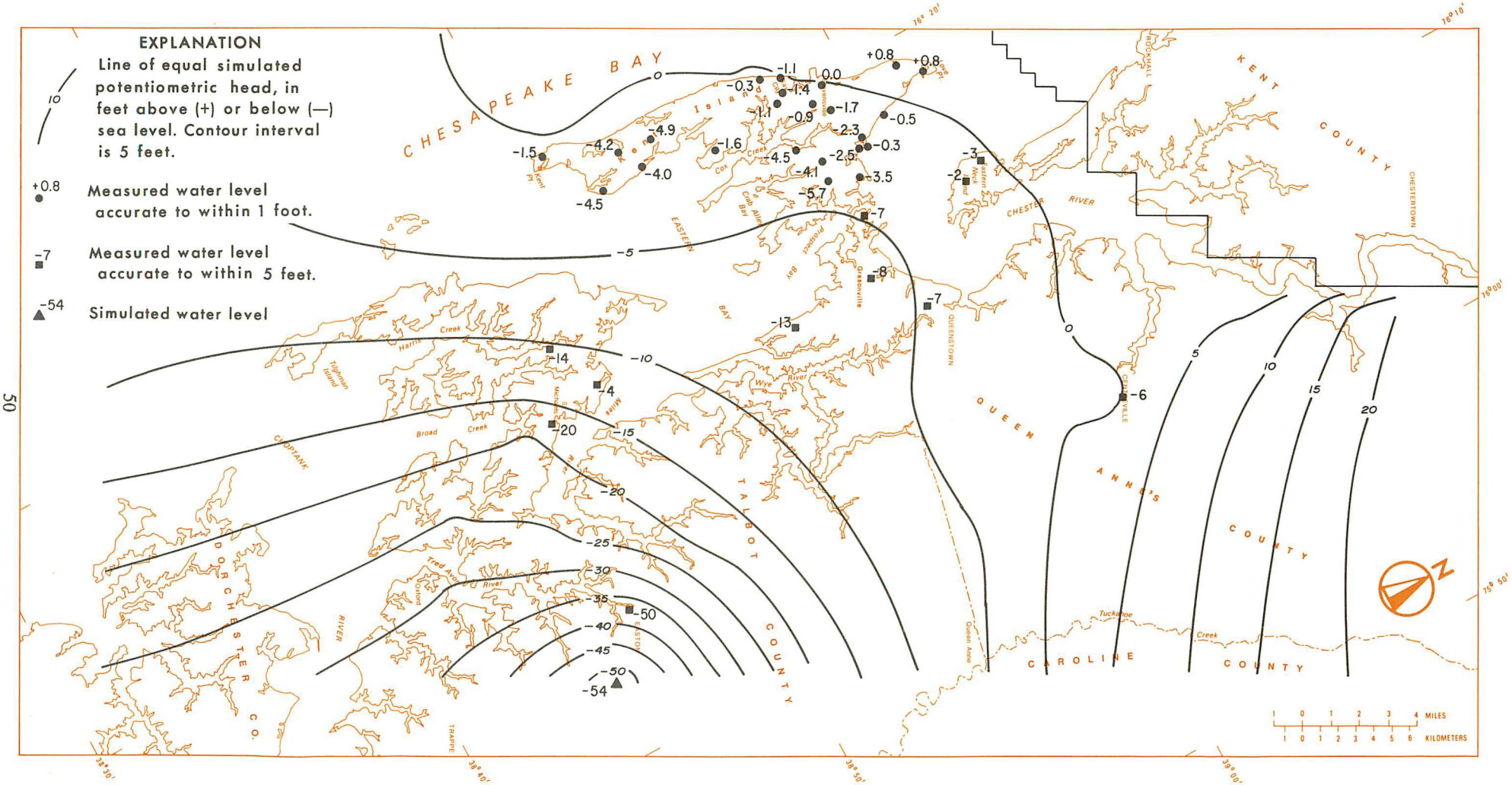


Figure 29. — Simulated potentiometric surface of the Aquia aquifer for 1984, with measured water levels.

cates that the flux values entered in the model for this boundary are reasonable.

SIMULATION OF PROJECTED PUMPAGE

The calibrated flow model was used to simulate the effect of projected pumpage on potentiometric head distribution on Kent Island. A best estimate for future pumpage was derived from population projections (Andrews, Miller & Assoc., Inc., 1984), population distribution, and per capita water use. The effects of uncertainties in projected pumpage estimates were evaluated by making additional simulations using pumpage rates 20 percent higher and lower than the best estimate. The model was also used to simulate alternative pumpage scenarios, such as replacement of all domestic and commercial wells on Kent Island with three centrally located community wells.

All projected pumpage simulations include the 21-year time period 1985-2005. The period was divided into four stress periods—1985-1990, 1991-1995, 1996-2000, and 2001-2005—to coincide with population projections (table 5). Simulated heads are averages for the entire cell and water levels in pumping wells could be deeper than those shown.

Simulation 1—This simulation represents the best estimate of future conditions. Future domestic pumpage at Kent Island and Grasonville was estimated by determining a population-increase factor for each of these areas from projected population estimates. These increase factors, when multiplied by the 1984 populations, give the population projections at the end of each period. These same increase factors were then multiplied by the 1984 pumpage amounts for each cell to give projected pumpage amounts at the end of each period. Thus, the projected pumpage distribution was kept the same as in the 1984 simulation; the total pumpage was increased proportionally with population. Pumpage elsewhere in the modeled area was kept the same as the 1984 simulation in as much as no significant population increases are projected for these areas.

Figures 30, 31, 32, and 33 show the results of simulation 1 for 1990, 1995, 2000, and 2005. By 2005, water levels have declined as much as 5 ft on Kent Island, with the greatest declines occurring at the eastern part of the island near Grasonville. A cone of depression has formed at Grasonville, which is more than 15 ft below sea level at its deepest point. The 0-ft contour line has moved westward to intersect the no-flow boundary. The cone of depression at Easton and water levels in the northern part of the modeled area have not changed significantly.

Simulations 2 and 3—These simulations bracket the pumpage increase used in simulation 1. They represent possible inaccuracies in the best-estimate domestic pumpage projection by increasing and decreasing the pumpage amounts. The domestic pumpage amounts used in simulation 1 were increased and decreased 20 percent to give bracketing growth rates for simulations 2 and 3. Pumpage elsewhere in the modeled area was kept the same as in simulation 1.

Figure 34 shows the results of simulation 2 for 2005. Water levels at Kent Island and Grasonville are 1 to 3 ft deeper than in simulation 1, or 6 to 8 ft deeper than 1984 water levels. The cone of depression at Grasonville is almost 20 ft below sea level at its deepest point. Water levels elsewhere in the modeled area are similar to those from simulation 1.

Figure 35 shows the results of simulation 3 for 2005. Water levels at Kent Island and Grasonville are 1 to 3 ft higher than in simulation 1, or 2 to 4 ft deeper than 1984 water levels. The cone of depression at Grasonville is almost 15 ft below sea level at its deepest point. Water levels elsewhere in the modeled area are similar to those from simulation 1.

Simulations 4 and 5—These simulations bracket the pumpage amounts used in simulation 1 for those areas other than Kent Island and Grasonville. All pumpage in the modeled area other than Kent Island and Grasonville (including the flux boundaries for Easton and Cambridge) was increased and decreased 20 percent while pumpage rates for Kent Island and Grasonville were kept the same as in simulation 1.

Figure 36 shows the results of simulation 4 for 2005. Water levels on Kent Island and at Grasonville are 0 to 2 ft deeper than in simulation 1, with the greatest difference occurring in the southeastern portion of the island. The cone of depression at Easton is about 65 ft below sea level at its deepest point, or about 11 ft deeper than in simulation 1. Water levels in the northern part of the modeled area are similar to those in simulation 1.

Figure 37 shows the results of simulation 5 for 2005. Water levels on Kent Island and at Grasonville are 0 to 2 ft higher than in simulation 1. The cone of depression at Easton is only about 43 ft below sea level at its deepest point, or about 11 ft higher than in simulation 1. Water levels in the northern part of the study area are similar to those in simulation 1.

Simulation 6—This simulation shows the effect of abandonment of all private and commercial wells on Kent Island and replacement by a community water system supplied by three large production wells. The total amount of pumpage is identical to that in simulation 1. Only the distribution has changed from dispersed domestic well withdrawal to concentrated supply-well withdrawal. Pumpage at Grasonville and elsewhere in the modeled area is identical to that in simulation 1.

Figure 38 shows the results of simulation 6 for 2005. Water levels are similar to those in simulation 1 throughout the modeled area. However, localized cones of depression have formed at the three production wells. The cones are

(Text continues on p. 61)

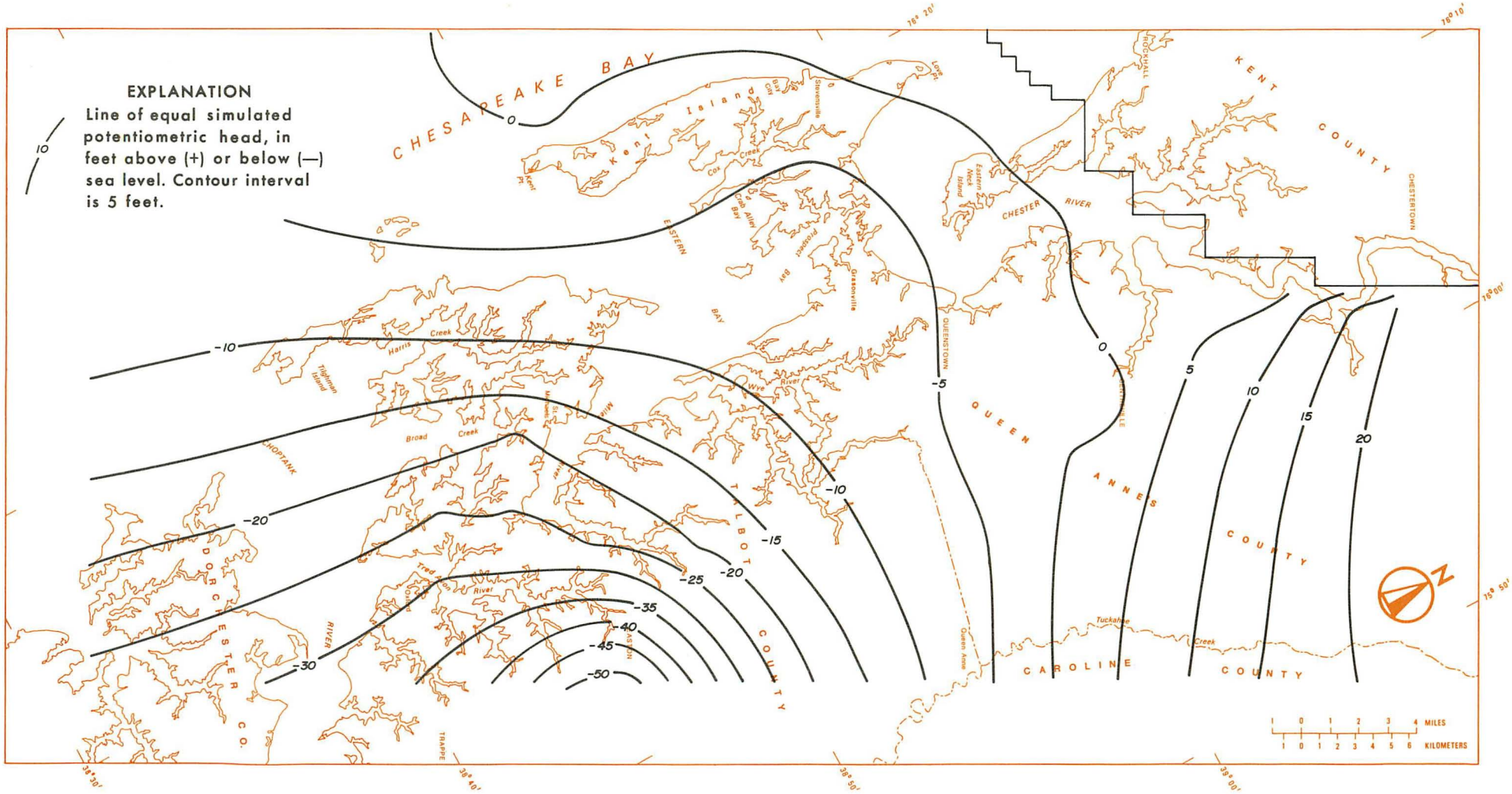


Figure 30. — Simulated potentiometric surface of the Aquia aquifer for 1990, based on projected pumpage.

SIMULATION 1

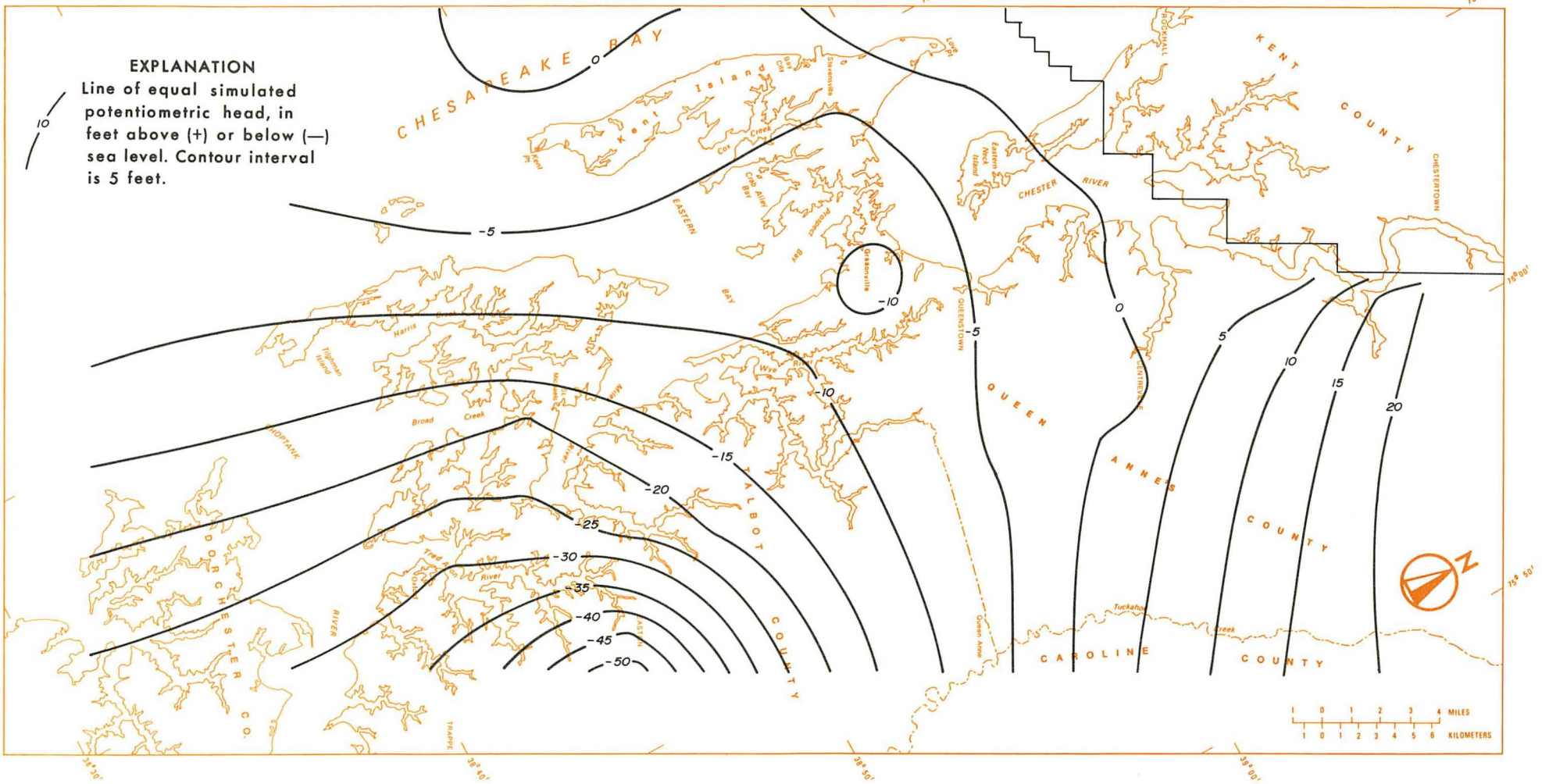


Figure 31. — Simulated potentiometric surface of the Aquia aquifer for 1995, based on projected pumpage.

SIMULATION 1

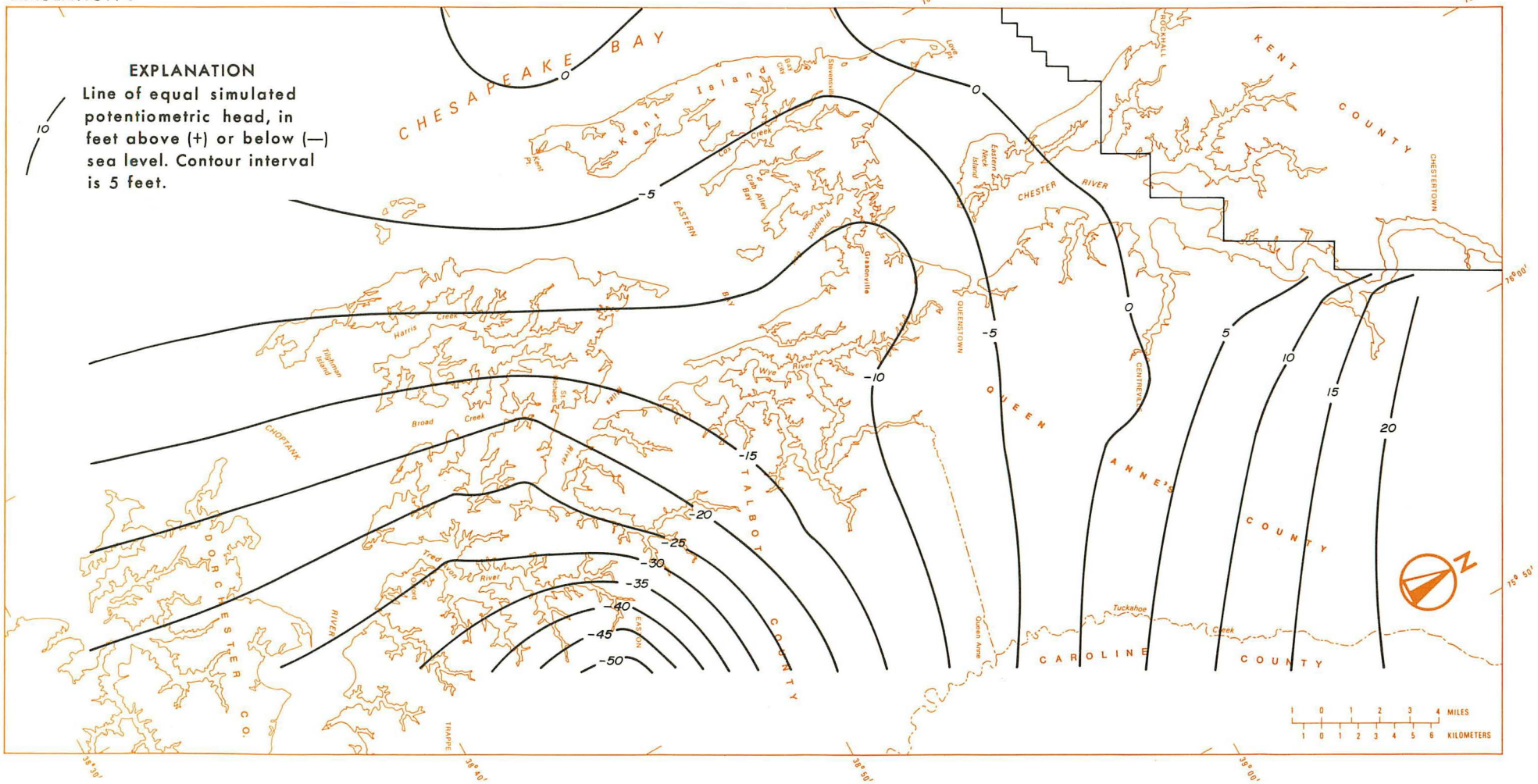


Figure 32. — Simulated potentiometric surface of the Aquia aquifer for 2000, based on projected pumpage.

SIMULATION 1

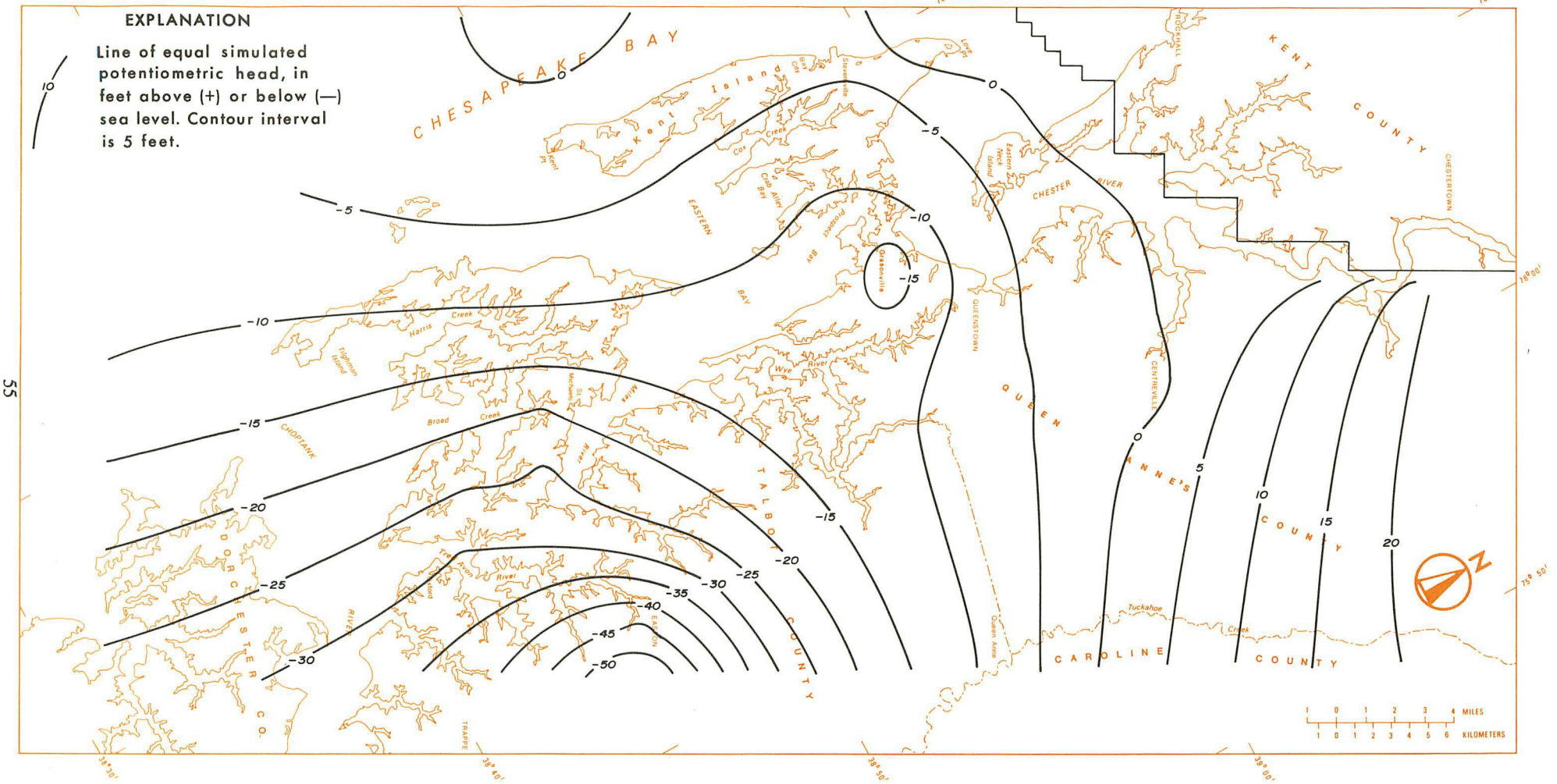


Figure 33. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on projected pumpage.

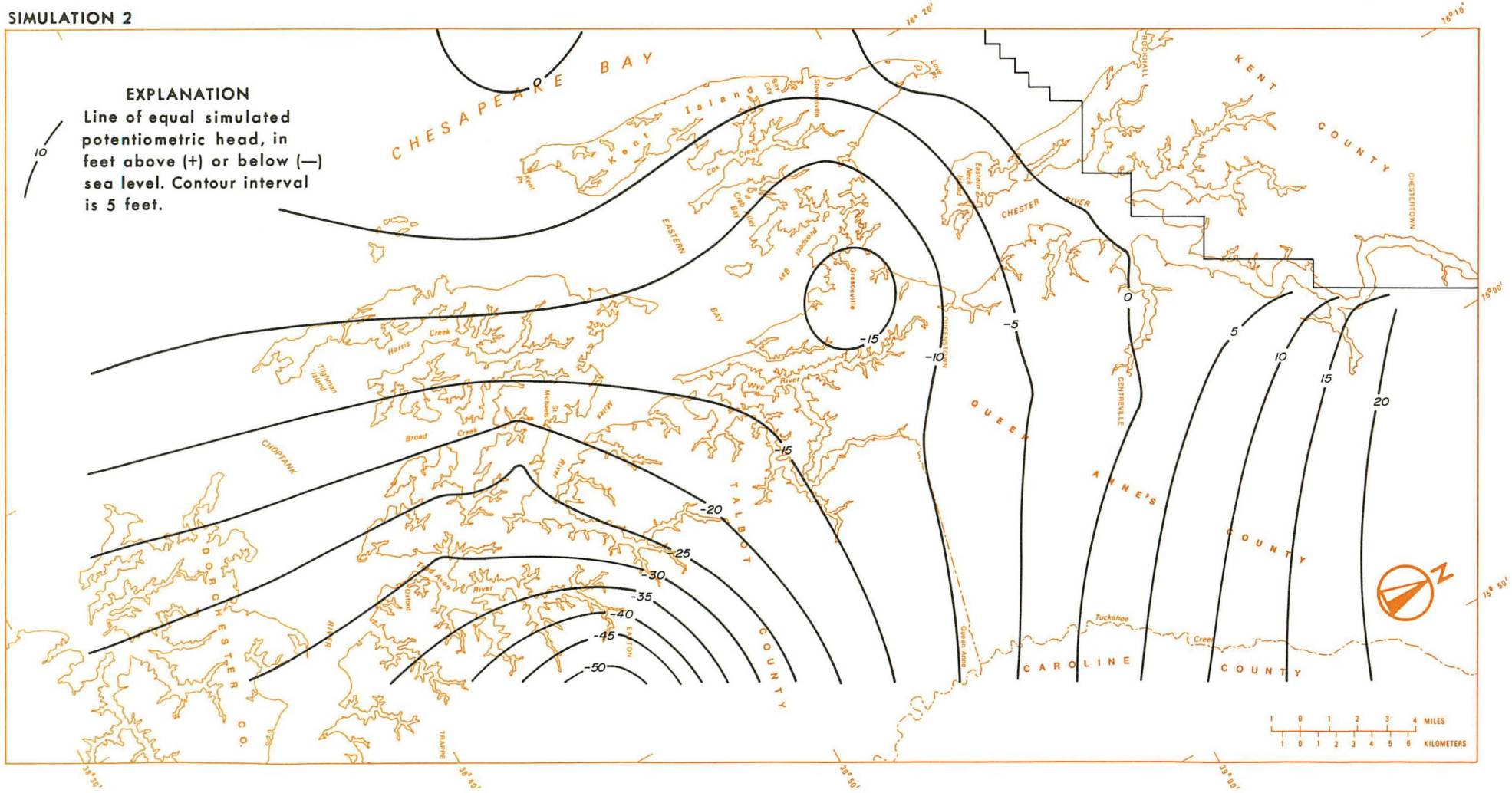


Figure 34. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on a 20-percent increase in projected pumpage at Kent Island and Grasonville.

SIMULATION 3

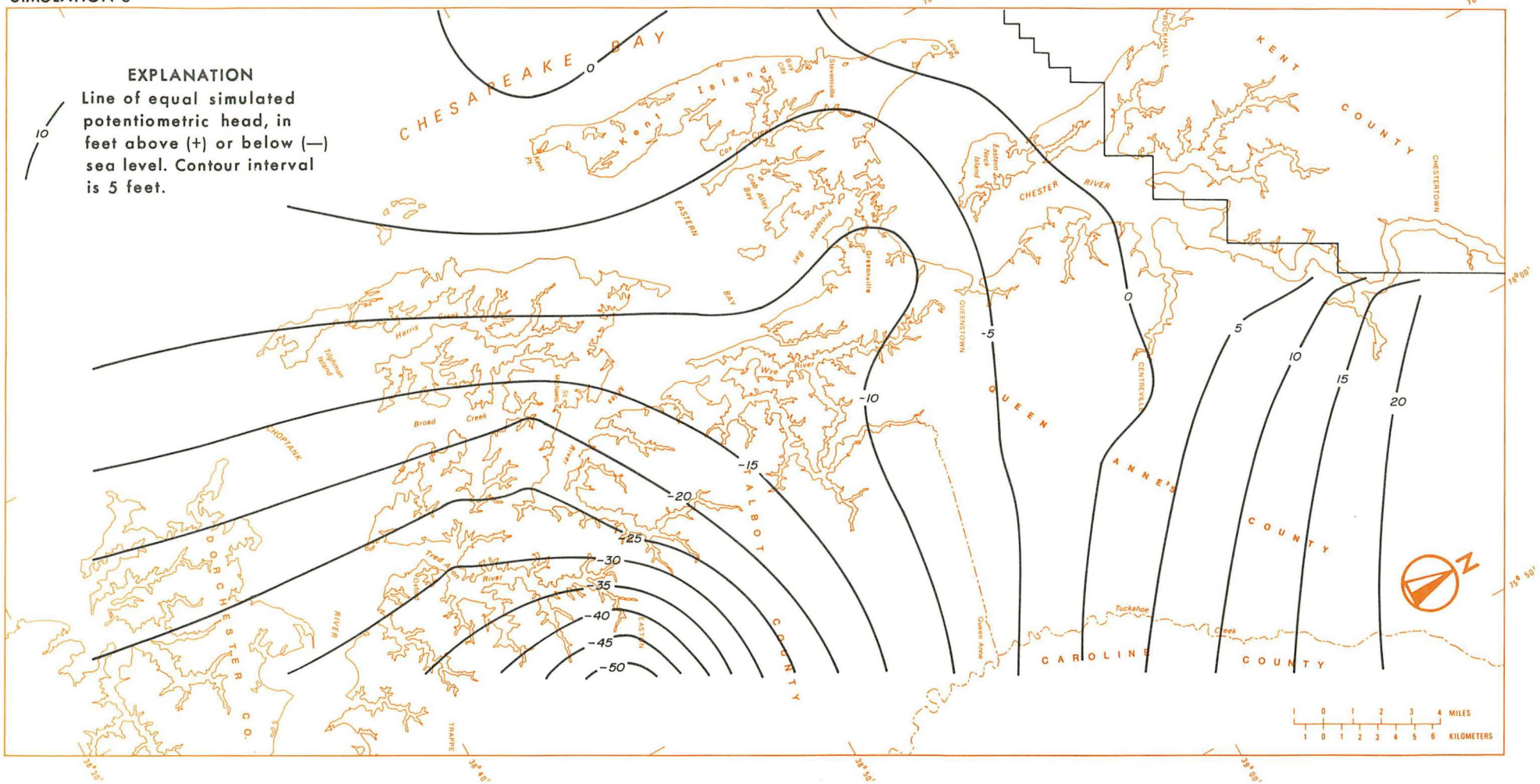


Figure 35. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on a 20-percent decrease in projected pumpage at Kent Island and Grasonville.

SIMULATION 4

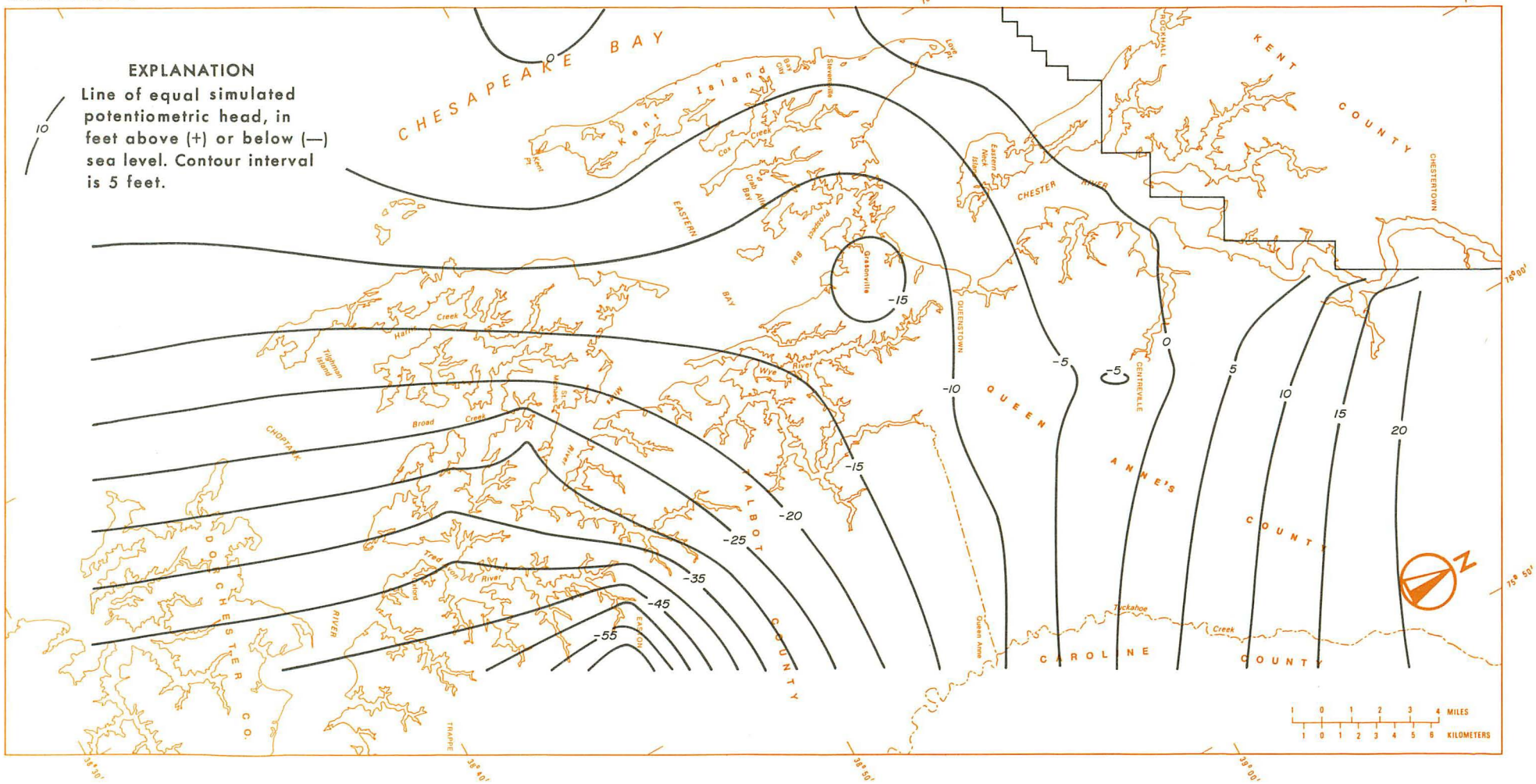


Figure 36. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on a 20-percent increase in projected pumpage in areas other than Kent Island and Grasonville.

SIMULATION 5

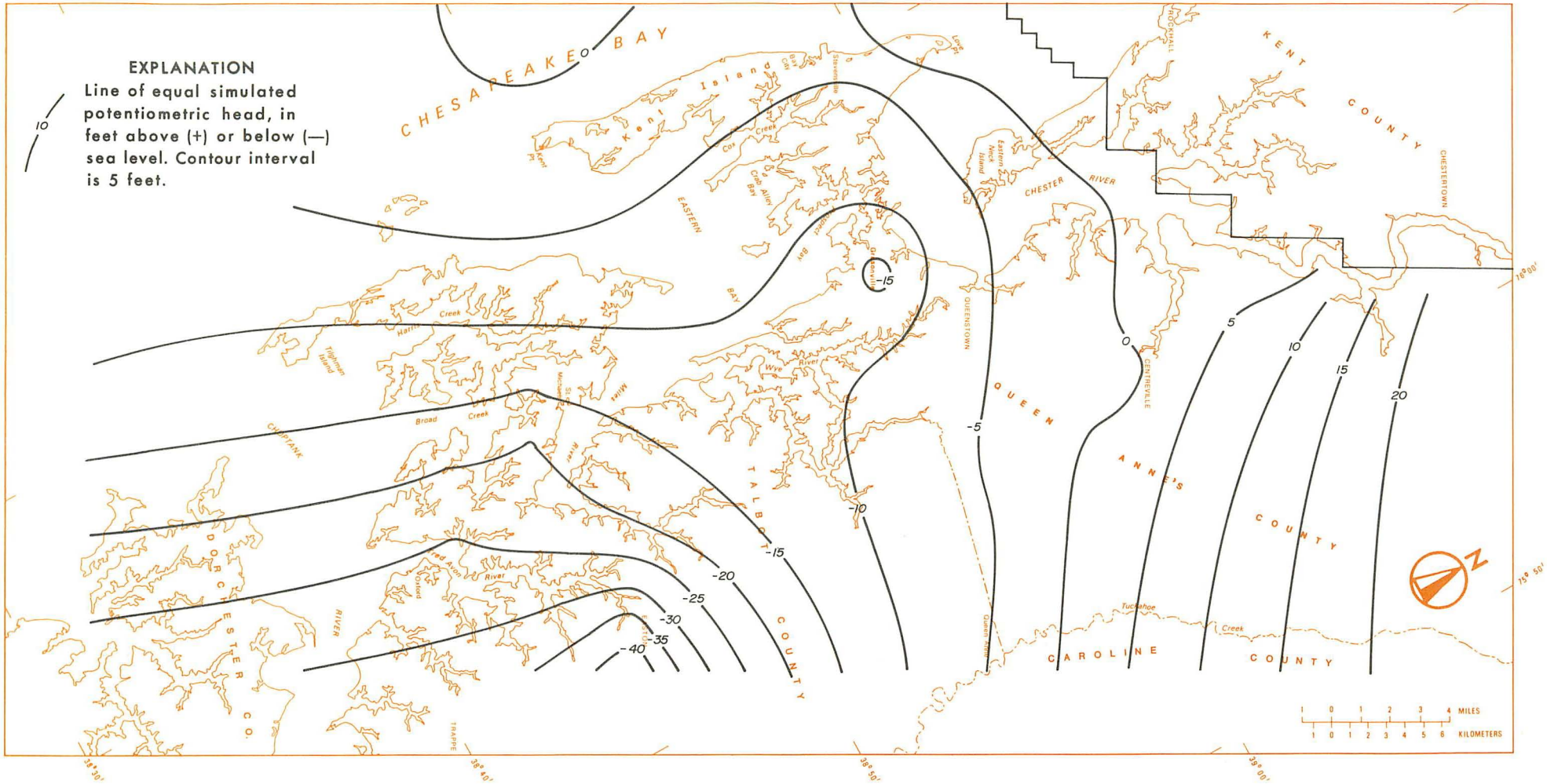


Figure 37. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on a 20-percent decrease in projected pumpage in areas other than Kent Island and Grasonville.

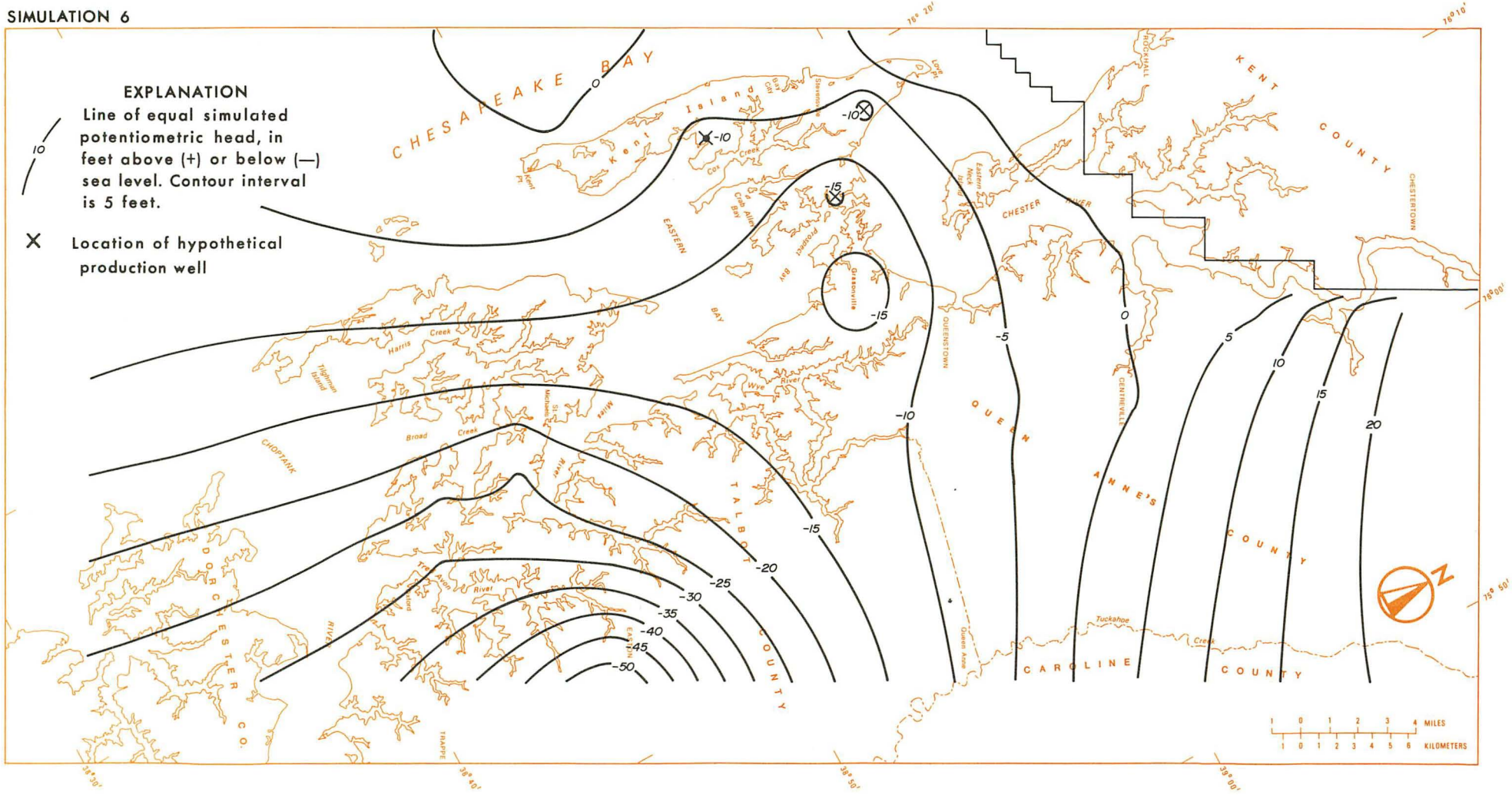


Figure 38. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on the replacement of all projected Kent Island pumpage by three production wells.

about 11, 13, and 17 ft below sea level at the southern, northern, and eastern production wells, respectively. The water level at Bay City is about 1 ft higher than in simulation 1.

Simulation 7—This simulation is somewhat similar to simulation 6, but only one-half of the domestic pumpage was replaced by the three supply wells. Again, the total amount of pumpage is identical to that in simulation 1; only the distribution was changed.

Figure 39 shows the results of simulation 7 for 2005. Water levels are similar to those in simulation 1 throughout the study area. However, localized cones of depression have formed at the locations of the production wells. The cones are about 7, 9, and 13 ft below sea level at the southern, northern, and eastern production wells, respectively.

Simulation 8—This simulation represents the replacement of one-half of the projected Aquia pumpage at Grasonville by an alternative water source. This alternative source would probably be deeper aquifers such as the Magothy or Potomac aquifers. Pumpage elsewhere in the modeled area was kept the same as in simulation 1.

Figure 40 shows the results of simulation 8 for 2005. The cone of depression at Grasonville is only about 11 ft below sea level, compared to 18 ft below sea level for simulation 1. Water levels on Kent Island are 1 to 2 ft higher than in simulation 1, with the greatest difference on the eastern part near Grasonville. Water levels elsewhere in the modeled area are similar to those in simulation 1.

Simulation 9—This simulation represents conditions if all pumpage on Kent Island and at Grasonville was discontinued in 1984. Water in these areas would hypothetically be supplied by deeper aquifers not included in the model, such as the Magothy and Potomac aquifers. In reality, pumpage from deeper aquifers may induce leakage from the Aquia, but this was not simulated.

Figure 41 shows the results of simulation 9 for 2005. Water levels have risen above sea level throughout most of Kent Island. The cone of depression at Grasonville has disappeared and water levels are about 2 ft below sea level. The cone of depression at Easton is about 50 ft below sea level, which is about 4 ft higher than in simulation 1.

SENSITIVITY ANALYSIS

Many of the data which are used as input for the flow model are not known accurately. A sensitivity analysis was performed on the calibrated flow model to determine the magnitude of error which might result from errors in the input data. This indicates the "sensitivity" of the model to the various inputs.

The sensitivity analysis was performed in the following manner. The calibrated flow model was used to simulate the best estimate of the effects of projected pumpage. This is referred to as the standard run (simulation 1). A series of model runs was then made in which a single input value was varied to its probable limits of error, while all others were kept the same as the standard run values. The simulated head distribution in the Aquia aquifer for each of these runs was then compared with that of the standard run. The flow model is most sensitive to input values which, when varied, produced head differences greater than the greatest error in the calibration on Kent Island (3 ft). The model is moderately sensitive to input values which, when varied, produced head differences less than the calibration error. The model is relatively insensitive to input values which, when varied, produced no head differences. The effects of varying the most sensitive inputs are described in detail.

The sensitivity analysis shows that the flow model results are most sensitive to input values for leakance of the Calvert and Nanjemoy Formations and the altitude of specified heads in the unconfined aquifer. Model results are moderately sensitive to transmissivity of the Aquia aquifer, leakance of bay-bottom sediments, leakance of the confining layer underlying the Piney Point aquifer, and the altitude of specified head in the bay. Model results are relatively insensitive to the storage coefficient in the Aquia aquifer, leakance of the confining layer where the Aquia aquifer subcrops beneath the unconfined aquifer, the placement of the lateral no-flow boundaries, and the specified flux boundary in the Aquia aquifer.

Increasing the leakance of the Calvert Formation by a factor of 10 produced heads in the Aquia as much as 8 ft higher on northern Kent Island than in the standard simulation. Increasing the leakance of the Nanjemoy Formation by a factor of 10 produced Aquia heads as much as 4 ft higher on western Kent Island than in the standard simulation. Increasing the altitude of specified heads in the unconfined aquifer by 5 ft increased heads in the Aquia aquifer by as much as 4 ft on northern Kent Island and by about 2 ft elsewhere on Kent Island.

Because the inputs were varied to their approximate limits of error, the variance in sensitivity analysis results provides an indication of the possible magnitude of error in the model results due to inaccuracies in model input. However, the use of a different input value would require the adjustment of other inputs to compensate during calibration, and this would probably also compensate in the predictive runs. Thus, the amounts of error indicated in the sensitivity analysis should be regarded as maximum values. The greatest variance determined in the sensitivity analysis was 8 ft, which results from changing the leakance value of the Calvert Formation. The amount of possible error in model results is somewhat less than that value, probably around 2 to 4 ft.

SIMULATION 7

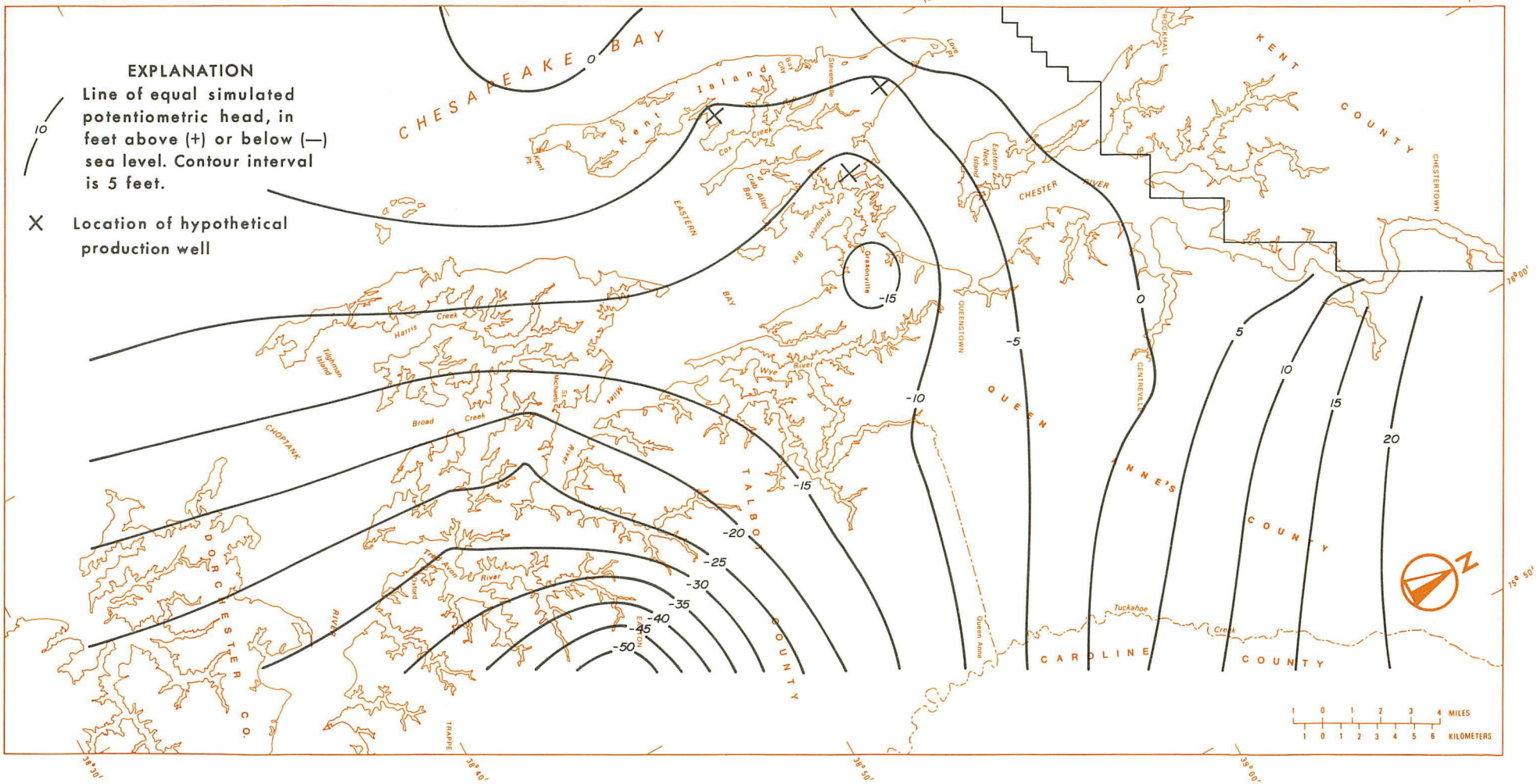


Figure 39. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on the replacement of one-half of projected Kent Island pumpage by three production wells.

SIMULATION 8

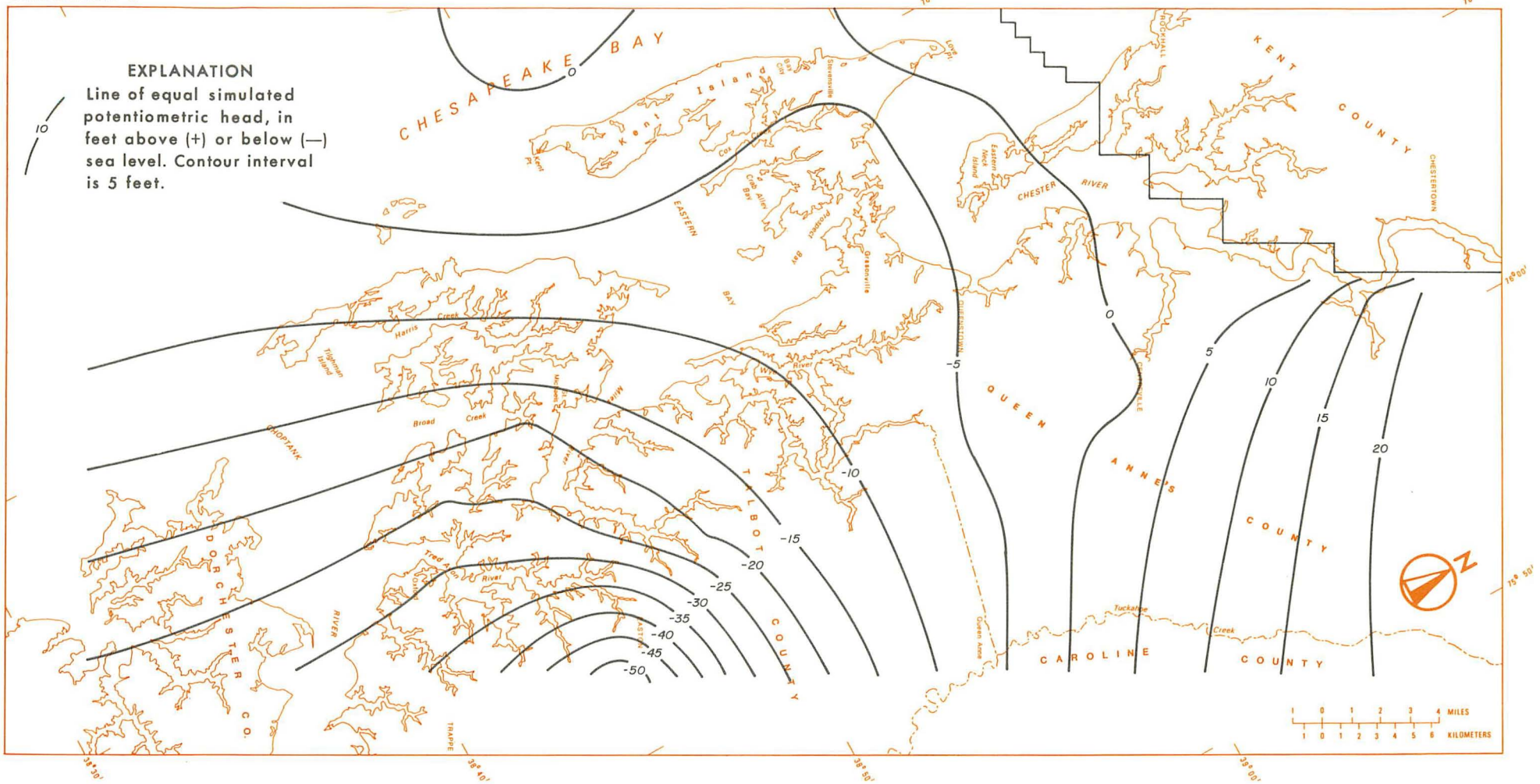


Figure 40. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on a 50-percent decrease in projected pumpage at Grasonville.

SIMULATION 9

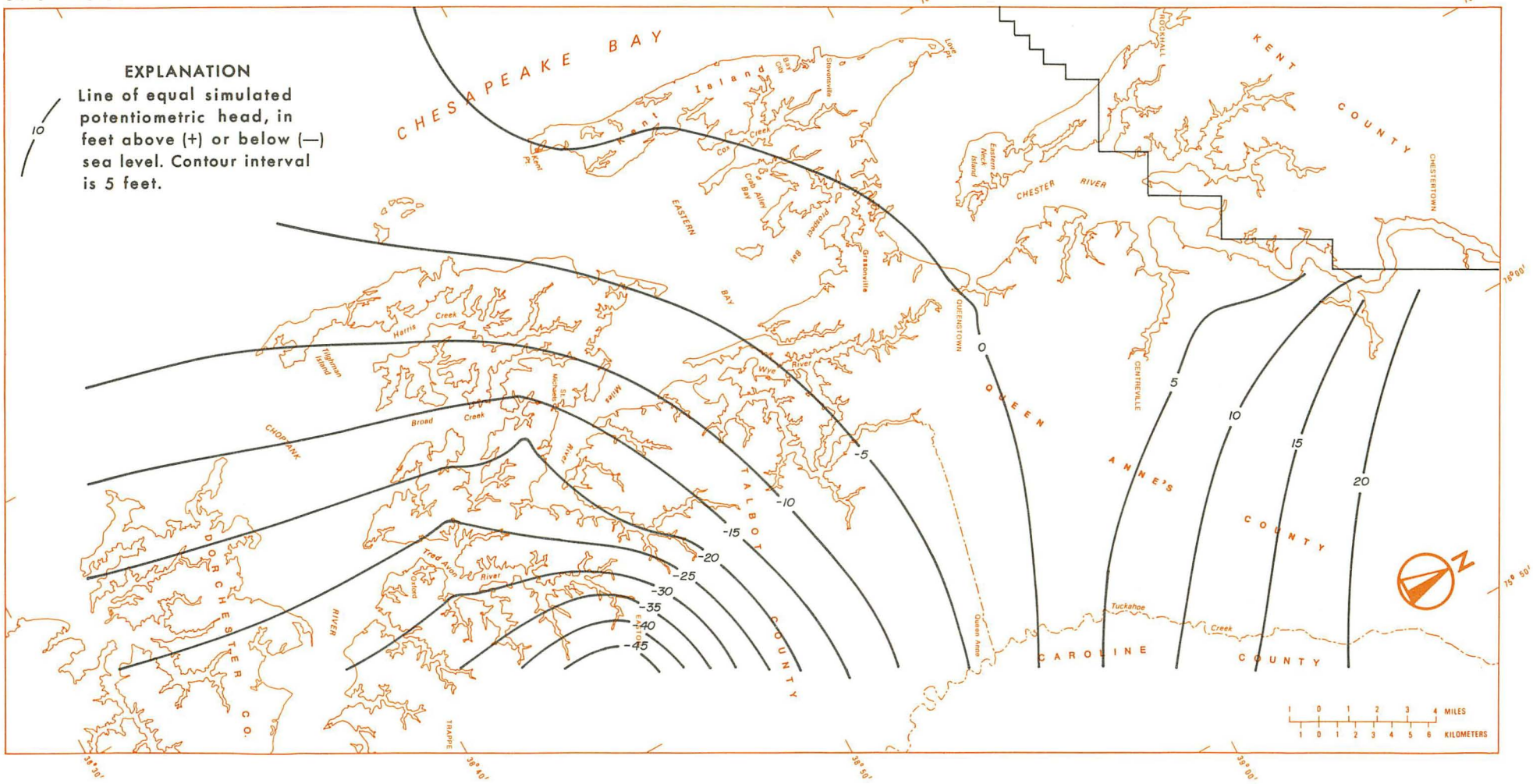


Figure 41. — Simulated potentiometric surface of the Aquia aquifer for 2005, based on discontinued pumpage at Kent Island and Grasonville after 1984.

SIMULATION OF BRACKISH-WATER MOVEMENT

A major objective of this study is to estimate the effect of projected pumpage on the distribution and movement of brackish water in the Aquia aquifer. Ideally, this would entail establishing a relationship between historical brackish-water movement and historical pumpage, then using that relationship to predict the movement of brackish water in response to future pumpage. However, because of the lack of historical chloride data in critical areas, it was not possible to quantitatively determine the rate of brackish-water movement in the past.

To compound the difficulty, the hydrogeologic controls which influence brackish-water movement differ significantly throughout the study area. Some controls, such as the hydraulic properties of paleochannel sediments, have not been clearly defined in all areas, and the relative importance of these controls has not been clearly established.

In order to evaluate the potential of brackish-water movement in response to pumpage stress, a cross-sectional solute-transport model was developed which is capable of simulating the important hydrogeologic controls. A cross section was chosen for modeling which includes these controls, and for which there are abundant data available (fig. 1). The distribution and movement of brackish water was simulated in response to prepumping and historical pumping conditions and the model was calibrated, to the extent possible, to 1984 data. The model was then used to simulate the distribution and movement of brackish water in response to projected and alternative pumping conditions. The importance of the hydrogeologic controls was evaluated by altering their hydraulic properties or removing them from the model and noting the effect on model results. The Saturated-Unsaturated Transport (SUTRA) model (Voss, 1984) was chosen because it can simulate density-dependent flow as well as solute dispersion, pumpage-induced stress, and a complex permeability field.

Because of the lack of historical data required to accurately calibrate the solute-transport model, its capacity to quantitatively predict the future distribution of brackish water in the Aquia aquifer is somewhat limited. The calculated results are regarded as qualitative, simulating the general features of the system. The accuracy of the results was evaluated in a sensitivity analysis in which individual values of input data were varied within reasonable limits in the calibrated model, and the effects on model results were noted. In this way, the sensitivity of model results to inaccuracies and variations in hydraulic properties was evaluated.

The solute-transport model was developed in a manner consistent with the flow model where possible. Boundary conditions were simulated similarly in both models. Hydraulic properties from the calibrated flow model were initially entered in the solute-transport model, although some of those properties were adjusted during calibration. Head values calculated from the flow model were used to calculate pressure values for the transport model boundaries to simulate prepumping, historic pumping, and projected pumping conditions. In addition, stress periods used in each model were identical, except that the prepumping period of the solute-transport model was much longer than that of the flow model to establish an equilibrium chloride distribution. By maintaining consistency in input data and setup between the two models, it was possible to compare results directly and to test assumptions of one model against the other.

THEORY

The transport of a solute dissolved in a fluid flowing through a porous medium can be described by the equation (Freeze and Cherry, 1979):

$$D_L \frac{\delta^2 C}{\delta S_L^2} + D_T \frac{\delta^2 C}{\delta S_T^2} - V_L \frac{\delta C}{\delta S_L} = \frac{\delta C}{\delta t} , \qquad (7)$$

where

C = concentration of the solute [M/L^3];

S_L and S_T = curvilinear coordinate directions directed parallel and orthogonal to the direction of flow, respectively [L];

V_L = average curvilinear velocity [L/T];

D_L and D_T = coefficients of dispersion in the longitudinal and transverse directions, respectively [L]; and

t = time [T].

Solution of this equation yields the concentration of the solute at a point in time and space. Analytical solutions of this equation are available for greatly simplified systems. However, most real hydrogeologic systems are much too complicated for this approach and numerical methods have been developed to solve equation 7. SUTRA[3/] is one such numerical method (solute-transport model) which calculates the concentration of a solute within a two-dimensional area.

SUTRA uses a hybrid finite-element and integrated finite-difference method to approximate the flow and transport equations. The area to be simulated is divided into elements by a mesh and values for hydraulic properties are assigned either to nodes (at intersections of mesh lines) or to elements (areas within mesh lines). Time is also divided into

3/ SUTRA is the U.S. Geological Survey Saturated-Unsaturated TRAnsport Model.

discrete periods referred to as time steps. The model calculates fluid pressure and solute concentration at each node at the end of each time step.

MODEL DESCRIPTION

Location

The cross section chosen for modeling (fig. 42) is 5 mi (26,400 ft) long by 300 ft deep. It extends 2.5 mi beneath the Chesapeake Bay and 2.5 mi beneath Kent Island (fig. 1). This section was chosen because it incorporates the excellent lithologic data for the paleochannel from the Bay Bridge borings, and incorporates lithologic and water-chemistry data from wells QA Eb 144, QA Eb 156, and QA Eb 157. In addition, the trace of the cross section is roughly parallel to the direction of ground-water flow during pre-pumping and 1984 conditions.

An inherent assumption of any cross-sectional model is that all flow is parallel to the plane of the cross section and no water enters or leaves the sides of the model. This

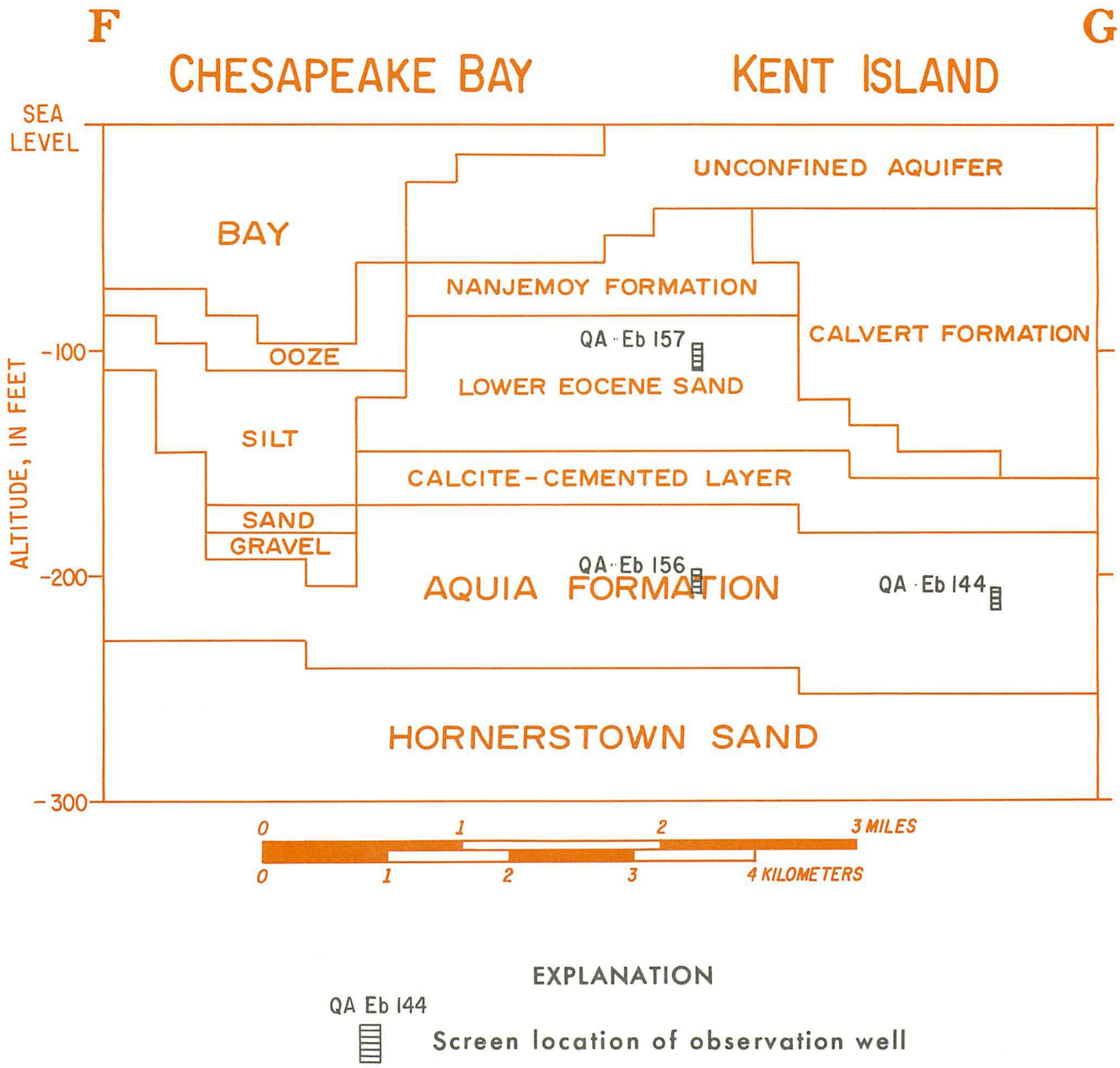


Figure 42. — Lithologic units simulated in the solute-transport model, and locations of observation wells.

assumption holds true in the Kent Island solute-transport model for prepumping and 1984 conditions, when flow was approximately parallel to the transport-model cross section (figs. 26 and 29). However, as simulated in the flow model during the interceding time period (1945-64), the flow direction swung around to the south (figs. 27 and 28) and was not parallel to the cross section. This could cause error in solute-transport model results if water entering from the side were of significantly different concentration than water in the model. In the Kent Island model, the error is small because the brackish-water interface is oriented roughly perpendicular to the model cross section (fig. 14) and water entering the side of the model would be of equal concentration to water in the model at that point of entry.

Grid Design

The cross-sectional area of the model was divided into rectangular elements by a regularly spaced grid (fig. 43). Grid spacing in the horizontal direction was 1,320 ft, and three spacings were tried in the vertical direction, 30, 12, and 3 ft. The coarsest grid spacing was used in the early stages of modeling to establish general flow patterns. It was found, however, that finer vertical discretization was required to properly simulate the thinner lithologic units and to simulate the proper shape of the brackish-water wedge. The 3-ft vertical spacing was used for all solute-transport simulations because it provided the best vertical definition of the brackish-water wedge. However, the results were not significantly different from those obtained using the 12-ft vertical discretization as demonstrated in the sensitivity analysis. Considering the reduced computation time of the 12-ft spacing, it probably would have been adequate for these simulations.

Elements and nodes were assigned hydraulic properties appropriate for the lithologic unit occupying that position in the cross section. Figure 42 shows the distribution of lithologic units simulated in the solute-transport model.

Boundary Conditions

Boundary conditions were assigned to the edges of the model that approximate hydraulic conditions in the aquifer system (fig. 43). A no-flow boundary was assigned to the bottom edge of the model, representing the lower confining bed in the Severn and Matawan Formations. A no-flow boundary also was assigned to the Calvert Formation at the right edge of the model since any flow through the low-permeability Calvert would most likely to be vertical and parallel to the model edge. A specified-pressure boundary was assigned to the left edge of the model, referred to as the Aquia brackish-water boundary. The specified pressures were calculated as a column of brackish water (chloride concentration = 10,500 mg/L) at a head of zero ft above sea level. A specified-pressure boundary was assigned to the left half of the top edge of the model representing the surface of the bay, referred to as the bay boundary. A pressure of zero was specified for this boundary. A specified-pressure boundary was assigned to the right half of the top edge of the model representing the water-table altitude, referred to as the unconfined boundary. Specified pressures were calculated from freshwater heads in the water table. A specified-pressure boundary was assigned to the Aquia aquifer at the right edge of the model, referred to as the Aquia freshwater boundary. Specified pressures were calculated as a column of freshwater at a given head. That head was varied to simulate various pumping conditions in the Aquia aquifer. Water entering the model through the bay and Aquia (brackish) boundaries was assigned a chloride concentration of 10,500 mg/L. Water entering the model through the unconfined and Aquia (fresh) boundaries was assigned a chloride concentration of 0 mg/L.

Initial Conditions

Initial conditions for chloride and water-pressure distribution are required to begin the model simulation. Values for chloride concentration and water pressure were obtained throughout the model by making a 30,000-year run using prepumping heads from the flow model to calculate pressures at the solute-transport model boundaries. Chloride concentrations at the beginning of the equilibrium run were arbitrarily chosen with the left half of the model filled with brackish water (10,500 mg/L) and the right half filled with freshwater (0 mg/L). This established an equilibrium distribution of chloride and pressure, consistent with flow-model heads, from which to start the stressed solute-transport simulations. The simulated prepumping chloride distribution is shown in figure 44.

The 30,000-year time interval required for the model to obtain equilibrium may exceed the actual time interval over which equilibrium conditions are assumed to have existed. This possibility is addressed in the section of the report entitled "Evaluation of Hydrogeologic Controls."

Input Data

Input data to the solute-transport model include fluid properties and solid matrix properties. Most of these properties were set constant throughout the model. Only the permeability of the solid matrix was assigned different values throughout the cross section to simulate the different hydrogeologic units consistent with the flow model.

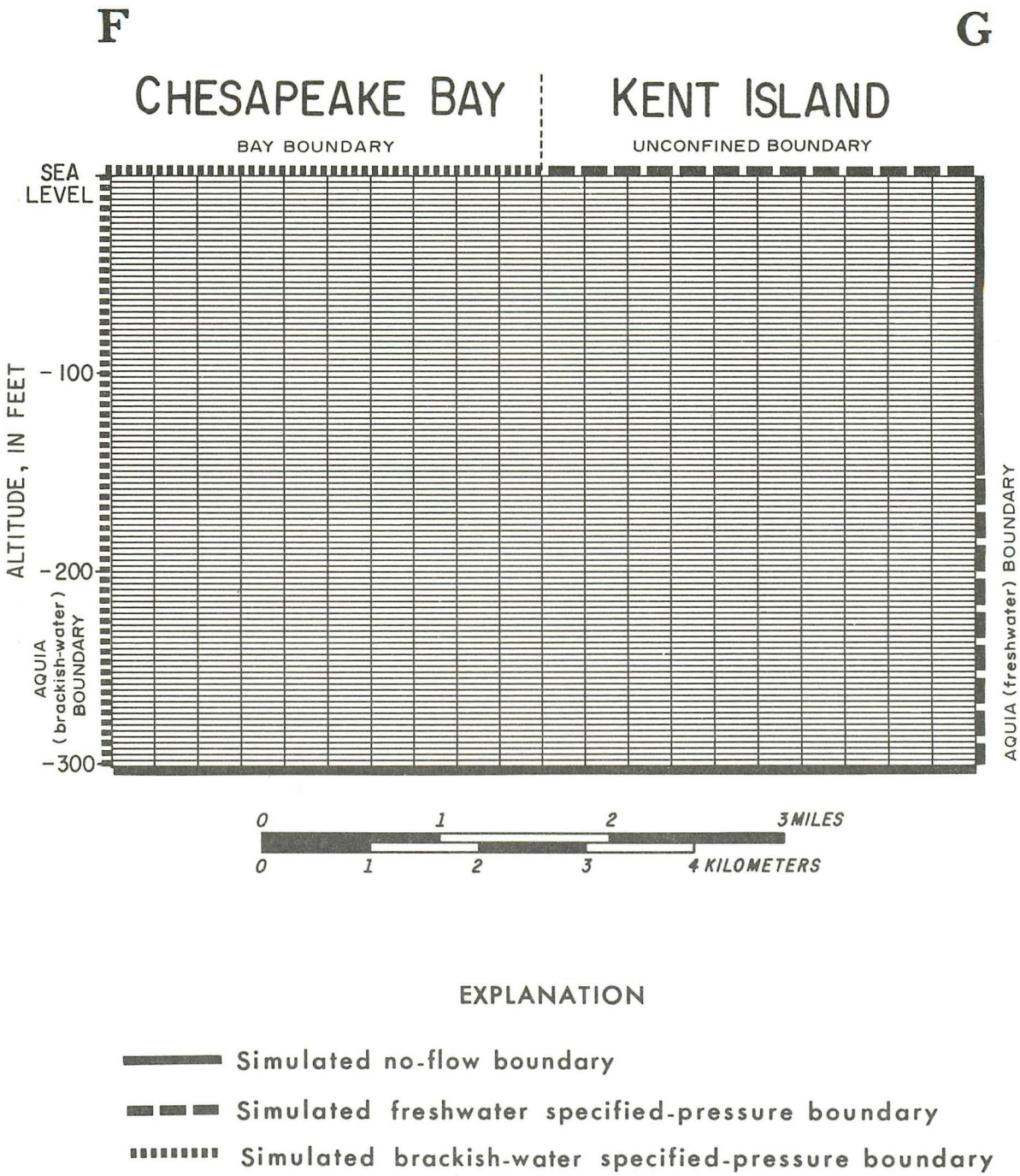
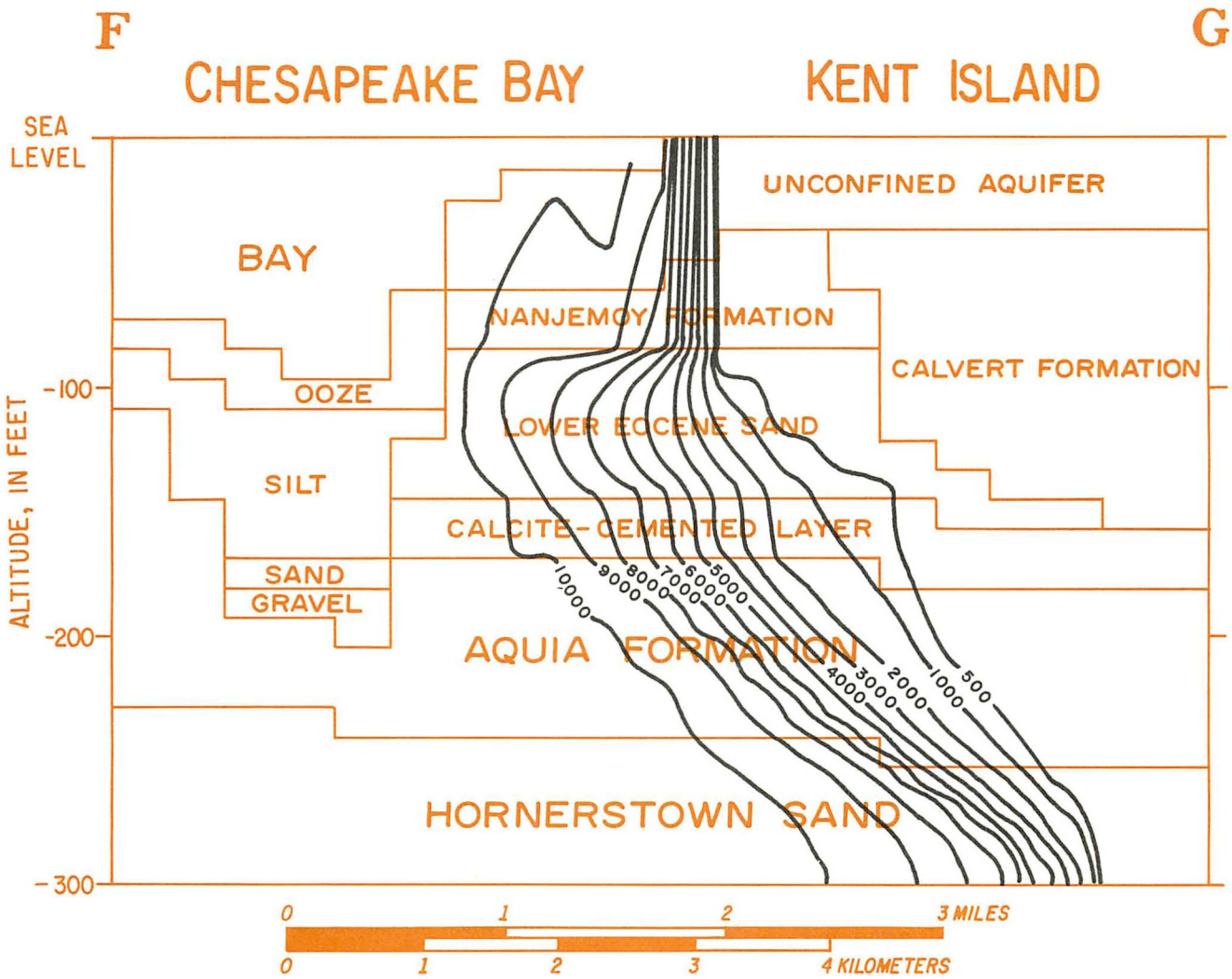


Figure 43. — Finite-element grid and simulated boundaries of the solute-transport model.



EXPLANATION

1000 Line of equal simulated chloride concentration, in milligrams per liter

Figure 44. — Simulated prepumping chloride distribution.

Fluid Properties

Fluid compressibility	= 4.4×10^{-7} per kilopascals
Base concentration	= 0.0 milligrams per liter
Density of fluid at base concentration	= 62.43 pounds (mass) per cubic foot
Coefficient of fluid density change with concentration change	= 1.173 (unitless)
Viscosity	= 6.72×10^{-4} pounds (mass) per second per square foot

No permeability data are available for the paleochannel sediments. These values were estimated on the basis of typical permeabilities for sediments of these types given in Freeze and Cherry (1979). There are also no data available for longitudinal and transverse dispersivity. These values were estimated from interface width and spatial discretization requirements given in Voss (1984). Comparable values (longitudinal dispersivity = 262 ft, transverse dispersivity = 0.66 ft) were used in a similar sea-water intrusion simulation in southern Oahu, Hawaii (Voss and Souza, U.S. Geological Survey, written commun., 1987).

Matrix Properties

Matrix compressibility	= 7.70×10^{-7} per kilopascals
Porosity	= 0.30 (dimensionless)
Longitudinal dispersivity	= 304.8 feet
Transverse dispersivity	= 0.0278 feet
Permeability	
Aquia Formation	= 8.62×10^{-11} feet squared
Lower Eocene sand	= 8.62×10^{-11} feet squared
Hornerstown Sand	= 4.31×10^{-12} feet squared
Nanjemoy Formation	= 1.94×10^{-14} feet squared
Calvert Formation	= 1.16×10^{-15} feet squared
Unconfined aquifer	= 8.62×10^{-13} feet squared
Calcite-cemented layer	= 8.62×10^{-13} feet squared
Paleochannel sediments	
Ooze	= 8.62×10^{-14} feet squared
Silt	= 8.62×10^{-14} feet squared
Sand	= 8.62×10^{-11} feet squared
Gravel	= 8.62×10^{-9} feet squared

SUTRA makes its calculations in terms of water pressure instead of hydraulic head. Input and output for the model are also in terms of pressure. Water pressure at a specified point in a water column of given head and uniform density can be calculated from the equation (Freeze and Cherry, 1979),

$$p = (h + d)\,\rho g, \qquad (8)$$

where

p = fluid pressure $[M/Lt^2]$,
h = hydraulic head above sea level $[L]$,
d = depth below sea level $[L]$,
ρ = fluid density $[M/L^3]$, and
g = gravitational acceleration $[L/T^2]$.

Water pressure can be calculated in a water column of variable density by dividing the column into n depth increments, d_i, and assigning a density value, ρ_i, to each increment. Assuming the water above sea level is fresh (ρ = 1.000), equation 8 becomes,

$$p = (h + \sum_{1}^{n} \Delta d_i\, \rho_i)\, g. \qquad (9)$$

CALIBRATION

The first step of model calibration was the adjustment of input data to obtain a reasonable prepumping pressure and chloride distribution. Since there are no accurate pressure or chloride data available for this time period, no attempt was made to quantitatively calibrate the model at this stage. Only the general features of the prepumping flow system were simulated. The pressure field was considered calibrated when the simulated flow pattern (fig. 45) was consistent with the conceptual (fig. 13) and flow models; that is, water flowed westward through the Aquia aquifer and discharged at the eastern portion of the Chesapeake Bay. The Aquia received recharge from the unconfined aquifer through the confining layer in the Calvert and Nanjemoy Formations. The chloride field was considered calibrated when brackish water from the bay formed an inclined interface with freshwater in the vicinity of the bay shore, as shown in figure 44.

The second step of model calibration was the entry of pumping conditions through 1984, and adjustment of input data to obtain a reasonable match between simulated and observed pressure and chloride data. The model was rerun with prepumping conditions and the results checked each time an input value was changed. The simulated chloride distribution for 1984 is shown in figure 46 as well as measured chloride concentrations at three wells for 1984. The simulated 1984 flow pattern is shown in figure 47. Table 6 lists chloride concentrations and head values calculated from simulated pressures at the end of each stress period, and the observed chloride and head values at the three observation wells in 1984. There is general agreement between the observed and simulated 1984 values. The simulated chloride concentration at well QA Eb 157, 415 mg/L, is significantly higher than the observed value, 28 mg/L, perhaps due to numerical dispersion in the model calcula-

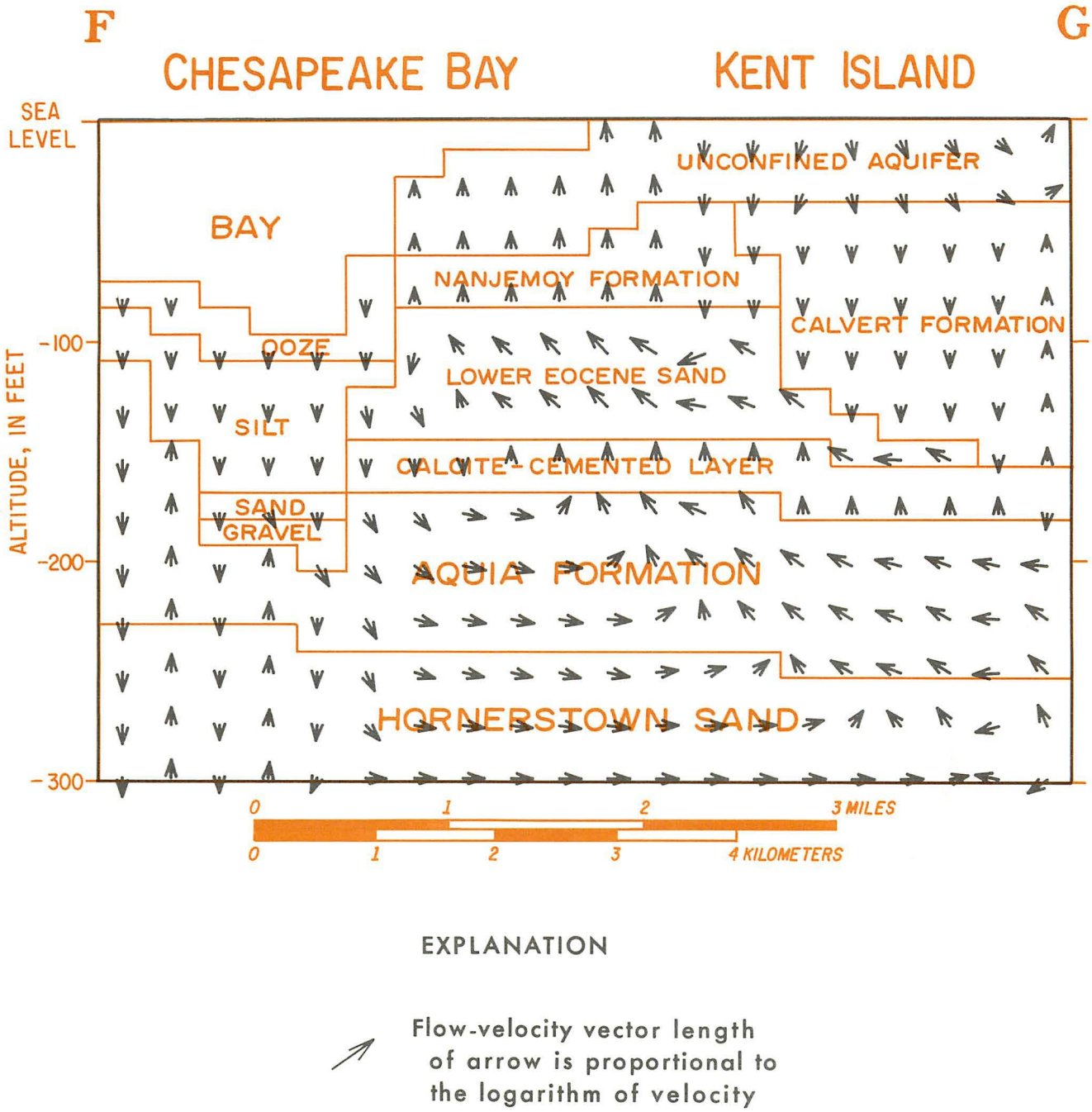


Figure 45. — Simulated prepumping ground-water flow-velocity vectors.

tions. This indicates that model results may not be accurate in the low concentration range of the interface.

Figure 48 shows the simulated chloride concentration and head values calculated from simulated pressure at well QA Eb 156, along with the observed values.

SIMULATION OF PROJECTED PUMPAGE

The calibrated solute-transport model was used to simulate the effects of projected pumpage on the distribution of chloride in the Aquia aquifer. The projected-pumpage sim-

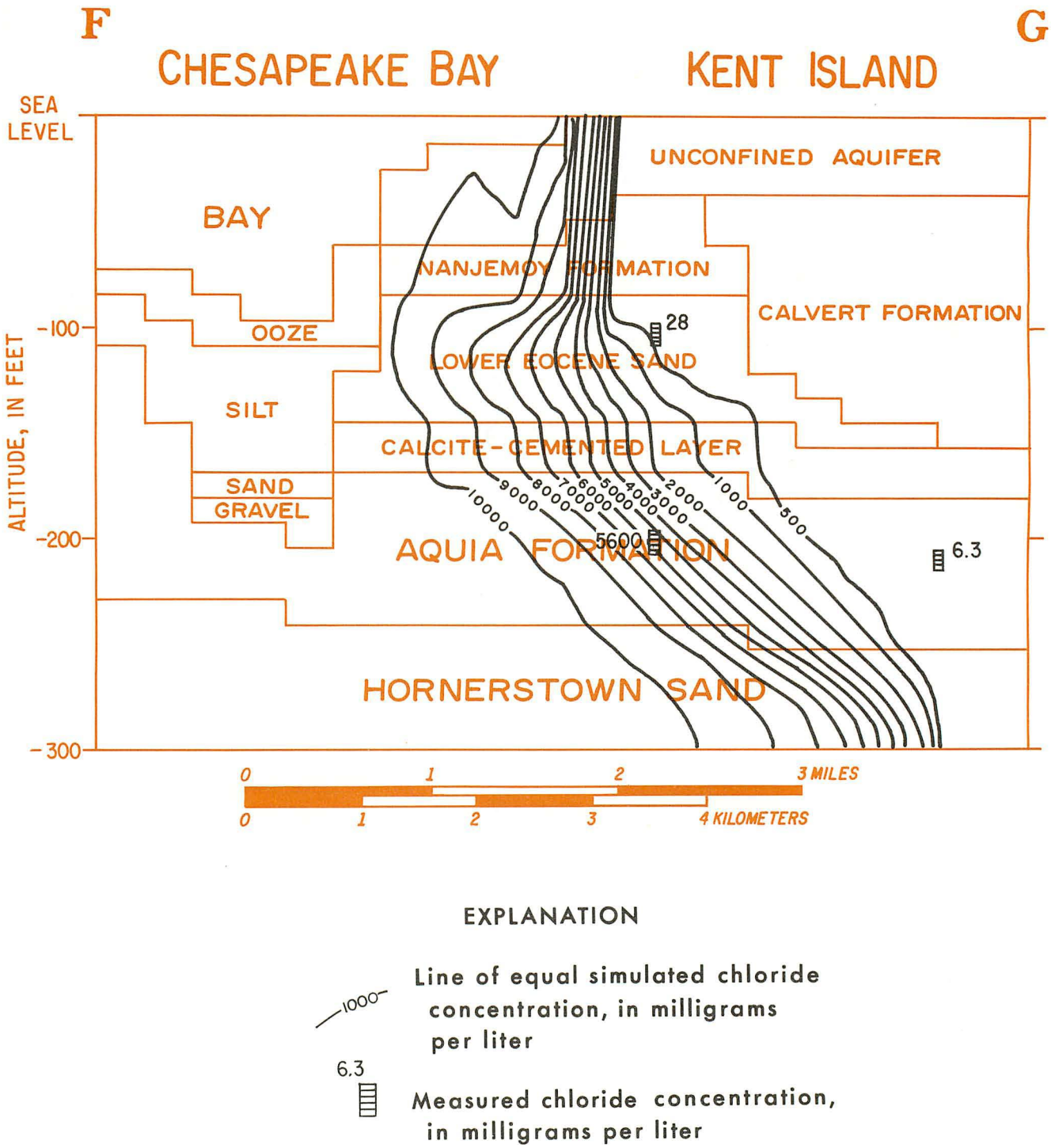


Figure 46. — Simulated 1984 chloride distribution with measured chloride concentrations.

ulations of the solute-transport model were made analogous to those of the flow model. Stress periods were identical in the two models and simulated heads from projected pumpage runs of the flow model were used to calculate pressures for the Aquia freshwater specified-pressure boundary in the solute-transport model using equation 9.

Three simulations were made with the transport model which bracket the best estimate of future pumpage. These simulations are analogous to simulations 1, 2, and 3 of the flow model. Solute-transport model simulations were also made which simulate the effects of maintaining 1984 pumpage through the year 2005, of returning Aquia heads to their

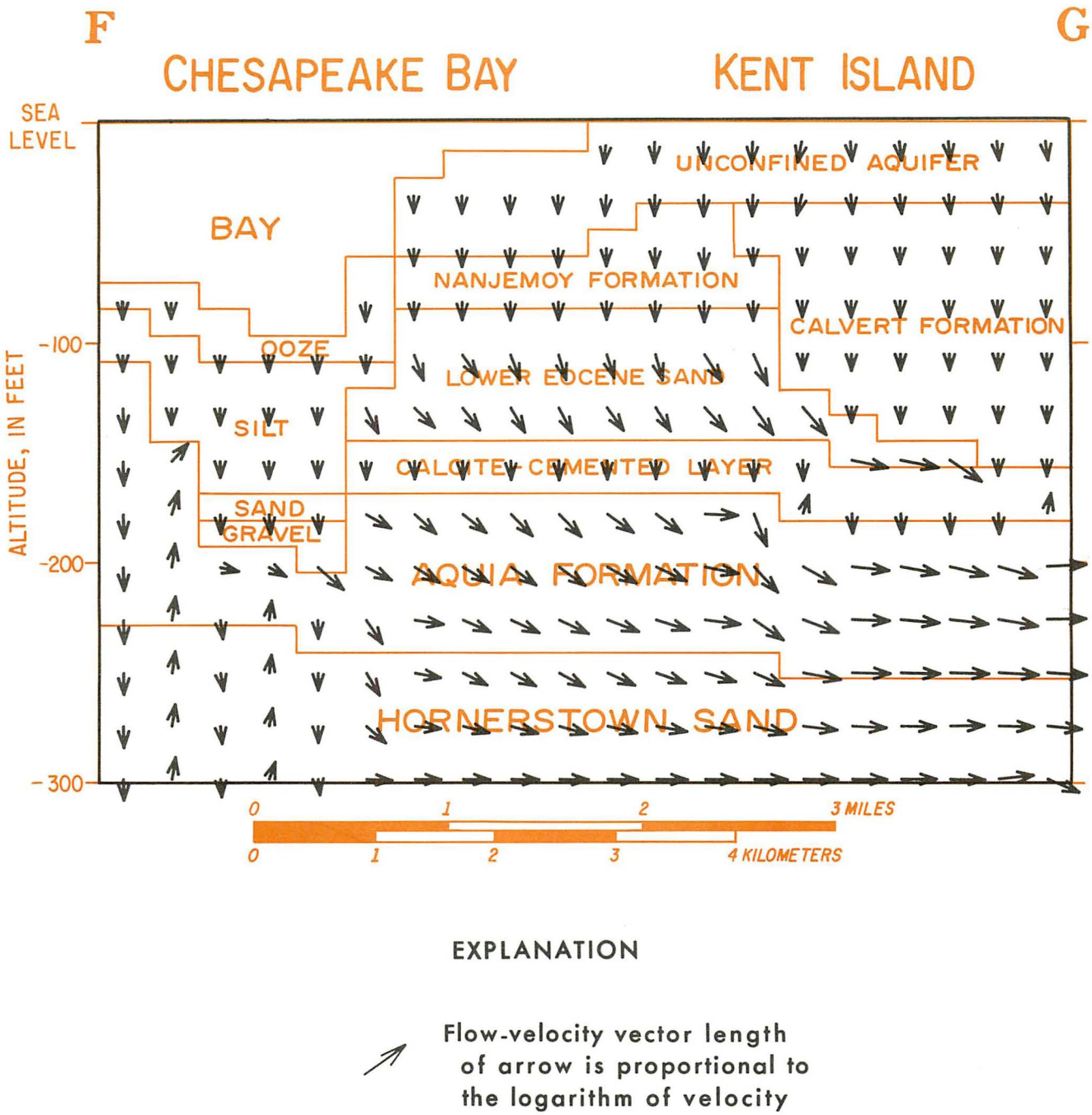


Figure 47. — Simulated 1984 ground-water flow-velocity vectors.

prepumping values from 1984 through 2005, and of discontinuing pumpage in the Aquia on Kent Island and at Grasonville as of 1984 while continuing pumpage elsewhere, analogous to simulation 9 of the flow model.

Figure 49 shows the 2005 simulated chloride distribution based on best-estimate projected pumpage from simulation 1 of the flow model. The position of the 1,000-mg/L isochlor advances about 440 ft in the Aquia Formation by 2005. The average velocity of the 1,000-mg/L isochlor advancement is therefore about 21 ft/yr (feet per year) during the 21-year period. The leading edge of the front moves more slowly in the Lower Eocene sand and the Hornerstown Sand.

Table 6. — Simulated and measured chloride concentrations and heads based on projected pumpage

[mg/L = milligrams per liter; ft = feet]

Observation well number	Prepumping		1984				1990		1995		2000		2005	
	Simulated		Simulated		Measured		Simulated		Simulated		Simulated		Simulated	
	Chloride (mg/L)	Head (ft)	Chloride (mg/L)	Head (ft)	Chloride (mg/L)	Head (ft)	Chloride (mg/L)	Head (ft)	Chloride (mg/L)	Head (ft)	Chloride (mg/L)	Head (ft)	Chloride (mg/L)	Head (ft)
QA Eb 157	342	2.1	415	0.7	28	0.1	415	0.5	411	0.3	408	0.1	404	-0.1
QA Eb 156	5,293	2.3	5,619	.9	5,600	* .5	5,668	.7	5,711	.5	5,753	.3	5,795	.1
QA Eb 144	3.1	2.9	3.1	-2.1	6.3	-1.7	3.6	-2.8	4.4	-3.6	5.5	-4.3	7.1	-5.1

*Measured water level corrected for brackish-water density in well bore.

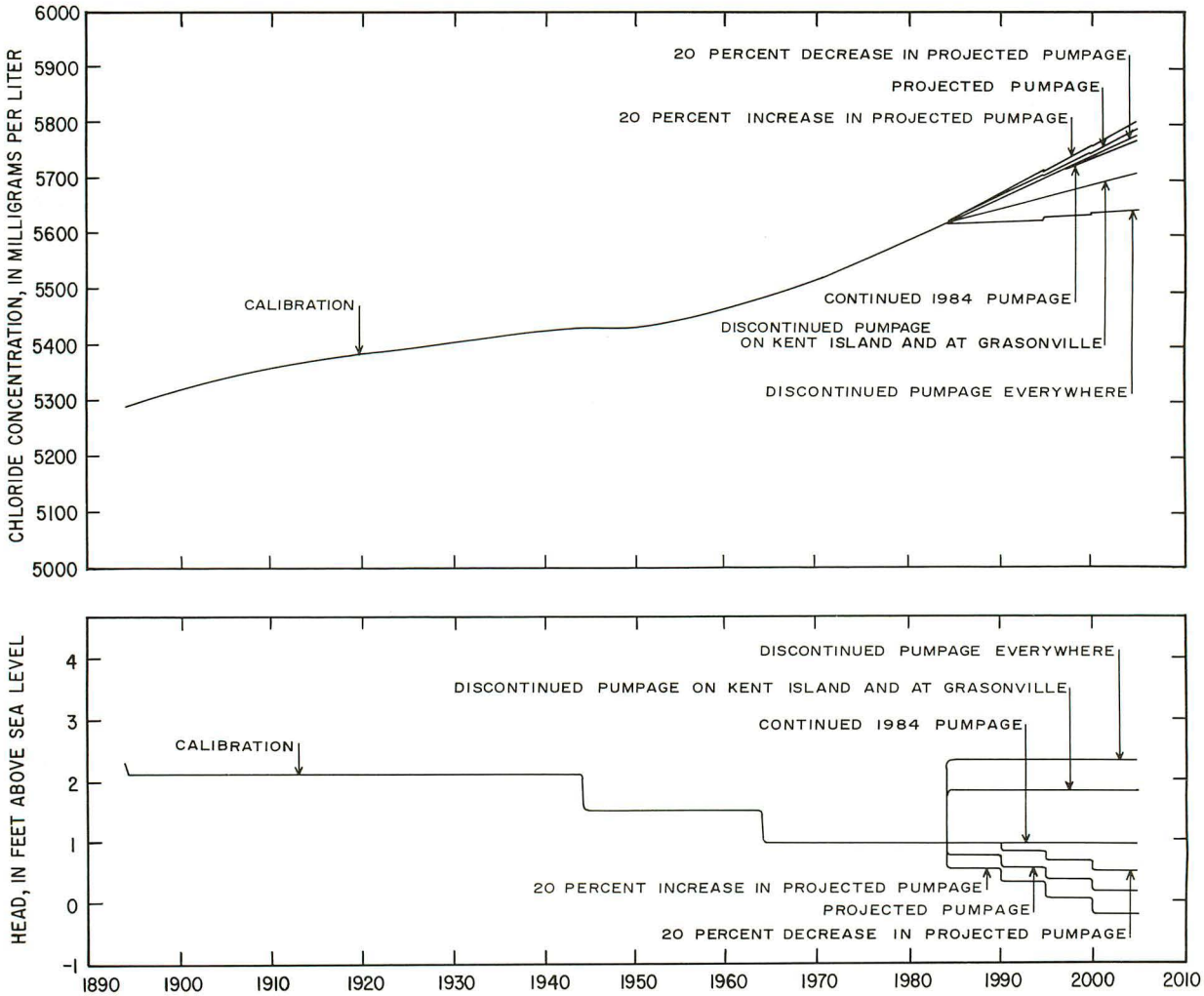


Figure 48. — Simulated head and chloride concentration at observation well QA Eb 156.

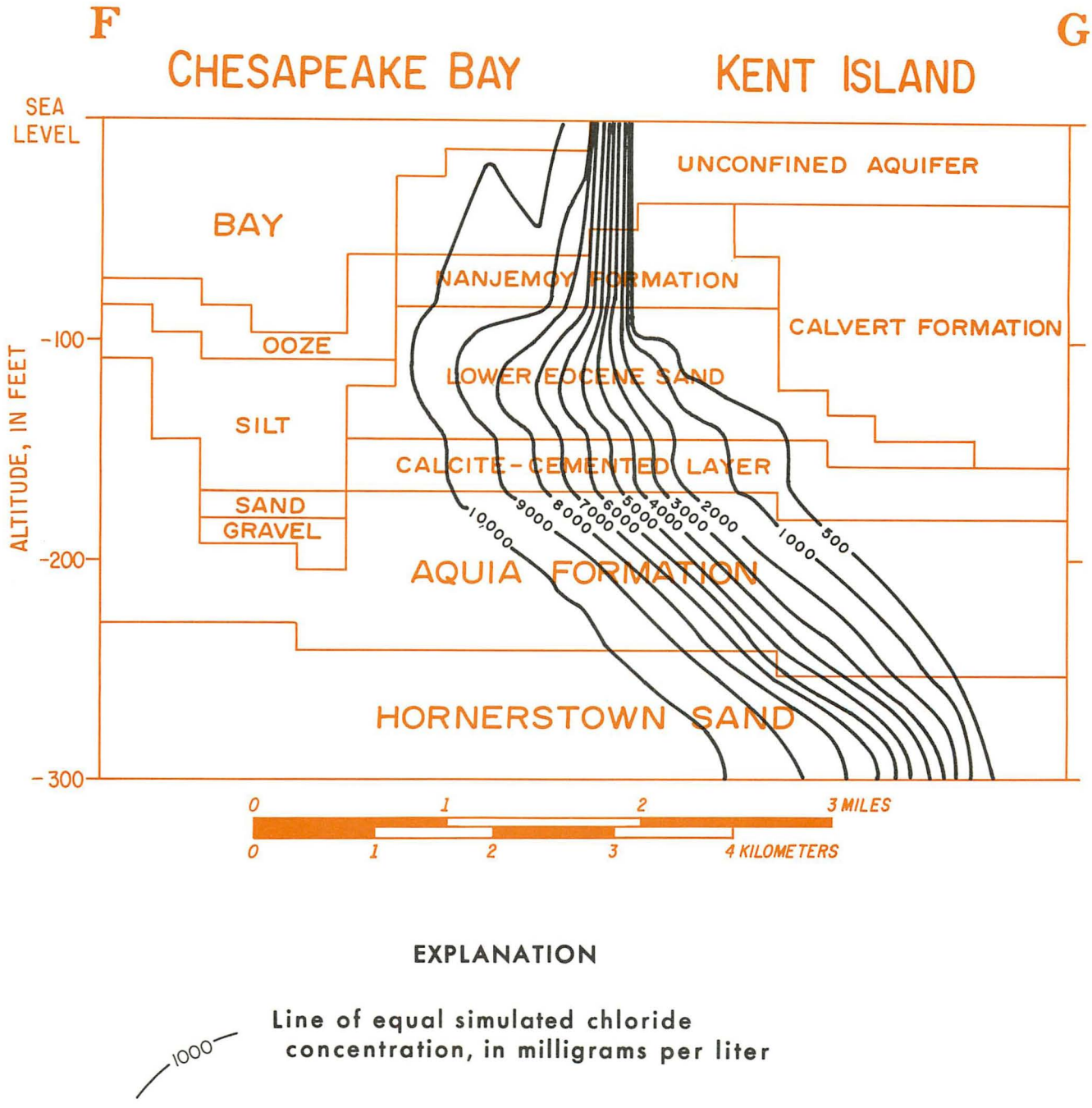


Figure 49. — Simulated 2005 chloride distribution based on projected pumpage.

Figure 50 shows the distribution of difference between simulated 1984 chloride concentration and simulated 2005 chloride concentration based on projected pumpage. Positive contours indicate increases in chloride concentration and negative contours (if present) indicate decreases. Contoured differences in concentration display small differences in concentrations more readily than contoured concentration and are used in figures where chloride movement is not great. Concentrations increased about 400 mg/L in the Aquia Formation and 750 mg/L in the Lower Eocene sand. Concentrations do not change significantly in the low-permeability calcite-cemented layer. Simulated heads and chloride concentrations at the end of each stress period are shown in table 6 for the projected-pumpage simulation. The simulated head and chloride concentration at well QA Eb 156 are shown in figure 48, along with those of other

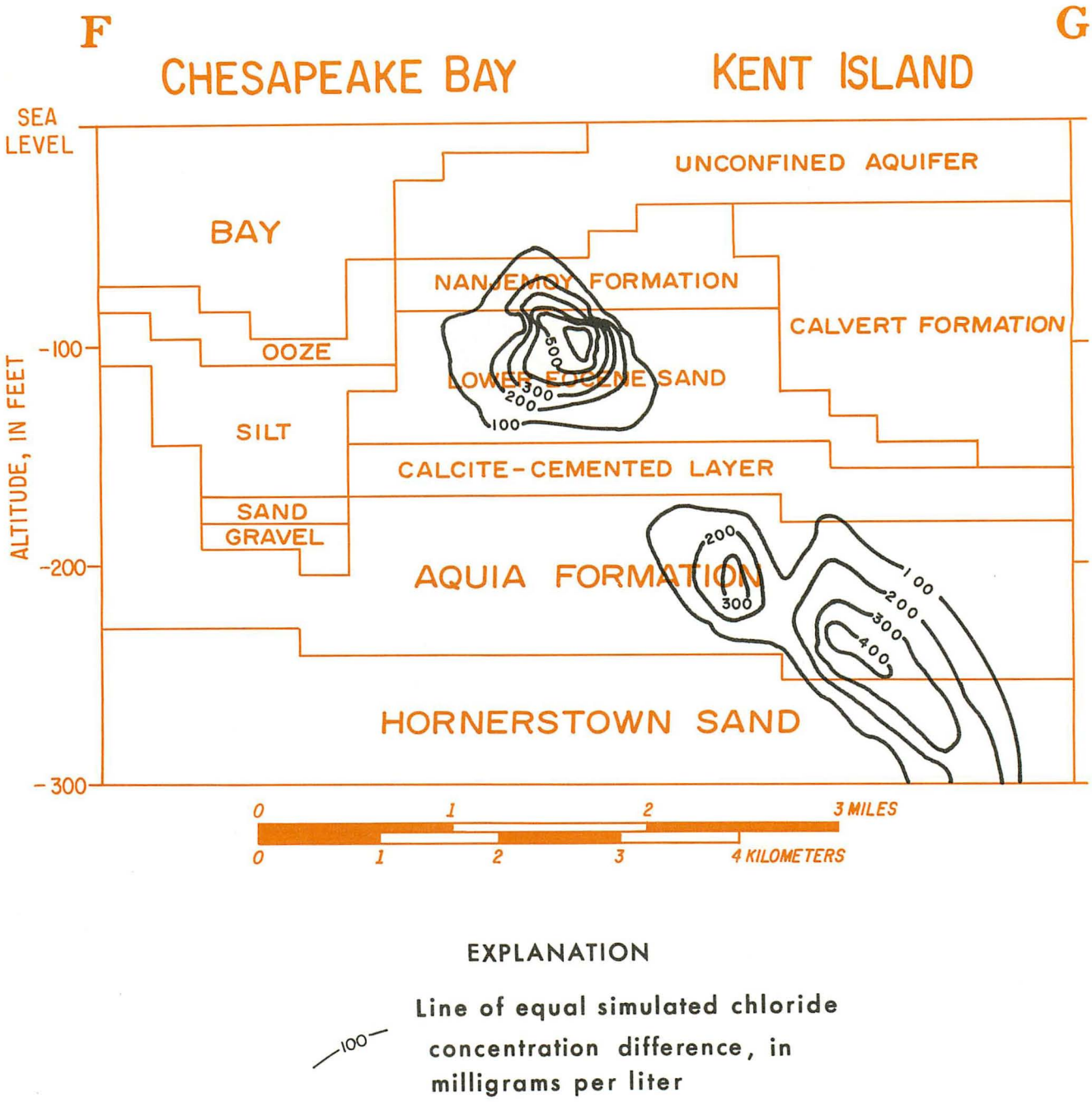


Figure 50. — Distribution of difference between simulated 1984 chloride concentrations and simulated 2005 chloride concentrations based on projected pumpage.

projected pumpage simulations. The head decreases from about 1.0 to about 0.2 ft above sea level and the chloride concentration increases from about 5,600 to 5,800 mg/L.

Figure 51 shows the simulated 2005 chloride difference distribution based on a 20-percent increase in projected pumpage at Kent Island and Grasonville (simulation 2 of the flow model). Chloride concentrations increase about 450 mg/L in the Aquia Formation and about 850 mg/L in the Lower Eocene sand. Although not shown in the figure, the 1,000-mg/L isochlor advances about 490 ft, with an average velocity of about 24 ft/yr. As shown in figure 48, the head at well QA Eb 156 decreases to about 0.3 ft below sea level and the chloride concentration increases to about 5,810 mg/L.

Figure 52 shows the simulated 2005 chloride-difference distribution based on a 20-percent decrease in projected

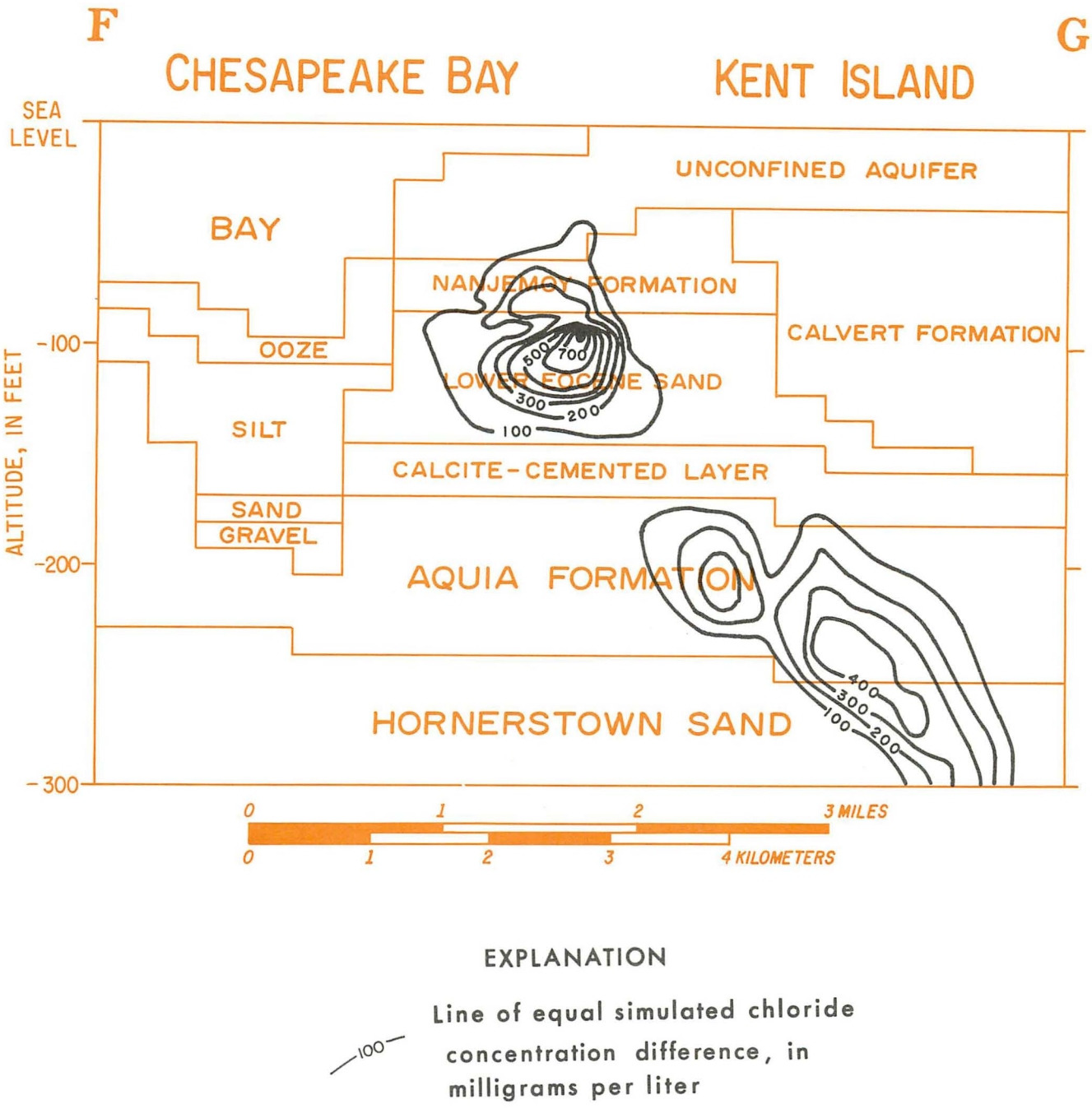


Figure 51. — Distribution of difference between simulated 1984 chloride concentrations and simulated 2005 chloride concentrations based on a 20-percent increase in projected pumpage at Kent Island and Grasonville.

pumpage at Kent Island and Grasonville (simulation 3 of the flow model). Chloride concentrations increase about 350 mg/L in the Aquia Formation and about 500 mg/L in the Lower Eocene sand. Although not shown in the figure, the 1,000-mg/L isochlor advances about 350 ft, with an average velocity of about 17 ft/yr. As shown in figure 48, the head at well QA Eb 156 decreases to about 0.5 ft above sea level and the chloride concentration increases to about 5,790 mg/L.

Figure 53 shows the simulated 2005 chloride difference distribution based on 1984 pumpage continued through 2005. This simulation represents no additional pumpage in the Aquia aquifer after 1984, with water levels remaining at their 1984 position. Chloride concentrations increase about 250 mg/L in the Aquia Formation and about 300 mg/L in the Lower Eocene sand. An area at the top of the Lower Eocene sand shows a decrease of about 100 mg/L. Although not shown in the figure, the 1,000-mg/L isochlor

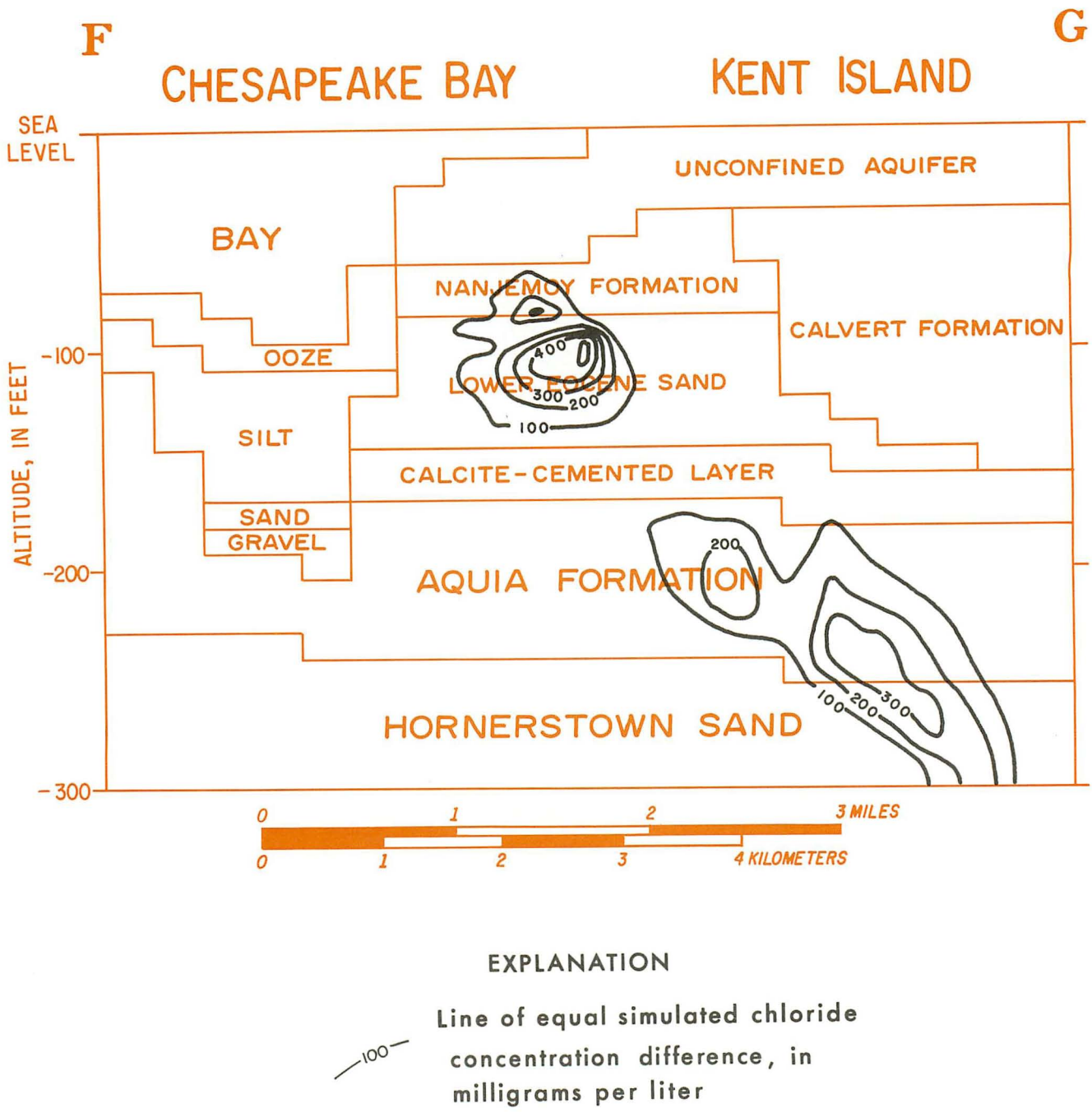


Figure 52. — Distribution of difference between simulated 1984 chloride concentrations and simulated 2005 chloride concentrations based on a 20-percent decrease in projected pumpage at Kent Island and Grasonville.

advances about 275 ft, with an average velocity of about 13 ft/yr. As shown in figure 48, the head at well QA Eb 156 remains at 1.0 ft above sea level and the chloride concentration increases to about 5,780 mg/L.

Figure 54 shows the simulated 2005 chloride difference distribution based on discontinued pumpage throughout the flow-model area. This simulation represents the replacement of all pumpage in the Aquia by an alternative water source, such as the deeper aquifers in the Cretaceous sediments, with a subsequent return of water levels to their prepumping position. Chloride concentrations remain essentially the same with a slight overall decrease. Although not shown in the figure, the 1,000-mg/L isochlor retreats about 40 ft, with an average velocity of about 2 ft/yr. As shown in

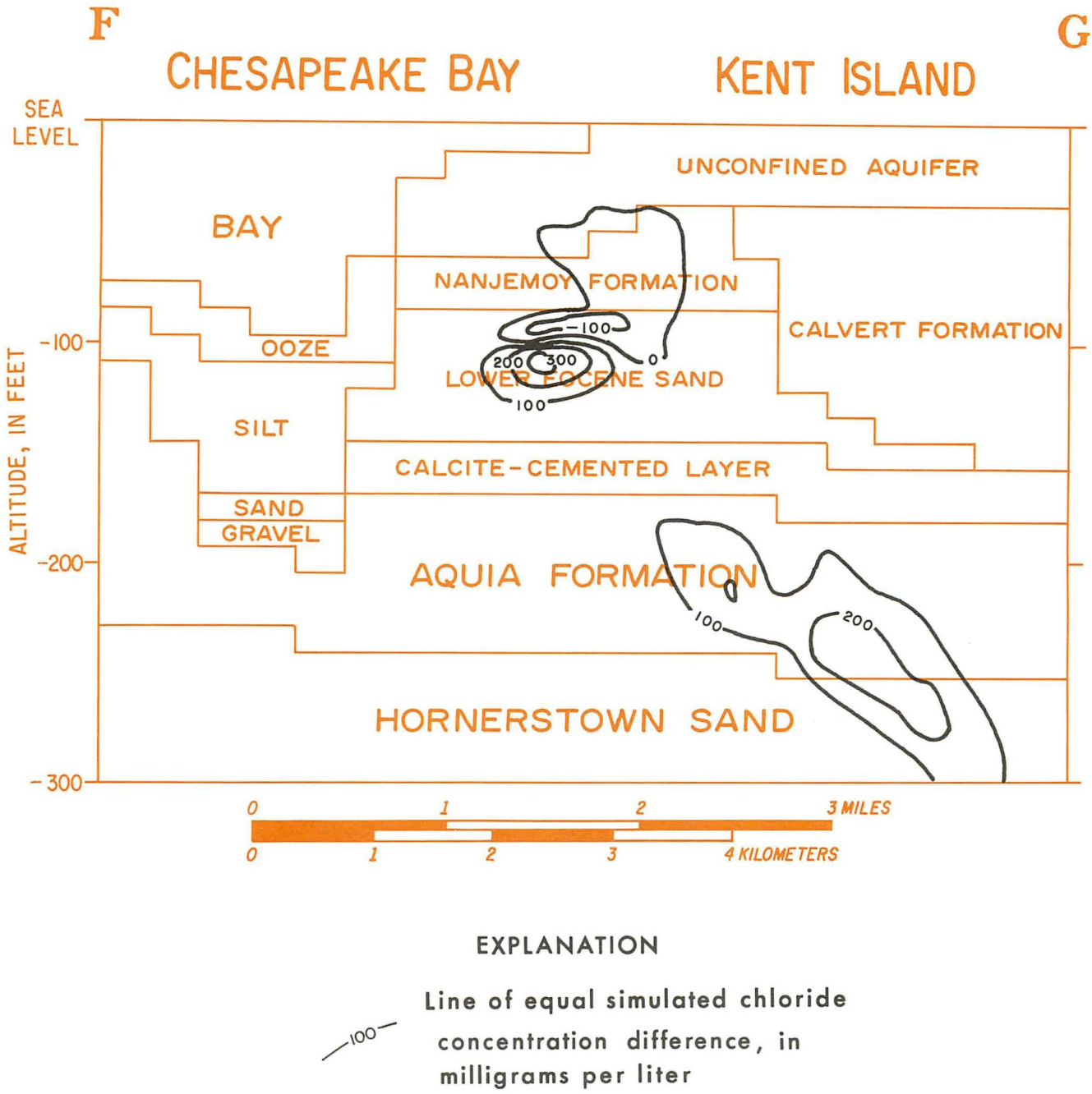


Figure 53. — Distribution of difference between simulated 1984 chloride concentrations and simulated 2005 chloride concentrations based on continued 1984 pumpage through 2005.

figure 48, the head at well QA Eb 156 increases to about 2.3 ft above sea level and the chloride concentration increases slightly to about 5,650 mg/L.

Figure 55 shows the simulated 2005 chloride difference distribution based on discontinued pumpage at Kent Island and Grasonville (simulation 9 of the flow model). Chloride concentrations increase about 100 mg/L in the Aquia Formation and remain essentially the same in the Lower Eocene sand. Although not shown in the figure, the 1,000-mg/L isochlor advances about 90 ft, with an average velocity of about 4 ft/yr. As shown in figure 48, the head at well QA Eb 156 increases to about 1.8 ft above sea level and the chloride concentration increases slightly to about 5,710 mg/L.

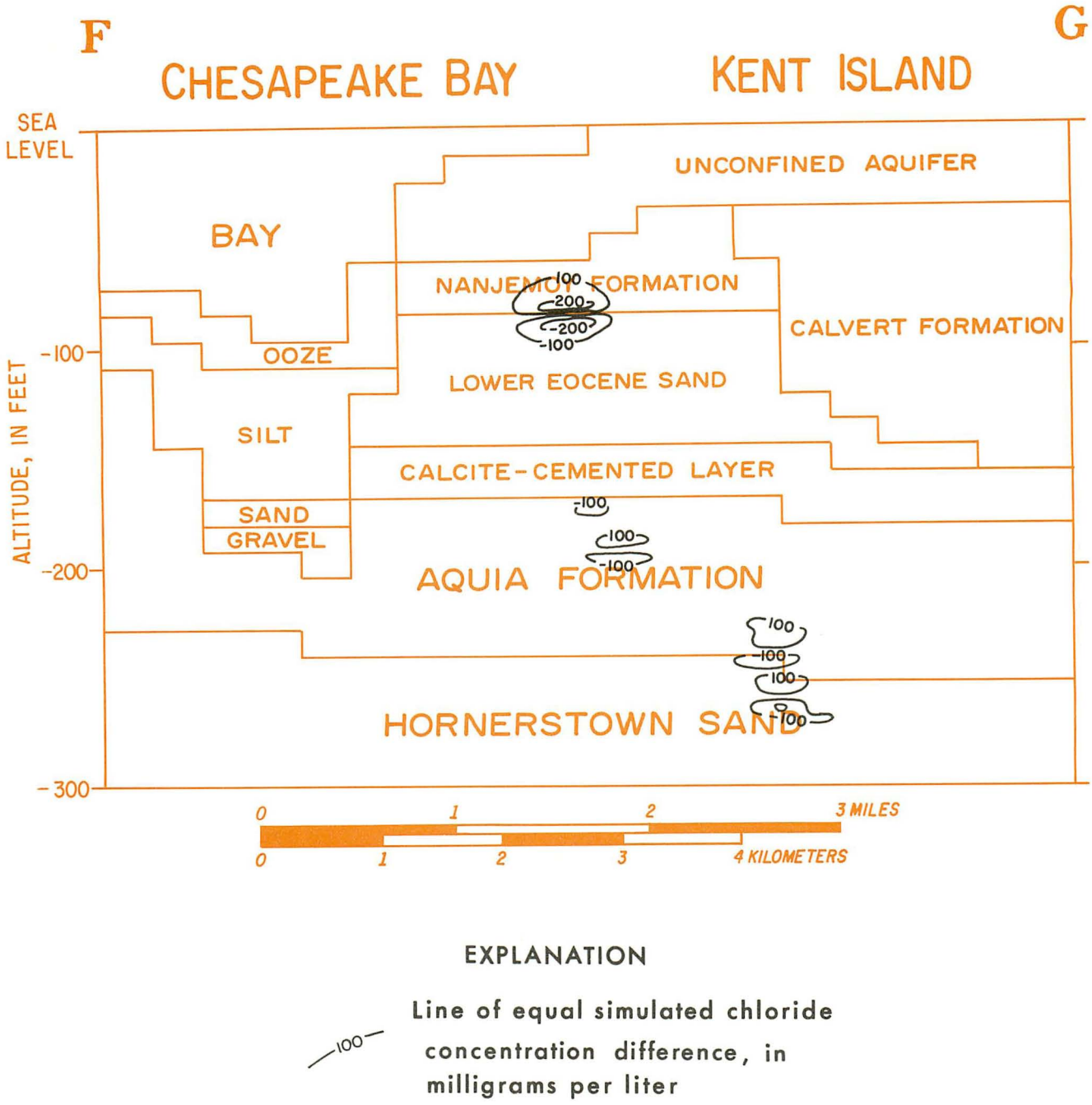


Figure 54. — Distribution of difference between simulated 1984 chloride concentrations and simulated 2005 chloride concentrations based on discontinued pumpage after 1984, throughout the model area.

SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the calibrated solute-transport model to evaluate the possible magnitude of error in model calculations as a result of possible inaccuracies in input data and model setup. This was performed in the following manner. A standard simulation was made using input data from the calibrated solute-transport model. The run started with the simulated 1984 chloride distribution and used specified pressure values at the Aquia freshwater boundary, which produced approximately the same 2005 chloride distribution as the four runs of the projected pumpage simulation. This was done to save computation time in the numerous sensitivity simulations to

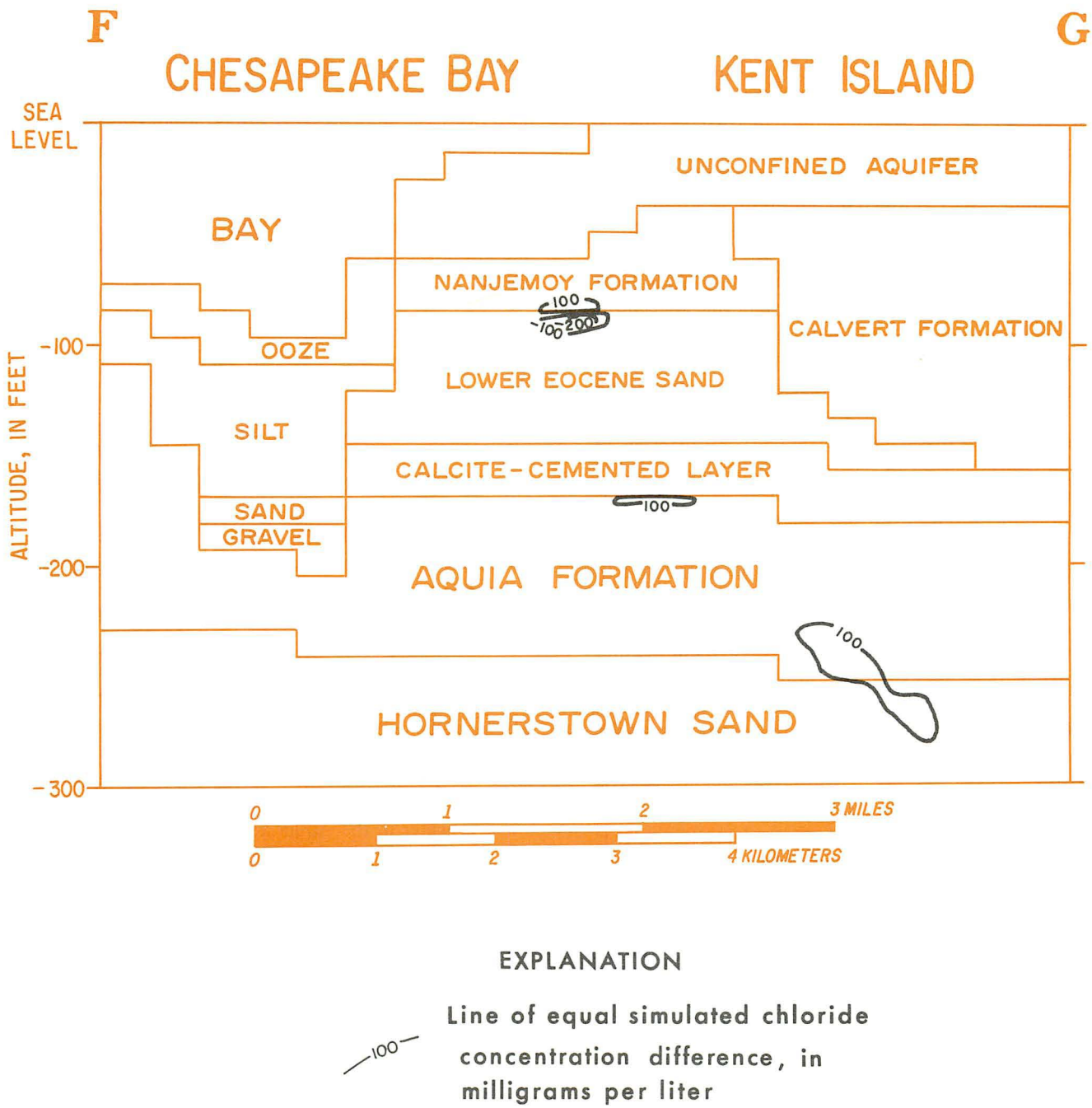


Figure 55. — Distribution of difference between simulated 1984 chloride concentrations and simulated 2005 chloride concentrations based on discontinued pumpage at Kent Island and Grasonville.

follow. Next, simulations were made identical to the standard simulation except that an individual input value was changed within the estimated limits of error of that value. The results were then compared to the results of the standard simulation. The greater the effect of altering an input data value on model results, the more sensitive the model is to that value.

The sensitivity analysis indicates the solute-transport model is very sensitive to the permeability of the Nanjemoy and Calvert Formations and to anisotropy. The model was moderately sensitive to the permeability of the Aquia Formation, the Hornerstown Sand, the calcite-cemented layer, and the ooze; vertical grid spacing; the elevation of the water table; porosity; and transverse dispersivity. The model was

relatively insensitive to the permeability of the unconfined aquifer, storage coefficient, change of density with change of chloride concentration, longitudinal dispersivity, matrix compressibility, choice of the Aquia freshwater boundary, and choice of Aquia brackish-water boundary.

The input values to which the solute-transport model is very sensitive produced changes in chloride concentrations in the same range as changes produced by pumpage and are discussed in detail. Increasing the permeability of the Nanjemoy Formation caused a decrease in chloride concentration in the Aquia Formation of as much as 1,350 mg/L. Decreasing the permeability of the Nanjemoy Formation caused an increase in chloride concentration in the Aquia Formation of as much as 550 mg/L. Increasing the permeability of the Calvert Formation caused a decrease in chloride concentration of as much as 750 mg/L in the Lower Eocene sand, and 100 mg/L in the Aquia Formation. Introducing an anisotropy factor of 10 (decreasing permeability in the vertical direction by a factor of 10) caused an increase in chloride concentration of 600 mg/L in the Aquia Formation and a decrease of 300 mg/L in the Lower Eocene sand.

As explained for the flow model, changes made in input data would have necessitated compensating changes in other data to obtain calibration of the solute-transport model. For this reason, the variations in model results caused by changes in input data represent maximum possible errors and the true error is probably much less. The greatest variation in model results shown in the sensitivity analysis was about 250 ft of interface advancement. It is estimated that the true error is about half of that or about 125 ft, which is about 28 percent of the best-estimate projection of 440 ft. This translates to about 6-ft/yr error in the interface advancement velocity over the 21-year simulation period.

EVALUATION OF HYDROGEOLOGIC CONTROLS

In order to understand the occurrence of brackish water in the Aquia aquifer fully, it is necessary to evaluate the factors which control its occurrence. These hydrogeologic controls were described in an earlier section in this report. The importance of these controls was evaluated with the solute-transport model by altering the input data for their hydraulic properties or by removing them from the model and comparing the results with those of a standard simulation. The greater the influence a particular control has on the system, the greater the effect on model results when its hydraulic properties are altered.

The evaluation was performed in the following manner. A standard simulation was first made using the calibrated solute-transport model, consisting of the prepumping simulation. Evaluation simulations were then made which were identical to the standard simulation except that input data associated with the hydrogeologic control of interest were altered, effectively removing the control from the model. In most cases, the model was run until chloride concentrations reached a steady-state distribution and equilibrium was obtained. The results of the evaluation simulations were then compared to those of the standard simulation. The greater the effect on model results of a particular control alteration, the greater the influence of that control in the aquifer.

Density-Dependent Flow

The influence of density-dependent flow on the occurrence of brackish water was evaluated by setting the coefficient of density change with concentration change equal to zero. This change rendered brackish water equal to freshwater in density, and thus removed density dependence from the flow system. Because the brackish water was no longer denser than freshwater, it could not sink beneath the freshwater to form a wedge and balance the higher heads in the freshwater portion of the aquifer. The interface was pushed bayward as the brackish water was flushed from the system. Figure 56 shows the interface after 400 time steps (20,000 years). The system had not yet reached equilibrium, but this position is shown for illustrative purposes. This simulation indicates that density-dependent flow is a major control in determining the prepumping distribution of brackish water in the Aquia aquifer. By altering only the input that controls the density dependence, a chloride distribution radically different from that of the standard simulation was obtained.

Water Pressure

Water pressure in the Aquia aquifer is an important consideration for several reasons. First, the prepumping pressure distribution in the freshwater portion of the Aquia aquifer is not well known, yet this input largely determines the simulated equilibrium position of the brackish-water/freshwater interface. The model was calibrated to move the interface from its estimated prepumping position to its known 1984 position in the allotted time period. The interface-encroachment velocity was calibrated based on the prepumping interface position which, in turn, is based on the equilibrium pressure input. The interface position simulated in future pumpage runs is determined partially by the interface-encroachment velocity. Thus, the results of the future simulations are influenced by the prepumping pressure input, and this unknown must be evaluated.

Second, water pressure exerted by the bay is variable in that changes in sea level (and thus in bay-water level) occur within the time frame of the solute-transport model simulations. It was assumed in making these simulations that the

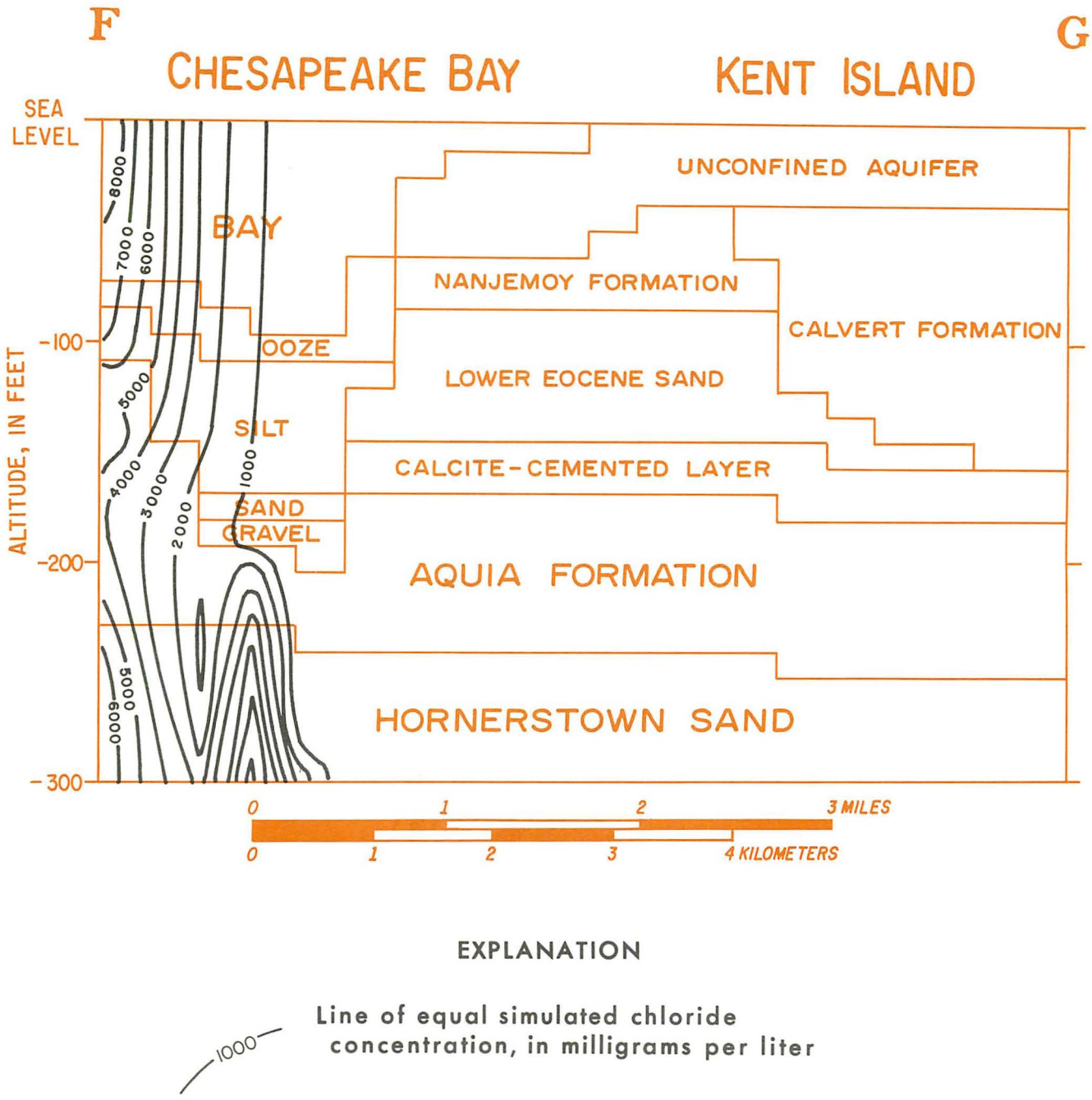


Figure 56. — Simulated prepumping chloride distribution based on a density-change coefficient of zero.

prepumping chloride distribution had achieved an equilibrium with present-day sea level. However, if sea-level changes occur more quickly than the chloride distribution can equilibrate to those changes, the assumption of equilibrium is not valid. In that case, the present-day chloride distribution, and thus interface position, would be changing due not only to pumpage stresses, but to the attempt of the system to equilibrate to a changing sea level.

Third, pumpage from the Aquia creates a variable pressure field in the freshwater portion of the Aquia aquifer, which will influence the future distribution and movement of brackish water. This variable was essentially evaluated in the projected-pumpage simulations in which several pressure distributions were input to the model representing various projected-pumpage scenarios.

The prepumping freshwater pressure distribution was evaluated by increasing and decreasing the head value used to calculate pressure at the Aquia freshwater boundary in the prepumping simulation. The head value was changed from the standard-run value of 3.1 ft, to 4.1 ft above sea

level. This value represents the approximate amount of error likely to exist in the prepumping head. When the head was increased to 4.1 ft (fig. 57), the interface was pushed back about 2,900 ft to balance the increased freshwater pressure. This value is significant when compared to the interface-advancement distance of about 1,050 ft simulated in the calibration and projected-pumpage simulations.

The pumping simulations shown in figures 49 through 55 also indicate that the distribution and movement of brackish water are controlled by pressure in the freshwater part of the Aquia aquifer. By reducing the head from +3.1 ft to -7.7 ft above sea level, the simulated interface position migrated about 1,050 ft inland during the 111-year simulation period.

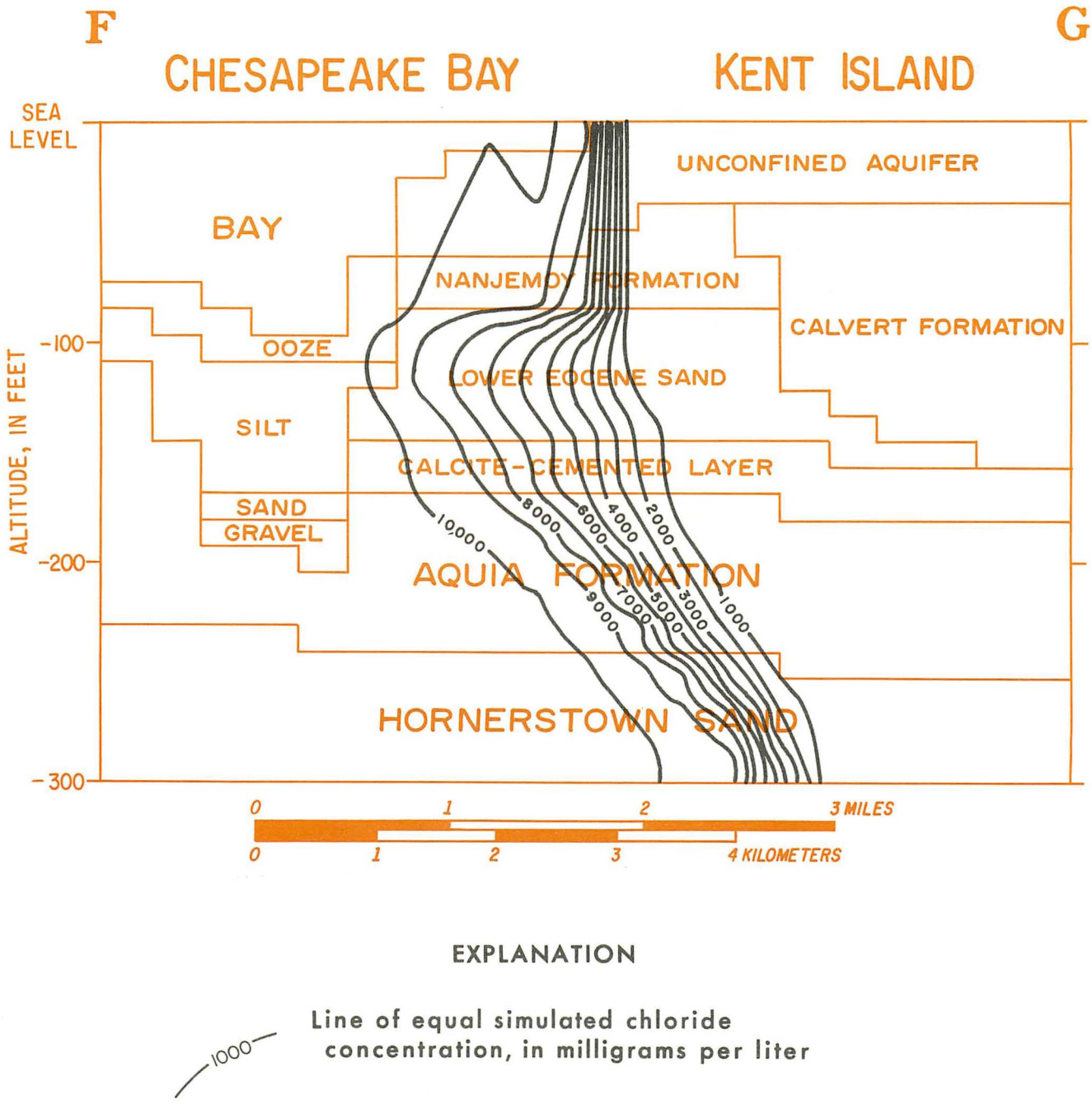


Figure 57. — Simulated prepumping chloride distribution based on a prepumping head of 4.1 feet above sea level.

A simulation was made to evaluate the effect of a fluctuating sea level. The 1895 prepumping chloride distribution was used for initial conditions and all inputs were the same as the prepumping simulation, except for the pressure inputs at the Aquia brackish-water and bay specified-pressure boundaries. These pressures were decreased the equivalent of a 1-ft drop in sea level at the start of the simulation. No attempt was made to simulate correlary effects of a sea-level drop such as a migrating shoreline, a decline in water-table elevation or changes in chloride concentration of the bay. The simulation was run until an equilibrium chloride distribution was obtained, which is shown in figure 58. The brackish-water interface migrated bayward about 3,000 ft in the 25,000 years required to reach equilibrium. Chloride concentrations at well QA Eb 156 are shown in figure 59. The concentration declines rapidly from the initial 5,300 mg/L to 2,400 mg/L in the first 5,000 years. Concentrations continue to decline over the next 20,000 years more slowly, reaching the equilibrium concentration of 2,000 mg/L at about 15,000 years.

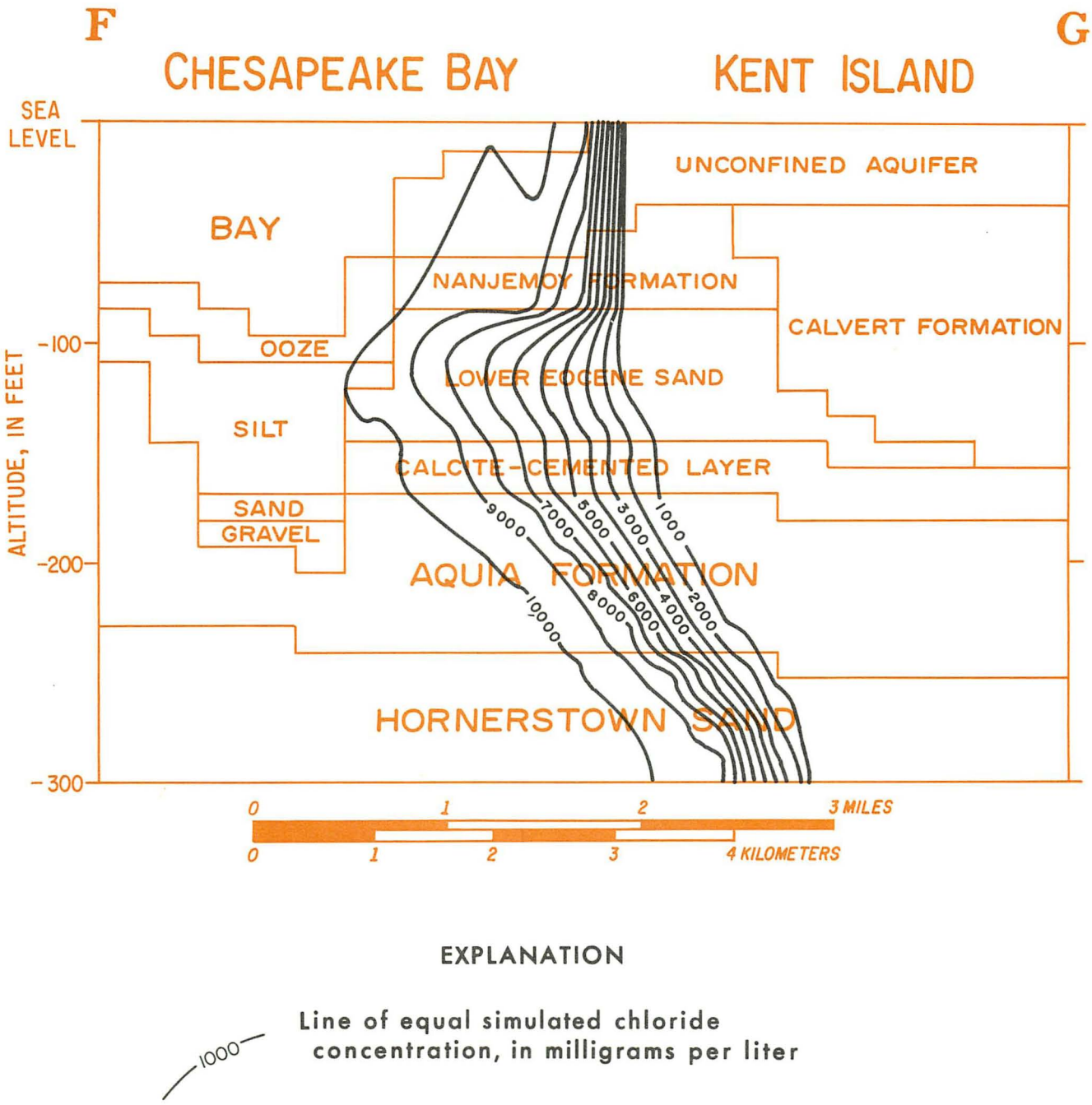


Figure 58. — Simulated prepumping chloride distribution based on a 1-foot decline in sea level.

A subsequent simulation was made in which sea level was returned to its present-day level, and the system allowed to equilibrate again. Concentrations at well QA Eb 156 (fig. 59) exhibit a virtual mirror image of the sea-level drop simulation, returning to the initial value at about 40,000 years total simulation time. These simulations indicate that the system would require about 5,000 years to partially equilibrate to a 1-ft change in sea level, and an additional 10,000 years to completely equilibrate. Sea-level curves of Milliman and Emery (1968) show a rise in sea level of about 12 ft in the past 5,000 years, indicating that the assumption of prepumping equilibrium may not be valid. If this is the case, there may be brackish-water encroachment caused by equilibration to a rising sea level, in addition to that caused by pumpage stress. This would make the advancement rates calculated in the projected-pumpage simulations too low.

Permeability Variations

Calcite-cemented layers

The influence of the calcite-cemented layer on the occurrence of brackish water was evaluated by changing the low-permeability nodes of the calcite-cemented sand to nodes of Aquia aquifer permeability, thus removing the calcite from the model.

Removal of the calcite layer has little overall effect on the position of the interface in the prepumping simulation (fig. 60). Chloride concentrations are increased in the Hornerstown Sand by about 1,200 mg/L, and decreased at the contact of the Aquia Formation and Lower Eocene sand by an equal amount. This indicates that the calcite-cemented layer inhibits chloride movement in the lower portion of the aquifer, but abets movement in the upper portion. The calcite-cemented layer forces freshwater entering the Aquia aquifer from the east to flow beneath it, rather than discharge directly to the nearby bay shore. This pushes the lower part of the interface farther bayward, in effect making the interface more vertical. The interface is about 300 ft farther inland in this simulation than in the standard simulation.

Paleochannels

The influence of the Chesapeake Bay paleochannel was evaluated in three ways. First, the paleochannel was removed from the model by replacing the paleochannel nodes with extended nodes in the Aquia aquifer. Second, the paleochannel was filled with gravel by replacing the silt and sand nodes with high-permeability gravel nodes. Third, the paleochannel was filled with silt by replacing all sand and gravel nodes with low-permeability silt nodes. These simulations cover a range of possible sediment arrange-

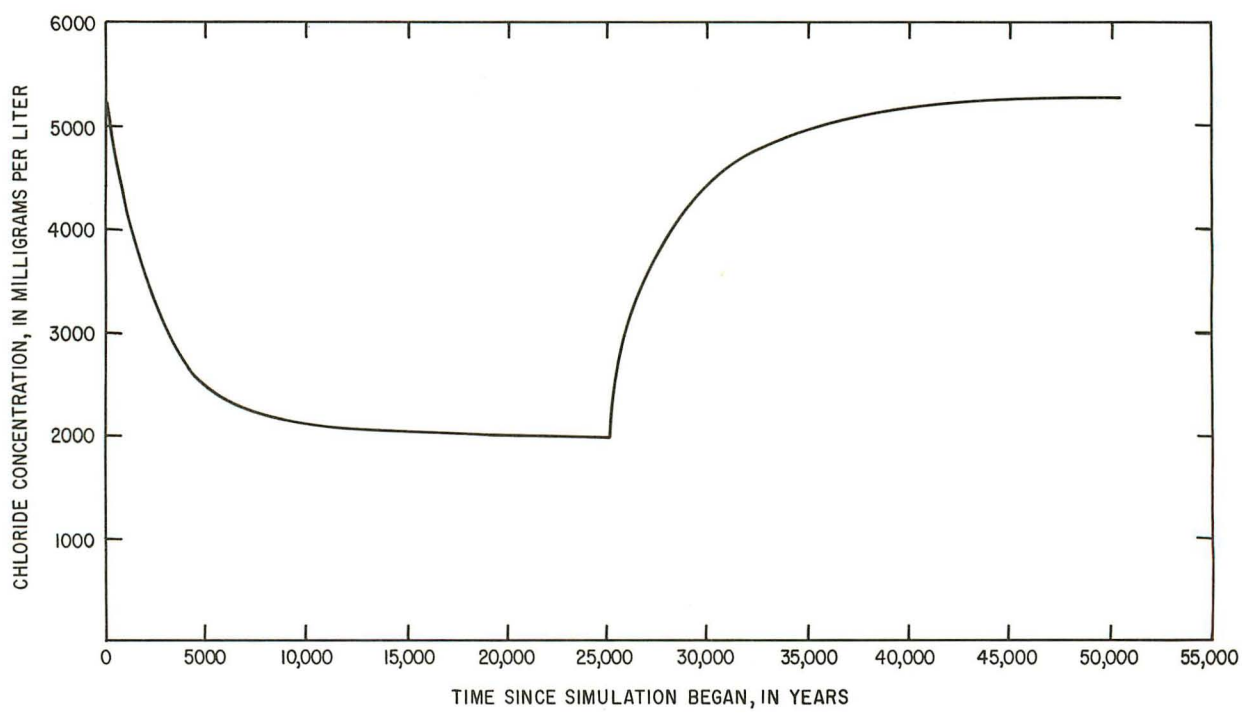


Figure 59. — Simulated chloride concentration at well QA Eb 156 based on a 1-foot decline and subsequent 1-foot rise in sea level.

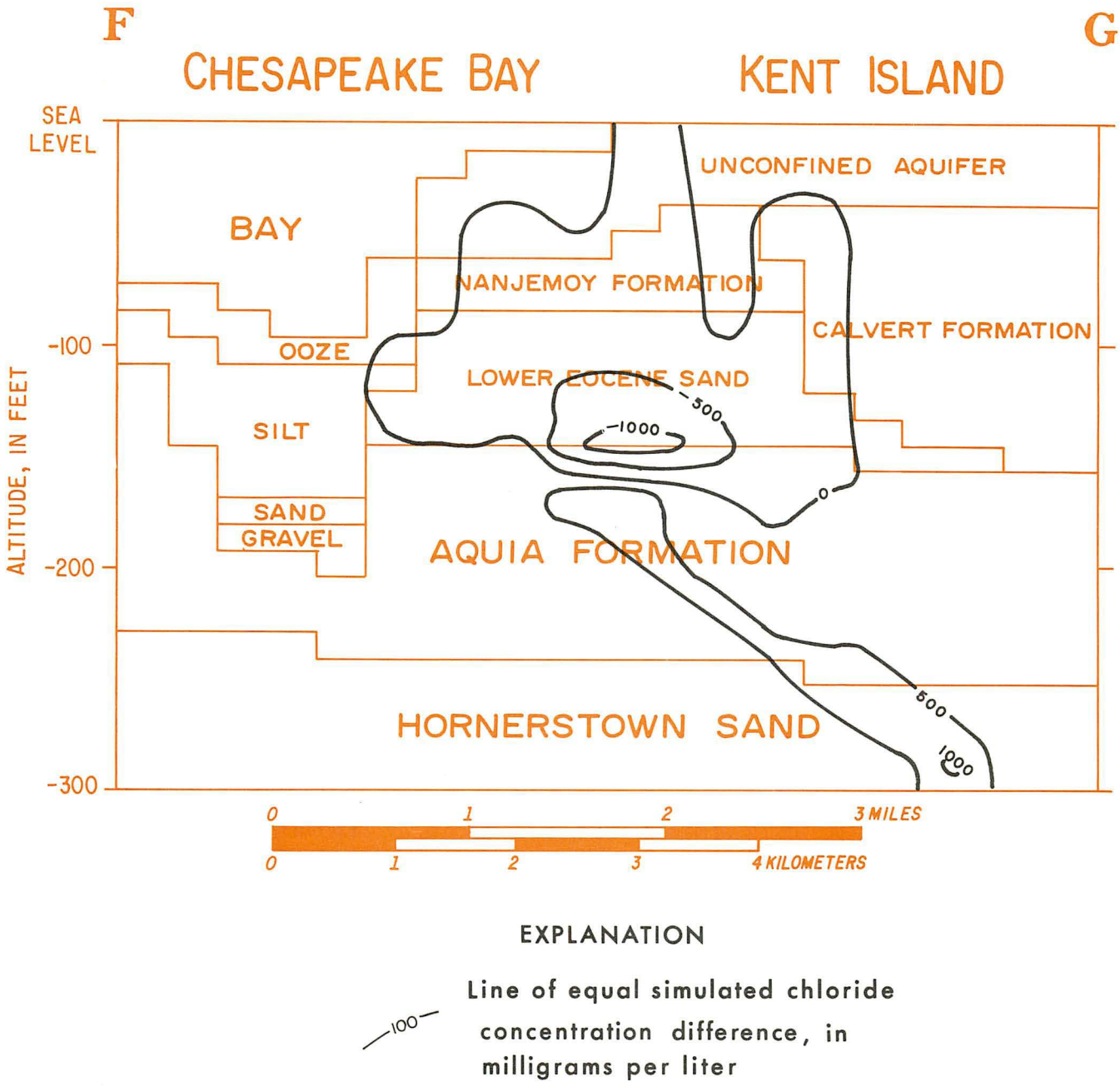
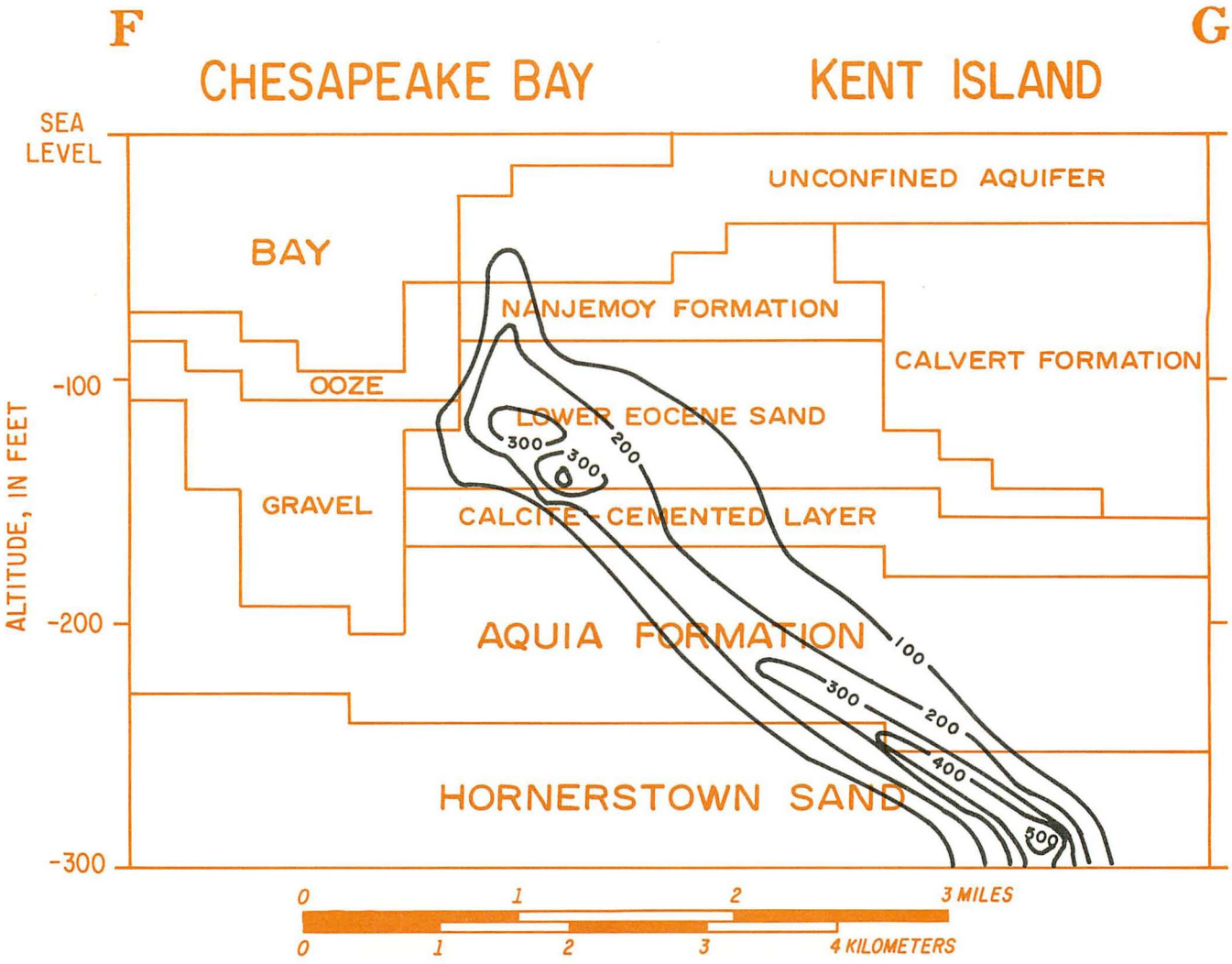


Figure 60. — Distribution of difference between simulated prepumping chloride concentrations of the standard simulation and those based on the removal of the calcite-cemented layer.

ments from which the importance of paleochannel sediments in the flow system can be evaluated.

The simulations in which the paleochannel was filled with silt and was removed from the system showed no significant difference from the standard simulation. These simulations showed changes in chloride concentration of about 200 mg/L. This is because there was little net change in the permeability of the sediments. There was a slight net decrease of permeability in the silt-filled simulation because the relatively small sand and gravel pockets were replaced by silt. Likewise, in the paleochannel-removal simulation the silt was replaced by sand and calcite-cemented sand, and the gravel was replaced by sand, producing little net change in permeability. The local changes in permeability would have a more pronounced effect if they were located in the vicinity of the interface.

Filling the paleochannel entirely with gravel produced a somewhat greater effect (fig. 61). This simulation produced changes in chloride concentration of about 600 mg/L from the standard simulation in the lower portion of the Aquia aquifer. In this simulation there was a significant net increase in permeability of the paleochannel sediments since



EXPLANATION

100 — Line of equal simulated chloride concentration difference, in milligrams per liter

Figure 61. — Distribution of difference between simulated prepumping chloride concentrations of the standard simulation and those based on the replacement of all paleochannel sediments with gravel.

the silt and sand were replaced by gravel. The increase in permeability created a conduit, making it easier for brackish water to flow through the paleochannel sediments into the Aquia aquifer.

These simulations show that the presence of the paleochannel has little effect on the movement of brackish water in the solute-transport model area. Even in the extreme case of filling the entire paleochannel with gravel, the effect was small. In other shoreline areas, however, paleochannel sediments may have a greater influence on brackish-water occurrence. On the southern portion of the island, for instance, all hydrogeologic units occur at greater depths because of the regional dip (figs. 6 and 7). In this area, the upper confining bed was probably removed and replaced by paleochannel sediments of higher permeability. These sediments would transmit more water than the confining bed and would potentially allow more brackish-water leakage.

Upper confining bed

To evaluate the effect of permeability variations in the upper confining bed, a simulation was made in which the Calvert Formation was removed from the system and replaced by the Nanjemoy and Aquia Formations. The same conditions were used as in the standard simulation except for the permeability values in the area occupied by the Calvert Formation.

The lower portion of the interface is about 4,000 ft less advanced than in the standard simulation (fig. 62). This indicates that the Calvert Formation encourages the advance of brackish water. The low-permeability sediments of the Calvert Formation inhibit freshwater recharge from the unconfined aquifer. By inhibiting freshwater recharge, the Calvert Formation allows the brackish-water interface to move farther inland.

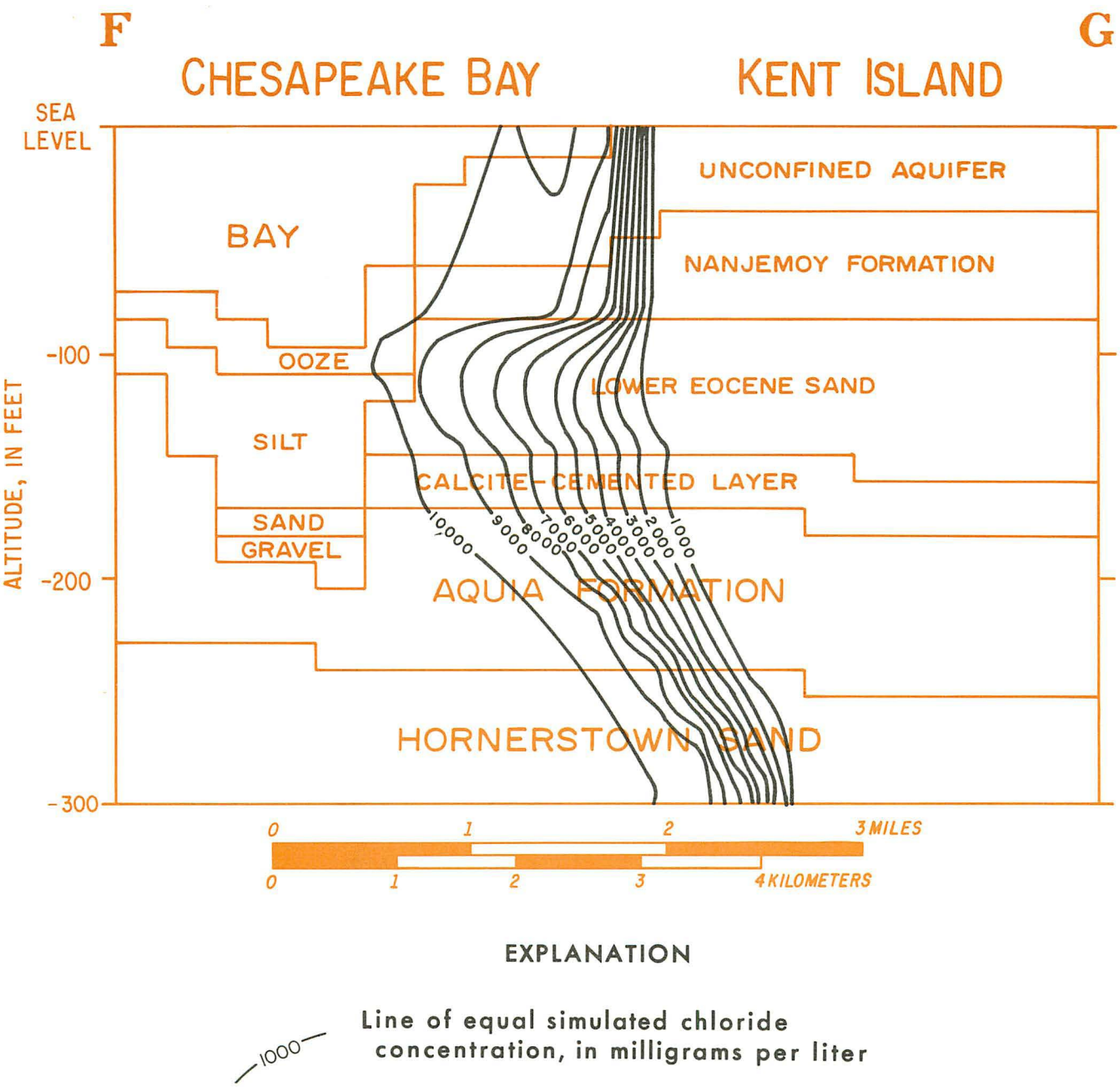


Figure 62. — Simulated prepumping chloride distribution based on the removal of the Calvert Formation.

The evaluation of hydrogeologic controls indicates that the most important controls on the distribution and movement of brackish water in the Aquia aquifer are density-dependent flow, water pressure in the Aquia aquifer, and the permeability of the upper confining bed. Calcite-cemented layers and paleochannel sediments provide minor controls.

It is not feasible to artificially control density-dependent flow or the nature of the upper confining bed. It is, however, possible to artificially control water pressures in the Aquia aquifer by controlling the amount and location of pumpage. Thus, the control of pumpage from the Aquia aquifer is a significant means with which to manage brackish-water intrusion on Kent Island.

FLUXES

Fluxes were calculated for each of the four boundaries at the ends of the prepumping, 1984, and 2005 runs. These fluxes are shown in table 7 as total flux through the boundary and as average flux per unit area. The total flux values indicate the amount of water entering and leaving the model through each boundary, and the sum of total fluxes indicates the amount of water accumulating in the model due to changes in storage. The average flux values indicate flow rates which can be compared to flow rates calculated by the flow model, calculated by the Darcy equation, and from precipitation. This assures that the amounts of water entering and leaving the solute-transport model are reasonable and consistent with the conceptual and flow models.

Most of the flux shown in table 7 for the Aquia brackish-water and bay boundaries is flowing in and out of the model in the shared corner occupied by the Chesapeake Bay. These values appear much too high. More reasonable values are obtained by combining the flux values for those two boundaries. The resulting combined flux values are shown in brackets.

The total fluxes for each boundary show that in the prepumping simulation, water is entering the model through the Aquia freshwater boundary (0.46 ft^3/d) and the unconfined boundary (0.32 ft^3/d), and leaving through the combined-bay boundary (0.83 ft^3/d). In the 1984 and 2005 simulations, the flow direction is reversed, with all of the water leaving the model through the Aquia freshwater boundary (3.62 and 6.06 ft^3/d) and approximately equal amounts entering through the combined-bay (1.95 and 3.64 ft^3/d) and unconfined (1.65 and 2.44 ft^3/d) boundaries. The general simulated flow pattern indicated by the total flux calculations is consistent with the conceptual flow model.

Table 7. — Simulated fluxes at specified-pressure boundaries of the solute-transport model

[Positive values indicate inflow, negative values indicate outflow; ft^3/d = cubic feet per day]

Boundary	Prepumping		1984		2005	
	Total (ft^3/d)	Per area[1] ($10^{-5}ft/d$)	Total (ft^3/d)	Per area ($10^{-5}ft/d$)	Total (ft^3/d)	Per area ($10^{-5}ft/d$)
Aquia freshwater	0.46	101	-3.62	796	-6.06	-1,332
Unconfined	.32	.94	1.65	4.77	2.44	7.05
Bay	3.57	8.2	6.17	14.2	8.59	19.7
Aquia brackish water	-4.40	-464	- 4.22	-445	-4.95	-522
[Combined bay]	[-.83]	[-1.88]	[1.95]	[4.41]	[3.64]	[8.22]
Total for model	-0.95		-0.02		0.02	

[1] Per area flux is the total flux divided by the boundary area.

The average flux values indicate that the greatest flow per area occurs at the Aquia freshwater boundary in all simulations, with the maximum value ($1,332 \times 10^{-5}$ ft/d) occurring in the 2005 simulation. To assure that this value does not exceed reasonable limits, a flux value was also calculated using the Darcy equation and input data from the 2005 solute-transport model simulation. This method yields a value of $1,347 \times 10^{-5}$ ft/d, which is very close to the value calculated from model results.

A check was also made on the average flux at the unconfined boundary which represents freshwater recharge to the unconfined aquifer. Although no data are available for actual recharge, the value calculated from model results should be somewhat less than precipitation. Precipitation is the only source of freshwater recharge to the unconfined aquifer. Surface runoff, evapotranspiration, and pumpage will reduce the amount of precipitation available for recharge to the aquifer. The maximum calculated average flux occurring at this boundary is 7.05×10^{-5} ft/d in the 2005 simulation. This value is equivalent to 0.31 in/yr, which is well below the annual precipitation at the Wye Research and Education Center (40.5 in/yr for 1981-86).

RESULTS OF THE SOLUTE-TRANSPORT MODEL

It is important to realize that the set of input data used to calibrate the model and make the predictive simulations is non-unique. That is, other combinations of input values could have been used to calibrate the model to available observed data, which would produce different results in the predictive simulations. For this reason, the estimated distances and rates of movement of brackish water should be regarded as general approximations rather than accurate predictions.

No attempt was made to recalibrate the solute-transport model using alternative sets of input data. However, the results of the sensitivity analysis and the hydrogeologic control evaluation indicate the amount of variance in model results due to variations in input data and model setup. Although changes in input data within reasonable limits cause significant variations in predicted rates of brackish-water movement, the general results are always the same. It can be concluded, therefore, that, although the predicted rates of movement may not be accurate, brackish water will move inland in response to projected pumpage.

SUMMARY AND CONCLUSIONS

The Aquia aquifer supplies the vast majority of freshwater to domestic and commercial users in the Kent Island area. It is a fine- to medium-grained quartz sand containing abundant glauconite and shell material with several layers of calcite-cemented sandstone. It is bounded on the bottom by the lower confining bed, which is formed by the Severn, Matawan, and Brightseat Formations, and on the top by the upper confining bed, which is formed by the Nanjemoy and Calvert Formations. The upper confining bed is overlain by the unconfined aquifer which supplies recharge to the Aquia aquifer in the form of leakage through the leaky upper confining bed. Parts of the Aquia aquifer and upper confining bed have been removed by Pleistocene erosional channels and replaced by paleochannel sediments of highly variable lithology. These paleochannels have altered the hydrology of the area by replacing the original sediments with sediments of different permeability.

Brackish water with chloride concentration greater than 1,000 mg/L is present in the Aquia aquifer within 0.25 mi of the Chesapeake Bay shore from Love Point in the north to at least as far south as Prices Creek. Brackish water with lower chloride concentration is present farther inland on the northern and southern tips of the island. A distinctive vertical zonation of chlorides was found throughout the zone of brackish water. Water with high chloride concentrations (as much as 7,000 mg/L at the Matapeake test well site) is present in the lower part of the Aquia aquifer, grading upward to freshwater (less than 10 mg/L chloride) or low-chloride water at the top. Although the chloride concentration at one well is known to have increased since 1940, no general trend of increasing concentrations with time was documented, perhaps because of the lack of historical chloride data in critical areas.

Five major hydrogeologic controls were determined to affect the distribution and movement of brackish water in the Aquia aquifer: density-dependent flow, water pressures in the Aquia aquifer, the presence of calcite-cemented layers, paleochannel sediments, and the permeability of the upper confining bed.

A quasi three-dimensional, finite-difference areal flow model was developed to estimate the effect of projected pumpage on water levels in the Aquia aquifer. The Aquia was modeled as a confined aquifer bounded on the bottom by a no-flow boundary and on the top by a leaky confining layer. An unconfined aquifer layer overlies the confining layer and supplies recharge to the Aquia as leakage through the confining layer. The flow model was calibrated primarily by adjusting the leakance of the confining layer to allow appropriate amounts of flow into and through the Aquia aquifer and to obtain a good match between simulated and measured hydraulic heads. The calibration period simulated pumpage from 1895 through 1984.

Future pumpage was simulated by the calibrated model through the year 2005. A simulation based on the best estimate of future pumpage indicates an additional 5 ft of drawdown from the 1984 potentiometric surface by 2005 on parts of Kent Island. The greatest declines occur on the eastern part of the island near Grasonville. Simulations based on pumpage amounts 20 percent higher and lower than the best estimate growth rate indicate additional drawdowns of 6 to 8 ft and 2 to 4 ft from the 1984 potentiometric surface. Other simulations were made to evaluate alternative pumpage conditions such as replacement of domestic pumpage by centralized supply wells and varying pumpage amounts in areas other than Kent Island.

A sensitivity analysis performed on the calibrated flow model to evaluate the effects of uncertainties in the input data on model results indicates that the flow model is most sensitive to input values for leakance of the Calvert and Nanjemoy Formations and the altitude of specified heads in the unconfined aquifer. Model results are moderately sensitive to transmissivity of the Aquia aquifer, leakance of bay-bottom sediments, leakance of the confining bed underlying the Piney Point aquifer, and the altitude of specified head in the bay. Model results are relatively insensitive to the storage coefficient of the Aquia aquifer and leakance of the confining layer underlying the unconfined aquifer. The sensitivity analysis indicates that simulated water levels could be in error by 2 to 4 ft in the Kent Island area because of possible inaccuracies in the input data.

A cross-sectional solute-transport model was developed to estimate the movement of brackish water in response to projected pumpage amounts and to evaluate the importance of the hydrogeologic controls on the distribution and movement of brackish water. Estimated distances and rates of movement should be regarded as general approximations rather than accurate predictions. The solute-transport model was developed in a manner similar to the flow model, using identical stress periods and similar boundary and initial conditions. Hydraulic heads from the flow model were used to calculate pressures for the vertical specified-pressure boundary of the Aquia aquifer in the solute-transport model. The solute-transport model was used to estimate the movement of brackish water in the Aquia aquifer in response to projected pumping conditions and alternative projected pumping conditions. Model results indicate that the freshwater/brackish-water interface will move about 440 ft inland during the 21-year simulation period (1984-2005) based on the best estimate of future pumpage.

Alternative simulations based on pumpage amounts 20 percent higher and lower than the best estimate indicate interface movement of about 490 ft and 350 ft for that same period. Average interface velocities for the three simulations are about 21, 24, and 17 ft/yr. A simulation based on continued 1984 pumpage rates through 2005 indicates interface movement of about 275 ft at an average velocity of about 13 ft/yr. A simulation based on no pumpage in the Aquia through 2005 indicates interface movement of about 40 ft in the opposite direction (bayward) at an average interface velocity of 2 ft/yr. A simulation based on discontinued pumpage at Kent Island and Grasonville as of 1984 indicates interface movement of about 90 ft at an average velocity of about 4 ft/yr.

A sensitivity analysis was run on the calibrated transport model to evaluate the effect of uncertainties in input data on model results. The sensitivity analysis indicates that the solute-transport model is very sensitive to permeability of the Nanjemoy and Calvert Formations, and to anisotropy. The model is moderately sensitive to permeability of the Aquia Formation, the Hornerstown Sand, the calcite-cemented layer, and the ooze; vertical grid spacing; altitude of the water table; porosity; and transverse dispersivity. The model is relatively insensitive to permeability of the unconfined aquifer, change of density with change of chloride concentration, longitudinal dispersivity, matrix compressibility, and choice of boundaries. The sensitivity analysis indicates that projected interface movement could be in error by 125 ft for the 21-year simulation period, or about 6 ft/yr, because of possible inaccuracies in the input data.

Simulations designed to evaluate the importance of the hydrogeologic controls on brackish-water movement indicate that density-dependent flow, water pressures in the Aquia aquifer, and the permeability of the upper confining bed are the most important factors. Calcite-cemented layers and paleochannel sediments provide minor controls on brackish-water movement in the Aquia aquifer in the Kent Island area. The prepumping brackish-water interface position may not be in equilibrium because of fluctuations in sea level.

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SUPPLEMENTAL DATA

This section contains supplemental data collected during the course of the project. It includes tables 8, 9a, 9b, 10a, 10b, and 11, and figure 63.

Table 8. — Records of selected wells in the Kent Island area

[ft = feet; gal/min = gallons per minute]

WELL NUMBER	STATE PERMIT NUMBER	OWNER	CONTRACTOR	YEAR COM-PLETED	ALTI-TUDE OF LAND SUR-FACE (FT)	DEPTH OF WELL (FT)	DIAMETER OF WELL (INCHES) CASING	DIAMETER OF WELL (INCHES) SCREEN	DEPTH OF BOTTOM OF CASING OR TOP OF SCREEN (FT BELOW LAND SURFACE)	TOTAL SCREEN LENGTH (FT)
QA Db 5	QA-00-8164	BROWN, MADISON, SR.	HUDSON WELL DRILLING	1951	18	170	1.25	--	135	--
QA Db 8	QA-00-9893	LOWE, ELIZABETH C.	HUDSON WELL DRILLING	1952	18	175	2	--	145	--
QA Db 10	--	WHITE, ALBERT	AARON WELL DRILLING	----	15	136	--	--	--	--
QA Db 12	QA-73-2927	MARKS, IRVING	BRANHAM CONTRACTORS, INC.	1979	9	27	4	2	20	7
QA Db 13	QA-73-2005	BIRKEL, JOSEPH, JR.	QUEENSTOWN WELL DRILLING	1977	15	35	4	4	25	10
QA Db 14	QA-73-2453	GUKANOVICH, BRONKO	QUEENSTOWN WELL DRILLING	1978	15	165	4-2	2	145	20
QA Db 15	QA-73-3144	KLOPP, ROBERT F.	SLATER WELL DRILLING	1980	15	103	4	2	96	7
QA Db 16	QA-73-2891	BELLO, DORIS	HUDSON WELL DRILLING	1979	15	126	2	--	96	30
QA Db 17	--	MCLEOD, GLADYS	---	----	20	--	--	--	--	--
QA Db 18	QA-73-3860	WALTERS, ROBERT F.	QUEENSTOWN WELL DRILLING	1982	23	38	4	4	28	10
QA Db 19	QA-01-7522	STIPE, REGINA	HUDSON WELL DRILLING	1955	23	60	2.5	--	55	--
QA Db 20	QA-05-7479	C. J. LANGENFELDER & SONS	AARON WELL DRILLING	1964	20	70	2	2	60	10
QA Db 21	QA-73-3605	C. J. LANGENFELDER & SONS	COLLIER WELL DRILLING	1981	22.4	48	4	4	40	8
QA Db 22	QA-73-3111	WISEMAN, FRED	QUEENSTOWN WELL DRILLING	1980	10	110	2	2	90	20
QA Db 23	QA-73-2961	GARLAND, FORREST	QUEENSTOWN WELL DRILLING	1979	18	185	4-2	2	165	20
QA Db 25	QA-73-3478	BUNCH, BARBIE	SLATER WELL DRILLING	1981	19	45	4	2	37	8
QA Db 26	--	HILKER, GENEVIEVE	---	1970	5	60	--	--	--	--
QA Db 27	QA-66-0101	MYLANDER, CHARLES	HUDSON WELL DRILLING	1966	15	145	1.5	--	110	--
QA Db 28	QA-73-3800	JONES, FORREST C.	SLATER WELL DRILLING	1982	19	47	4	2	40	7
QA Db 29	QA-73-2229	MATTES, FRANK	QUEENSTOWN WELL DRILLING	1978	15	35	4	4	25	10
QA Db 30	QA-81-0473	MD. GEOL. SURVEY LOVE POINT I	BURNS WELL DRILLING CO.	1984	17.8	220	4	4	210	10
QA Db 31	QA-81-0473	MD. GEOL. SURVEY LOVE POINT II	BURNS WELL DRILLING CO.	1984	18	180	4	4	170	10
QA Db 32	QA-81-0473	MD. GEOL. SURVEY LOVE POINT III	BURNS WELL DRILLING CO.	1984	18.1	116	4	4	106	10
QA Db 33	QA-81-0471	MD. GEOL. SURVEY CLOVERFIELDS I	BURNS WELL DRILLING CO.	1984	7	250	4	4	240	10
QA Db 34	QA-81-0471	MD. GEOL. SURVEY CLOVERFIELDS II	BURNS WELL DRILLING CO.	1984	7.4	180	4	4	170	10
QA Db 35	QA-81-0472	MD. GEOL. SURVEY MYLANDER	BURNS WELL DRILLING CO.	1984	7.5	200	4	4	190	10
QA Db 36	QA-81-0473	MD. GEOL. SURVEY LOVE POINT IV	BURNS WELL DRILLING CO.	1984	18.1	180	4	4	170	10
QA Db 37	QA-81-0471	MD. GEOL. SURVEY CLOVERFIELDS III	BURNS WELL DRILLING CO.	1984	7.1	250	4	4	240	10
QA Db 38			COLLIER WELL DRILLING	1985	18	175	4			
QA De 30	QA-67-0030	COMM. OF CENTREVILLE	SHANNAHAN ARTESIAN WELL CO.	1966	--	448	10	10	272	176
QA Ea 4	--	MD. DEPT. OF NATURAL RESOURCES	AARON WELL DRILLING	----	20	160	2.5	--	--	--
QA Ea 10	QA-01-0585	RHODES, PATRICIA	AARON WELL DRILLING	1952	12	120	1.5	--	100	--
QA Ea 26		U.S. ARMY CORPS OF ENGINEERS	CORPS OF ENGINEERS	1972	20	--	--	--	--	--
QA Ea 31	QA-68-0151	CAMP WRIGHT	SHANNAHAN ARTESIAN WELL CO.	1968	17	144	4	--	120	--
QA Ea 32	QA-73-0963	QUEEN ANNE'S COUNTY DEPT. OF RECREATION	KELLY WELL DRILLING	1975	11.02	225	4	4	215	10
QA Ea 33	--	WHILDIN	---	----	18	--	--	--	--	--
QA Ea 34	QA-73-3871	MURPHY, CHARLES	QUEENSTOWN WELL DRILLING	1982	18	85	4	4	75	10
QA Ea 35	QA-66-0085	BELAIR, FRANCIS X.	AARON WELL DRILLING	1965	17	125	2	--	--	--
QA Ea 36	QA-73-1637	COOLEY, JERRY	QUEENSTOWN WELL DRILLING	1977	18	140	2	2	120	20
QA Ea 37	QA-73-3317	WASSERMAN, JUDD	BRANHAM CONTRACTORS, INC.	1980	17	92	4	2	85	7
QA Ea 38	QA-73-1638	SHANABERGER	QUEENSTOWN WELL DRILLING	1977	17	140	2	2	120	20
QA Ea 39	QA-73-3240	JUCHNO, EDWIN A.	QUEENSTOWN WELL DRILLING	1980	15	95	4	4	80	15
QA Ea 40	--	HONASKI	---	1975	18	--	--	--	--	--
QA Ea 41	QA-73-2871	HARTLE, PHIL	QUEENSTOWN WELL DRILLING	1979	20	125	2	2	105	20
QA Ea 42	QA-73-2611	BRUNS, JACK C.	QUEENSTOWN WELL DRILLING	1978	18	120	2	2	100	20
QA Ea 43	QA-73-3446	BUTLER, CHARLES	QUEENSTOWN WELL DRILLING	1981	15	180	2	2	160	20
QA Ea 44	QA-73-1267	JACKSON, CAROLYN	PURNER WELL DRILLING	1976	13	153	4	2	143	10
QA Ea 45	QA-73-2731	STEVENS	SLATER WELL DRILLING	1979	15	210	4	2	200	10
QA Ea 46	QA-73-3738	STEWART, JOHN A., JR.	QUEENSTOWN WELL DRILLING	1982	10	180	4-2	2	160	20
QA Ea 47	QA-73-3077	DEL PUPPO, JOSEPH	QUEENSTOWN WELL DRILLING	1980	14	120	4	4	100	20
QA Ea 48	QA-73-0747	ROYS, ALLEN	HUDSON WELL DRILLING	1974	5	160	2	--	129	--
QA Ea 50	QA-03-7540	GERMAN, ELVA	AARON WELL DRILLING	1960	8	145	1.5	--	--	--
QA Ea 51	QA-73-2575	MOUCK, SEYMOUR	COLLIER WELL DRILLING	1978	8	140	2	2	120	20
QA Ea 52	QA-72-0204	SMITH, ROBERT	COLLIER WELL DRILLING	1972	8	170	2	--	150	--
QA Ea 53	QA-73-3677	LEUSCHNER, JAMES T.	QUEENSTOWN WELL DRILLING	1981	17	90	4	4	80	10
QA Ea 54	QA-73-1323	FAULKES, GARFIELD	COLLIER WELL DRILLING	1976	18	170	2	--	150	--
QA Ea 55	QA-73-3634	WAY, ROBERT	QUEENSTOWN WELL DRILLING	1981	19	110	2	2	95	15
QA Ea 56	QA-73-1781	BACHMAN, R. C.	COLLIER WELL DRILLING	1977	10	140	2	2	120	20
QA Ea 57	QA-68-0064	KANE, FRANCIS	AARON WELL DRILLING	1967	10	194	1.5	--	165	--
QA Ea 58	QA-73-2677	MATZEL, RICHARD	SLATER WELL DRILLING	1979	18	67	4	2	60	7

WATER-BEARING FORMATION	WATER LEVEL (FT BELOW LAND SURFACE)	DATE	PUMPING TEST DATA: WATER LEVELS BELOW LAND SURFACE (FT) STATIC	PUMPING	DATE	YIELD (GAL/MIN)	HOURS PUMPED	SPECIFIC CAPACITY [(GAL/MIN)/FT]	TYPE OF PUMP	USE OF WATER	REMARKS	WELL NUMBER
125AQUI	--	---	15	20	07/13/51	20	5	4	P	H	F	QA Db 5
125AQUI	--	---	12	21	05/01/52	20	6	2.2	P	H	F	QA Db 8
125AQUI	--	---	--	--	---	--	--	--	-	H	Q	QA Db 10
112PLSC	9.66	10/10/84	11	14	08/07/79	5	2	1.7	S	H	F	QA Db 12
112PLSC	--	---	15	23	09/30/77	6	3	.8	J	H	F	QA Db 13
125AQUI	13.51	10/10/84	15	30	09/06/78	25	4	1.7	S	H	F	QA Db 14
125AQUI	13.86	10/10/84	10	15	03/26/80	30	24	6	S	H	Q	QA Db 15
125AQUI	--	---	12	94	07/13/79	30	4	.4	J	H		QA Db 16
125AQUI	--	---	--	--	---	--	--	--	-	-	F	QA Db 17
112PLSC	21.04	04/27/83	18	25	06/14/82	6	2	.9	-	H	F	QA Db 18
112PLSC	--	---	--	--	---	--	--	--	-	H	F	QA Db 19
112PLSC	19.29	04/28/83	21	--	04/28/64	19	4	--	J	I		QA Db 20
112PLSC	19.64	10/10/84	20	32	07/28/81	15	5	1.3	S	N	F	QA Db 21
125AQUI	--	---	12	25	04/17/80	25	3	1.9	-	H		QA Db 22
125AQUI	17.81	10/10/84	12	30	09/14/79	30	4	1.7	S	H	Q	QA Db 23
112PLSC	18.75	10/10/84	22	28	03/13/81	30	4	5	S	H	Q	QA Db 25
125AQUI	--	---	--	--	---	--	--	--	-	H	Q	QA Db 26
125AQUI	--	---	17	--	02/07/66	25	3	--	-	H	Q	QA Db 27
112PLSC	22.49	10/10/84	20	30	04/02/83	6	4	.6	-	H		QA Db 28
112PLSC	17.47	10/11/83	18	22	04/08/78	6	3	1.5	-	H		QA Db 29
125AQUI	16.80	10/05/84	--	--	08/27/84	10	--	--	-		Q, G	QA Db 30
125AQUI	--	---	--	--	07/13/84	10	--	--	-	U	Q, G WELL ABANDONED; REPLACED BY QA Db 36	QA Db 31
125AQUI	16.82	10/05/84	--	--	07/16/84	15	--	--	-	U	Q, G	QA Db 32
125AQUI	--	---	--	--	00/00/84	1	--	--	-	U	WELL ABANDONED; REPLACED BY QA Db 37	QA Db 33
125AQUI	7.92	10/05/84	8.49	29.79	08/29/84	54	24	2.5	-	U	Q, G	QA Db 34
125AQUI	6.88	10/05/84	--	--	08/23/84	16	--	--	-	U	Q, G	QA Db 35
125AQUI	16.69	10/05/84	16.93	109.74	09/12/84	37	24	.4	-	U	Q, G REPLACES QA Db 31	QA Db 36
125AQUI	7.56	10/05/84	--	--	08/28/84	39	--	--	-	U	Q, G REPLACES QA Db 33	QA Db 37
125AQUI											G	QA Db 38
125AQUI	61.49	10/19/84	57	73	09/30/66	211	20	13.2	-	P		QA De 30
125AQUI			8	--	---	42	--	--	-		F	QA Ea 4
125AQUI	16	09/03/53	--	--	07/22/52	20	5	2.2	P	H	Q	QA Ea 10
-------	--	---	--	--	---	--	--	--	-	-	Q, G TEST BORING	QA Ea 26
125AQUI			19	26	05/18/68	20	6	2.9	S	R	F	QA Ea 31
125AQUI	12.86	10/10/84	12	25	07/01/75	10	24	.8	-	R	Q	QA Ea 32
125AQUI			--	--	---	--	--	--	-	H	F	QA Ea 33
125AQUI	18.70	04/05/82	18	40	09/20/82	40	3	1.8	S	H		QA Ea 34
125AQUI			21	--	12/14/65	25	2	--	-	H	F	QA Ea 35
125AQUI			10	15	02/10/77	10	4	2	-	H	Q	QA Ea 36
125AQUI	15.74	10/10/84	16	30	07/03/80	30	2	2.1	S	H	Q	QA Ea 37
125AQUI	--	---	10	15	02/11/77	10	4	2	J	H		QA Ea 38
125AQUI	13.47	10/10/84	14	30	04/29/80	40	3	2.5	S	H	F	QA Ea 39
125AQUI			--	--	---	--	--	--	-	H	F	QA Ea 40
125AQUI			12	22	07/25/79	25	4	2.5	-	H	Q	QA Ea 41
125AQUI			12	18	11/09/78	15	4	2.5	-	H	F	QA Ea 42
125AQUI			14	26	02/11/81	25	4	2.1	-	H	F	QA Ea 43
125AQUI	16.96	10/11/84	25	50	05/10/76	30	2	1.2	S	H		QA Ea 44
125AQUI	12.90	05/12/83	12	18	03/14/79	30	4	5	S	H	Q	QA Ea 45
125AQUI	9.53	05/12/83	12	30	01/11/82	50	3	2.8	S	H		QA Ea 46
125AQUI	17.70	05/19/83	15	35	01/15/80	50	4	2.5	S	H	F	QA Ea 47
125AQUI			10	--	10/28/74	30	3	--	-	H	F	QA Ea 48
125AQUI			11	28	02/05/60	27	4	1.6	-	H	F	QA Ea 50
125AQUI			15	23	11/13/78	20	6	2.5	J	H	F	QA Ea 51
125AQUI			19	24	12/18/72	18	3	3.6	J	H	F	QA Ea 52
125AQUI	18.53	05/25/83	22	50	09/04/81	45	3	1.6	S	H	F	QA Ea 53
125AQUI			20	28	07/16/76	20	3	2.5	J	H		QA Ea 54
125AQUI			20	50	07/07/81	25	4	.8	-	H	F	QA Ea 55
125AQUI			16	22	07/06/77	20	3	3.3	J	H	F	QA Ea 56
125AQUI			14	--	12/14/67	20	3	--	J	H	F	QA Ea 57
125AQUI			6	13	08/02/79	20	24	2.9	S	H	F	QA Ea 58

Table 8. - Records of selected wells in the Kent Island area - Continued

WELL NUMBER	STATE PERMIT NUMBER	OWNER	CONTRACTOR	YEAR COM-PLETED	ALTI-TUDE OF LAND SUR-FACE (FT)	DEPTH OF WELL (FT)	DIAMETER OF WELL (INCHES) CASING	DIAMETER OF WELL (INCHES) SCREEN	DEPTH OF BOTTOM OF CASING OR TOP OF SCREEN (FT BELOW LAND SURFACE)	TOTAL SCREEN LENGTH (FT)
QA Ea 59	QA-73-2746	THOMPSON, JOHN	QUEENSTOWN WELL DRILLING	1979	10	215	2	2	195	20
QA Ea 60	QA-73-1361	WOODHEAD	QUEENSTOWN WELL DRILLING	1976	7	185	2	2	165	20
QA Ea 61	QA-73-0605	FOSTER, CARLTON	QUEENSTOWN WELL DRILLING	1974	18	170	2	--	150	20
QA Ea 62	QA-81-0149	MORITTI, JOSEPH	COLLIER WELL DRILLING	1983	12	?	--	--	--	--
QA Ea 63	QA-81-0192	KNELL, CHARLES	COLLIER WELL DRILLING	1983	16.55	--	--	--	--	--
QA Ea 65	QA-81-0104	DEGRAFFT	SLATER WELL DRILLING	1983	16.76	140	4	2	133	7
QA Ea 66		PAXSON	COLLIER WELL DRILLING	1983	11.3	100	4			
QA Ea 67	--	JOHNSON, VERNON L.	COLLIER WELL DRILLING	----	18	--	--	--	--	--
QA Ea 68	--	ELSON, TOM	---	----	18	--	--	--	--	--
QA Ea 69	--	MAZZA, GARY	---	----	5	--	--	--	--	--
QA Ea 70	QA-73-2729	THEIL, FRED	SLATER WELL DRILLING	1979	10	227	4-2	2	220	7
QA Ea 71	QA-73-2351	MUIR, MARK	QUEENSTOWN WELL DRILLING	1978	20	135	4	4	115	20
QA Ea 72	QA-73-3865	BOSS	WOLFORD WELL DRILLING	1982	16.6	88	4	2	81	7
QA Ea 73	--	AMERICAN LEGION	COLLIER WELL DRILLING	----	--	--	4	--	--	--
QA Ea 74	QA-73-3742	PADDY, CARL	SLATER WELL DRILLING	1981	23.91	113	4	2	106	7
QA Ea 75	QA-73-2352	ALLNUTT, ROBERT	COLLIER WELL DRILLING	1978	8	140	4	2	120	20
QA Ea 76	QA-73-1472	NIX, BOYZE	QUEENSTOWN WELL DRILLING	1976	15	140	4	4	120	20
QA Ea 77	QA-81-0474	MD. GEOL. SURVEY MATAPEAKE I	BURNS WELL DRILLING CO.	1984	10.8	205	4	4	195	10
QA Ea 78	QA-81-0474	MD. GEOL. SURVEY MATAPEAKE II	BURNS WELL DRILLING CO.	1984	11.8	135	4	4	125	10
QA Ea 79	QA-81-0469	MD. GEOL. SURVEY MOWBRAY PARK I	BURNS WELL DRILLING CO.	1984	8.3	298	4	4	288	10
QA Ea 80	QA-81-0469	MD. GEOL. SURVEY MOWBRAY PARK II	BURNS WELL DRILLING CO.	1984	8.5	130	4	4	120	10
QA Ea 81	QA-81-0474	MD. GEOL. SURVEY MATAPEAKE III	BURNS WELL DRILLING CO.	1984	12.4	310	4	4	300	10
QA Eb 34	QA-01-1870	PIER 1 MOTEL	AARON WELL DRILLING	1953	18	210	4-2.5	--	183	--
QA Eb 109	QA-73-0037	U.S. GEOL. SURVEY	DELMARVA DRILLING CO.	1971	13	--	--	--	--	--
QA Eb 110	QA-73-2979	U.S. GEOL. SURVEY	A. C. SCHULTES & SONS	1980	14	2461	4	4	2399	20
QA Eb 111	QA-73-3122	U.S. GEOL. SURVEY	A. C. SCHULTES & SONS	1979	14	1026	4	4	941	20
QA Eb 112	QA-73-3123	U.S. GEOL. SURVEY	A. C. SCHULTES & SONS	1980	14	1688	4	4	1638	20
QA Eb 113	QA-73-3172	U.S. GEOL. SURVEY	A. C. SCHULTES & SONS	1979	--	204	6	6	164	40
QA Eb 116	--	BAY BRIDGE AIRPORT	---	----	10	--	--	--	--	--
QA Eb 117	QA-73-0904	YOUNG	PURNER WELL DRILLING	1975	12.83	165	4	2	155	10
QA Eb 118	QA-73-3200	QUEEN ANNE'S COUNTY SANITARY COMMISSION	DELMARVA DRILLING CO.	1980	3.97	--	4	--	--	--
QA Eb 119	QA-73-2176	DUTROW, JACK	SLATER WELL DRILLING	1978	5	237	4	2	230	7
QA Eb 120	QA-73-3316	JONES, REGINALD	COLLIER WELL DRILLING		17.7		4			
QA Eb 121	QA-71-0142	GROOME, WALLACE	AARON WELL DRILLING	1971	5	151	2	--	118	--
QA Eb 122	QA-73-3775	ACE AUTO SALES	QUEENSTOWN WELL DRILLING	1982	18	140	2	2	120	20
QA Eb 123	QA-73-3864	PIER 1 MARINA	COLLIER WELL DRILLING	1982	5	120	4	4	100	20
QA Eb 124	QA-73-3156	QUEEN ANNE'S COUNTY SANITARY COMMISSION	COLLIER WELL DRILLING	1980	20	150	4	4	130	20
QA Eb 125	QA-73-2242	CHANCE, CLIFF	COLLIER WELL DRILLING	1978	10	230	2	2	210	20
QA Eb 126	--	WALKER, BERTHA	---	----	18	--	--	--	--	--
QA Eb 127	QA-73-2504	GUYTON, EMMART	QUEENSTOWN WELL DRILLING	1978	17	265	2	2	245	20
QA Eb 128	QA-71-0129	PRICE, CLAYTON	HUDSON WELL DRILLING	1971	15	136	2	--	105	--
QA Eb 129	QA-73-1614	CORDER, MICHAEL	H. H. BUNKER & SONS, INC.	1977	10	183	4	2	178	5
QA Eb 130	--	QUEEN ANNE'S COUNTY SANITARY COMMISSION	---	----	5	--	--	--	--	--
QA Eb 131	QA-73-0789	MALLET, GEORGE	QUEENSTOWN WELL DRILLING	1975	10	260	2	--	240	--
QA Eb 132	QA-73-2651	CURRY, HENRY E.	SLATER WELL DRILLING	1979	12.66	217	4	2	210	7
QA Eb 133	QA-73-3187	QUEEN ANNE'S COUNTY COLLECTION STATION	DELMARVA DRILLING CO.	1980	3	--	--	--	--	--
QA Eb 134	QA-73-3994		KELLY WELL DRILLING	1982	5	--	4	--	--	--
QA Eb 135	QA-73-0900	MCGRAW REALTY	PURNER WELL DRILLING	1975	10	240	4	2	230	10
QA Eb 136	QA-73-3392	DOELER, RICHARD	QUEENSTOWN WELL DRILLING	1980	5.35	260	4-2	2	240	20
QA Eb 137	--	QUEEN ANNE'S COUNTY COLLECTION STA. E	---	----	13.81	--	4	--	--	--
QA Eb 138	QA-81-0049	BOGGS, RAYMOND	SLATER WELL DRILLING	1983	12.29	270	4	2	260	10
QA Eb 139	--	QUEEN ANNE'S COUNTY PUMPING STA. C	---	----	7	--	4	--	--	--
QA Eb 140	--	QUEEN ANNE'S COUNTY PUMPING STA. C	---	----	8	--	4	--	--	--
QA Eb 141	--	LEONARD	---	----	10	--	--	--	--	--
QA Eb 142	QA-68-0126	LITVINUCK, WALTER	AARON WELL DRILLING	1968	10	230	2	--	205	--

WATER-BEARING FORMATION	WATER LEVEL (FT BELOW LAND SURFACE)	DATE	PUMPING TEST DATA: WATER LEVELS BELOW LAND SURFACE (FT) STATIC	PUMPING	DATE	YIELD (GAL/MIN)	HOURS PUMPED	SPECIFIC CAPACITY [(GAL/MIN)/FT]	TYPE OF PUMP	USE OF WATER	REMARKS	WELL NUMBER
125AQUI			12	21	03/15/79	20	4	2.2	J	H	F	QA Ea 59
125AQUI			10	15	07/12/76	10	4	2	J	H	Q	QA Ea 60
125AQUI			8	12	05/22/74	12	5	3	-	H	F	QA Ea 61
125AQUI	12.53	10/11/84	--	--	---	--	--	--	-	H	F, G	QA Ea 62
125AQUI	17.59	10/10/84	--	--	---	--	--	--	-	H	F, G	QA Ea 63
125AQUI	17.86	10/10/84	16	28	06/16/83	60	4	5	S	H		QA Ea 65
125AQUI	12.33	10/10/84									G	QA Ea 66
125AQUI			--	--	---	--	--	--	-	H		QA Ea 67
125AQUI			--	--	---	--	--	--	-	H		QA Ea 68
125AQUI	5.94	10/10/84	--	--	---	--	--	--	-	H	F	QA Ea 69
125AQUI	17.34	10/11/84	8	16	10/10/79	30	24	3.8	S	H	F	QA Ea 70
125AQUI	19.23	10/10/84	12	25	06/29/78	25	4	1.9	S	H	F	QA Ea 71
125AQUI	18.37	08/03/83	15	30	06/30/82	20	2.5	1.3	S	H		QA Ea 72
125AQUI	16.03	10/11/84	--	--	---	--	--	--	-	Z		QA Ea 73
125AQUI	24.48	10/10/84	16	23	11/23/81	40	4	5.7	S	H		QA Ea 74
125AQUI	10.27	10/10/84	18	28	07/18/78	20	4	2	S	H		QA Ea 75
125AQUI			10	15	11/03/76	20	3	4	S	H		QA Ea 76
125AQUI	12.24	10/05/84	11.89	96.38	08/02/84	35	24	.4	-	U	Q, G	QA Ea 77
125AQUI	11.86	10/05/84	--	--	07/31/84	45	--	--	-	U	Q, G	QA Ea 78
125AQUI	9.62	10/05/84	--	--	08/08/84	15	--	--	-	U	Q, G	QA Ea 79
125AQUI	9.92	10/05/84	--	--	08/08/84	60	--	--	-	U	Q, G	QA Ea 80
125AQUI	11.39	10/05/84	--	--	07/30/84	10	--	--	-	U	Q, G	QA Ea 81
125AQUI			12	26	04/30/53	50	18	3.6	P	C		QA Eb 34
---											G TEST BORING	QA Eb 109
217PTNX	-4.06		-4.06	11.76	09/16/80	6.7	--	3	--	U	G, Q	QA Eb 110
217PPSC	10.44	02/05/80	10.44	30.9	02/05/80	65	24	3.2	-	U	Q	QA Eb 111
217PPSC	8.70	02/13/80	8.70	57.04	02/13/80	64	24	1.3	-	U	Q	QA Eb 112
125AQUI	16.10	11/15/79	16.10	24.1	11/15/79	10	3.5	1.2	-	U	Q	QA Eb 113
125AQUI			--	--	---	--	--	--	-	C	F	QA Eb 116
125AQUI	15.29	10/16/84	11	--	05/27/75	25	2	--	S	H	Q	QA Eb 117
125AQUI	7.47	10/16/84	--	--	---	--	--	--	-	C		QA Eb 118
125AQUI			8	16	04/14/78	30	24	3.8	S	H	F	QA Eb 119
125AQUI	18.55	10/19/84	--	--	---	--	--	--	-	-	F	QA Eb 120
125AQUI			14	--	03/19/71	27	2	--	-	H	F	QA Eb 121
125AQUI			12	30	03/15/82	25	3	1.4	-	C	F	QA Eb 122
125AQUI	4.58	10/19/84	9	22	08/13/82	20	5	1.5	S	C	F	QA Eb 123
125AQUI	13.31	10/16/84	12	26	04/16/80	50	5	3.6	S	N	F	QA Eb 124
125AQUI			14	21	03/21/78	20	4	2.9	J	H		QA Eb 125
125AQUI			--	--	---	--	--	--	-	H	F	QA Eb 126
125AQUI			12	20	11/07/78	15	4	1.9	-	H	F	QA Eb 127
125AQUI			17	--	03/11/71	30	3	--	-		F	QA Eb 128
125AQUI			15	25	01/08/77	30	3	3	S	H		QA Eb 129
125AQUI	9.11	10/16/84	--	--	---	--	--	--	-	Z		QA Eb 130
125AQUI			10	12	02/24/75	12	5	6	-	H	F	QA Eb 131
125AQUI	11.89	10/16/84	8	16	01/20/79	30	4	3.8	S	H	Q	QA Eb 132
125AQUI			--	--	---	--	--	--	-	-		QA Eb 133
125AQUI	10.14	10/19/84	--	--	---	--	--	--	-	-		QA Eb 134
125AQUI	12.13	10/19/84	20	100	05/08/75	50	3	.6	-	C	Q	QA Eb 135
125AQUI	9.78	10/16/84	12	25	09/18/80	50	4	3.8	S	H	Q	QA Eb 136
125AQUI	16.10	10/16/84	--	--	---	--	--	--	-	H		QA Eb 137
125AQUI	13.91	10/11/84	6	20	03/14/83	60	4	4.3	S	H		QA Eb 138
125AQUI	9.55	10/16/84	--	--	---	--	--	--	-	Z		QA Eb 139
125AQUI	8.89	05/26/83	--	--	---	--	--	--	-	Z		QA Eb 140
125AQUI			--	--	---	--	--	--	-	H	F	QA Eb 141
125AQUI			16	--	05/17/68	25	3	--	J	H	F	QA Eb 142

Table 8. - Records of selected wells in the Kent Island area - Continued

WELL NUMBER	STATE PERMIT NUMBER	OWNER	CONTRACTOR	YEAR COM-PLETED	ALTI-TUDE OF LAND SUR-FACE (FT)	DEPTH OF WELL (FT)	DIAMETER OF WELL (INCHES) CASING	DIAMETER OF WELL (INCHES) SCREEN	DEPTH OF BOTTOM OF CASING OR TOP OF SCREEN (FT BELOW LAND SURFACE)	TOTAL SCREEN LENGTH (FT)
QA Eb 143	QA-73-3198	QUEEN ANNE'S COUNTY PUMPING STA. D	DELMARVA DRILLING CO.	1980	5.30	--	--	--	--	--
QA Eb 144	QA-73-1817	HOXTER, RONALD	COLLIER WELL DRILLING	1977	15.11	240	4	4	220	20
QA Eb 145	QA-81-0150	BAY AREA HOMES	COLLIER WELL DRILLING	1983	15	--	--	--	--	--
QA Eb 146	QA-81-0152	CASTLE MARINA	DELMARVA DRILLING CO.	1983	15.05	280	8	4	180	100
QA Eb 147	QA-73-3189	QUEEN ANNE'S COUNTY SANITARY COMMISSION	DELMARVA DRILLING CO.	1980	3	--	--	--	--	--
QA Eb 148	QA-73-0270	JONES, ROBERT E.	H. H. BUNKER & SONS, INC.	1973	10	151	4	2	146	5
QA Eb 149	QA-73-0942	BROOKFIELD BLDRS.	SLATER WELL DRILLING	1975	13	107	4	2	100	7
QA Eb 150										
QA Eb 152	QA-73-3050	TENNYSON, CLYDE, JR.	COLLIER WELL DRILLING	1979	7.62	250	4-2	2	230	20
QA Eb 153	QA-81-0470	MD. GEOL. SURVEY PINEY CREEK I	BURNS WELL DRILLING CO.	1984	4	245	4	4	235	10
QA Eb 154			DELMARVA DRILLING CO.	1984						
QA Eb 155	QA-81-0470	MD. GEOL. SURVEY PINEY CREEK II	BURNS WELL DRILLING CO.	1984	3.9	245	4	4	235	10
QA Eb 156	QA-81-0475	MD. GEOL. SURVEY SEWAGE PLANT I	BURNS WELL DRILLING CO.	1984	11.9	220	4	4	210	10
QA Eb 157	QA-81-0475	MD. GEOL. SURVEY SEWAGE PLANT II	BURNS WELL DRILLING CO.	1984	11.9	120	4	4	110	10
QA Eb 158	QA-81-0547	HUDSON, JOSEPH M.	QUEENSTOWN WELL DRILLING	1984	10	250	2	2	230	20
QA Eb 159	QA-81-0872	QUEEN ANNE'S COUNTY DEPT. OF RECREATION AND PARKS	COLLIER WELL DRILLING	1985	12	485	4	4	465	20
QA Eb 160		KENT ISLAND VENTURES	EAST COAST WELL & PUMP, INC.	1985	15	--	--	--	--	--
QA Eb 161	QA-81-1501	QUEEN ANNES BUSINESS PARK	DELMARVA DRILLING CO., INC.	1986	20	--	--	--	--	--
QA Ec 85	QA-81-0128	MEARS POINT MARINA	C. Z. ENTERPRIZES	1983	5	412	6	6	392	20
QA Ec 86	QA-73-3109	BAY COUNTY MOOSE LODGE	QUEENSTOWN WELL DRILLING	1980	15	260	4-2	2	240	20
QA Ec 87	--	GRASONVILLE SENIOR CITIZENS CENTER	---	----	10	--	6	--	--	--
QA Fa 49	QA-04-3108	QUEEN ANNE MARINA	AARON WELL DRILLING	1961	8	210	4	--	--	--
QA Fa 50	QA-73-2309	WOOD, ROBERT M.	PURNER WELL DRILLING	1978	8	245	4-2	2	238	7
QA Fa 51	QA-73-3015	FRITSCH, JOSEPH	QUEENSTOWN WELL DRILLING	1980	8	270	2	2	250	20
QA Fa 52	QA-73-0313	SWAIN, L. H.	SHANNAHAN ARTESIAN WELL CO.	1973	10	293	4-2	2	273	20
QA Fa 53	QA-69-0019	VEGA, C.	HUDSON WELL DRILLING	1968	5	275	1.5	--	237	--
QA Fa 54	QA-73-1131	COALE, TILGHMAN C.	QUEENSTOWN WELL DRILLING	1975	10	260	2	2	240	20
QA Fa 55	--	WILLARD, CHARLES	---	----	10	60	--	--	--	--
QA Fa 56	--	BLOODY POINT FARM	---	----	10	--	--	--	--	--
QA Fa 57	QA-73-0589	REID, HUNTER M.	BRANHAM CONTRACTORS, INC.	1974	10	192	4	2	185	7
QA Fa 58	QA-81-0002	GOSNELL, JOHN G.	QUEENSTOWN WELL DRILLING	1983	7.07	280	4-2	2	260	20
QA Fa 59	QA-73-2943	COVE CREEK CLUB	COLLIER WELL DRILLING	1979	10	270	6-4	--	250	--
QA Fa 60	QA-73-2330	UNITED COMMUNITIES V.F.D.	COLLIER WELL DRILLING	1978	10.12	240	6-4	--	230	--
QA Fa 61	QA-73-2621	GILL, ANGELA E.	PURNER WELL DRILLING	1978	8	292	4-2	2	278	14
QA Fa 63	QA-73-0220	JUDY, ELIZABETH	HUDSON WELL DRILLING	1973	15	235	4-2	--	200	--
QA Fa 64	QA-73-2736	KENTMOOR MARINA	SHANNAHAN ARTESIAN WELL CO.	1977	5	231	4	4	191	40
QA Fa 65	QA-73-0542	GRIER, THOMAS	QUEENSTOWN WELL DRILING	1974	12	240	2	2	220	20
QA Fa 66	QA-73-2988	LEDER	QUEENSTOWN WELL DRILLING	1979	13	270	4-2	2	250	20
QA Fa 67	QA-73-2158	ELLISON, JAMES, JR.	COLLIER WELL DRILLING	1978	7.35	270	2	2	250	20
QA Fa 68	QA-81-0069	DIDYOUNG, MARIE	COLLIER WELL DRILLING	1983	11.26	--	--	--	--	--
QA Fa 70	--	WESTERGARD	--	----	10	--	--	--	--	--
QA Fa 71	QA-73-3555	REID, PETER	QUEENSTOWN WELL DRILLING	1981	8.85	270	4-2	2	250	20
QA Fa 72		MASK, JAMES	QUEENSTOWN WELL DRILLING	1984	10		4			
QA Fa 73		MD. GEOL. SURVEY PRICES CREEK	DELMARVA DRILLING CO.	1985	4		--	--	--	--
QA Fb 1	QA-73-1517	GLYNN, JAMES	QUEENSTOWN WELL DRILLING	1976	10	250	2	2	230	20
QA Fc 7		PROSPECT PLANTATION	CALVERT WELL DRILLING CO.	1978	10					
KE Eb 7	--	EASTERN NECK WILDLIFE REFUGE	---	----	--	--	--	--	--	--
KE Eb 8	KE-73-0524	EASTERN NECK WILDLIFE REFUGE	KELLY WELL DRILLING	1976	21	100	4	4	90	10
KE Eb 9	--	EASTERN NECK WILDLIFE REFUGE	---	----	10	--	4	--	--	--
KE Eb 10	--	EASTERN NECK WILDLIFE REFUGE	---	----	21	--	6	--	--	--
KE Eb 11	KE-73-0769	EASTERN NECK WILDLIFE REFUGE	STEWART WELL DRILLING	1978	21	109	4-2.5	3	99	10
TA Bb 5	TA-81-0470	CLAIBORNE WATER SUPPLY CO.	SHANNAHAN ARTESIAN WELL CO.	1983	8	347	4	4	317	30
TA Cb 94	TA-73-0009	WILKINSON, MONTE	SHANNAHAN ARTESIAN WELL CO.	1972	7	414	4-1.5	1.5	404	10
TA Cc 34	TA-71-0042	MARTINGHAM INN, INC.	SHANNAHAN ARTESIAN WELL CO.	1970	10	208	8	--	168	40
TA Cc 37	TA-72-0143	MARTINGHAM INN, INC.	SHANNAHAN ARTESIAN WELL CO.	1972	10	395	6-4	4	374	21
TA Cc 38	--	ST. MICHAELS UTILITIES	---	----	8	--	--	--	--	--
TA Cd 55	TA-71-0080	EASTON UTILITY CO.	SHANNAHAN ARTESIAN WELL CO.	1971	20.97	669	16-8	8	575	94
TA Dc 49	TA-81-0271	OXFORD UTILITIES	SHANNAHAN ARTESIAN WELL CO.	1983	5	578	8-5	5	538	40
TA Dc 50	--	OXFORD UTILITIES	SHANNAHAN ARTESIAN WELL CO.	----	3	675	--	--	--	--

WATER-BEARING FORMATION	WATER LEVEL (FT BELOW LAND SURFACE)	DATE	PUMPING TEST DATA: WATER LEVELS BELOW LAND SURFACE (FT) STATIC	PUMPING	DATE	YIELD (GAL/MIN)	HOURS PUMPED	SPECIFIC CAPACITY [(GAL/MIN)/FT]	TYPE OF PUMP	USE OF PUMP	REMARKS	WELL NUMBER
125AQUI	9.79	10/16/84	--	--	---	--	--	--	-	Z		QA Eb 143
125AQUI	16.79	10/16/84	12	21	07/22/77	30	4	3.3	S	H	Q	QA Eb 144
125AQUI	14.04	07/07/83	--	--	---	--	--	--	-	H	G	QA Eb 145
125AQUI			19	64	07/25/83	300	24	6.7	-	P	G	QA Eb 146
125AQUI	5.70	10/16/84	--	--	---	--	--	--	-	Z		QA Eb 147
125AQUI	16.02	10/10/84	6	60	05/14/73	15	2	.3	S	H		QA Eb 148
125AQUI			10	20	11/03/75	30	3	3	S	H		QA Eb 149
	17.20	10/16/84										QA Eb 150
125AQUI	13.30	10/16/84	11	22	11/08/79	10	5	.9	S	H	Q	QA Eb 152
125AQUI			--	--	---	--	--	--	-	U	G WELL ABANDONED; REPLACED BY QA Eb 155	QA Eb 153
											G	QA Eb 154
125AQUI	7.38	10/05/84	7.22	97.08	08/20/84	48	24	.5	-	U	Q, G REPLACES QA Eb 153	QA Eb 155
125AQUI	12.98	10/05/84	--	--	07/23/84	60	--	--	-	U	Q, G	QA Eb 156
125AQUI	11.96	10/05/84	15.66	30.61	---	44.6	24	3.0	-	U	Q, G	QA Eb 157
125AQUI			24	60	06/19/84	25	3	.7	J	H	G	QA Eb 158
125AQUI	12.59	03/22/85	14	60	01/23/85	140	8	3.2	-	H	G	QA Eb 159
125AQUI	--	---	--	--	---	--	--	--	-	-	G	QA Eb 160
210CRCS	--	---	--	--	---	--	--	--	-	-	G	QA Eb 161
125AQUI	11.98	10/19/84	10.25	143.5	10/29/83	68	11	.5	S	-	G	QA Ec 85
125AQUI	22.37	10/19/84	22	50	01/25/80	50	3	1.8	S	-		QA Ec 86
125AQUI	17.65	10/19/84	--	--	---	--	--	--	S	T		QA Ec 87
125AQUI			12	65	06/14/61	105	6	2.0	T	C	F	QA Fa 49
125AQUI	13.33	10/11/84	9	80	05/31/78	20	2	.3	S	H	Q	QA Fa 50
125AQUI			12	25	02/22/80	25	4	1.9	J	H	F	QA Fa 51
125AQUI	13.81	05/10/83	16	34	09/18/73	40	4	2.2	S	H		QA Fa 52
125AQUI			12	--	08/15/68	25	3	--	-	H	F	QA Fa 53
125AQUI			6	16	12/08/75	10	5	1	-	H	F	QA Fa 54
125AQUI			--	--	---	--	--	--	-	H	F	QA Fa 55
125AQUI			--	--	---	--	--	--	-	H	F	QA Fa 56
125AQUI	13.24	10/11/84	7	10	05/02/74	20	3	6.7	S	H	F	QA Fa 57
125AQUI	11.55	10/11/84	10	30	04/03/83	70	4	3.5	S	H	F	QA Fa 58
125AQUI	9.98	05/25/83	11	40	10/09/79	100	10	3.4	S	I		QA Fa 59
125AQUI	12.11	10/19/84	11	40	05/15/78	100	5	3.4	-	N	Q	QA Fa 60
125AQUI			18	80	10/18/78	30	1	.5	S	H	F	QA Fa 61
125AQUI	19.76	06/02/83	15	--	04/16/73	40	3	--	-	H		QA Fa 63
125AQUI	7.75	10/11/84	10	18	07/26/77	30	7	3.8	S	C	Q	QA Fa 64
125AQUI			14	18	03/20/74	12	5	3	--	-	F	QA Fa 65
125AQUI	12.11	10/11/84	12	30	11/03/79	40	3	2.2	S	H	F	QA Fa 66
125AQUI	8.84	10/11/84	9	18	06/20/78	20	4	2.2	S	H	Q	QA Fa 67
125AQUI	15.25	10/11/84	--	--	---	--	--	--	S	H	Q	QA Fa 68
125AQUI			--	--	---	--	--	--	-	-	F	QA Fa 70
125AQUI	13.08	10/11/84	14	40	06/26/81	50	4	1.9	S	H	F	QA Fa 71
125AQUI											G	QA Fa 72
	--	---	--	--	---	--	--	--	-	-	G TEST BORING	QA Fa 73
125AQUI			10	15	10/22/76	10	4	2	-	H	Q	QA Fb 1
	23.29	10/18/84									G	QA Fc 7
125AQUI	18.21	10/19/84	--	--	---	--	--	--	-	-	F	KE Eb 7
125AQUI	23.16	10/19/84	20	70	12/20/76	8	3	.2	S	-	F	KE Eb 8
125AQUI			--	--	---	--	--	--	-	-	F	KE Eb 9
125AQUI			--	--	---	--	--	--	-	-		KE Eb 10
125AQUI			25	105	07/14/78	60	10	.8	-	H		KE Eb 11
125AQUI	16.25	10/23/84	19	26	12/10/83	25	2	3.6	S	P		TA Bb 5
125AQUI	20.98	10/23/84	17	41	08/01/72	28	5	1.2	S	H		TA Cb 94
125AQUI	14.38	10/23/84	16	27	10/27/70	34	15	3.1	-	C		TA Cc 34
124PNPN	23.39	05/23/80	22	53	08/04/72	132	8	4.3	S	P		TA Cc 37
125AQUI	27.96	10/23/84	--	--	---	--	--	--	-	-		TA Cc 38
125AQUI	71.30	10/23/84	41	222	01/13/71	530	24	2.9	T	P		TA Cd 55
125AQUI	32.15	10/25/83	30	109	07/11/83	275	8	3.5	S	P		TA Dc 49
125AQUI			35	94	07/05/79	192	--	3.3	-	P		TA Dc 50

Table 8. — Records of selected wells in the Kent Island area - Continued - Explanation of codes

Pump-type codes

J - Jet
P - Piston
S - Submersible
T - Turbine

Water-use Codes

C - Commercial
H - Domestic
I - Irrigation
N - Industrial
P - Public supply
R - Recreaion
T - Institution
U - Unused
Z - Other

Remarks codes

F - Field water-quality data available
G - Geophysical logs available
Q - Laboratory water-quality data available

Table 9a. — Major dissolved constituents and nutrients in water from selected wells in the Kent Island area

[mv = millivolts; deg C = degrees Celsius; mg/L = milligrams per liter; μS/cm = microsiemens per centimeter at 25° Celsius; μg/L = micrograms per liter; -- = data not collected; > = greater than; < = less than]

Well number	Permit number	Aquifer	Date	Specific conductance (μS/cm)	Specific conductance lab (μS/cm)	pH (standard units)	pH lab (standard units)	Oxidation reduction potential (mv)	Temperature (deg C)	Oxygen, dissolved (mg/L)
QA Db 10		Aquia	12-20-54	975	--	7.1	--	--	11.0	--
QA Db 10		Aquia	08-16-83	1,060	1,060	7.2	7.0	--	16.0	0
QA Db 15	QA-73-3144	Aquia	07-08-83	960	983	>7.2	7.0	--	16.5	0
QA Db 23	QA-73-2961	Aquia	07-06-83	440	457	7.4	7.3	--	15.5	.1
QA Db 25	QA-73-3478	Aquia	07-06-83	370	352	5.7	5.6	--	15.0	.5
QA Db 26		Unconfined	07-06-83	3,450	3,980	6.6	6.7	--	18.0	0
QA Db 27		Aquia	07-14-83	--	1,430	7.2	7.2	--	14.5	0
QA Db 30	QA-81-0473	Aquia	08-27-84	15,900	15,500	6.8	4.6	-457	17.0	0
QA Db 31	QA-81-0473	Aquia	07-13-84	19,200	19,400	7.0	6.4	-89	15.0	0
QA Db 32	QA-81-0473	Aquia	07-16-84	9,400	9,450	6.7	6.5	--	15.0	0
QA Db 34	QA-81-0471	Aquia	08-29-84	518	518	7.4	7.3	-189	15.0	0
QA Db 35	QA-81-0472	Aquia	08-23-84	14,900	15,000	7.0	6.8	-149	15.0	0
QA Db 36	QA-81-0473	Aquia	09-12-84	18,600	18,900	6.8	6.3	--	15.0	0
QA Db 37	QA-81-0471	Aquia	08-28-84	570	573	7.5	7.5	-188	16.0	0
QA Ea 10	QA-01-0585	Aquia	12-20-54	297	--	7.5	--	--	12.0	--
QA Ea 26		Magothy	04-11-72	150	--	6.8	--	--	18.0	--
QA Ea 32	QA-73-0963	Aquia	03-19-85	350	383	7.8	7.6	--	15.0	.4
QA Ea 36	QA-73-1637	Aquia	07-05-83	2,050	2,090	7.4	7.4	--	15.5	.1
QA Ea 37	QA-73-3317	Aquia	07-05-83	350	312	7.6	7.3	--	17.0	--
QA Ea 41	QA-73-2871	Aquia	08-18-83	1,580	1,520	7.3	7.4	--	17.0	.3
QA Ea 45	QA-73-2731	Aquia	08-17-83	360	353	7.4	7.4	--	17.0	0
QA Ea 61	QA-73-0605		09-06-83	--	1,530	--	--	--	--	--
QA Ea 77	QA-81-0474	Aquia	08-01-84	15,400	15,600	7.0	6.3	-149	15.0	0
QA Ea 78	QA-81-0474	Aquia	07-31-84	302	301	7.6	7.4	-196	15.0	0
QA Ea 79	QA-81-0469	Aquia	08-08-84	380	347	9.3	9.3	--	17.0	--
QA Ea 80	QA-81-0469	Aquia	08-08-84	335	348	7.7	7.7	--	15.0	.5
QA Ea 81	QA-81-0474	Aquia	07-30-84	640	642	7.7	7.6	-188	15.0	--
QA Eb 110	QA-73-2979	Patuxent	03-04-80	225	--	7.2	--	--	24.5	--
QA Eb 110	QA-73-2979	Patuxent	11-19-80	180	212	7.5	7.6	--	23.5	--
QA Eb 111	QA-73-3122	Patapsco	02-06-80	154	--	6.5	--	--	21.0	0
QA Eb 112	QA-73-3223	Patapsco	02-14-80	135	--	6.2	--	--	25.0	0
QA Eb 113		Aquia	01-15-80	360	--	7.5	--	--	15.5	--
QA Eb 117	QA-73-0904	Aquia	07-13-83	480	456	7.8	7.6	--	15.5	.3
QA Eb 132	QA-73-2651	Aquia	08-16-83	500	515	7.5	7.4	--	17.0	0
QA Eb 135	QA-73-0900	Aquia	07-13-83	370	326	7.9	7.9	--	15.5	.2
QA Eb 136	QA-73-3392	Aquia	07-14-83	460	419	7.9	7.8	--	16.5	.1
QA Eb 144	QA-73-1817	Aquia	07-13-83	440	429	7.8	7.8	--	16.0	.6
QA Eb 152	QA-73-3050	Aquia	03-22-85	382	415	7.7	7.7	--	15.0	.3
QA Eb 155	QA-81-0470	Aquia	08-20-84	330	329	7.8	7.7	-195	15.5	1.0
QA Eb 156	QA-81-0475	Aquia	07-23-84	14,800	15,100	7.1	6.5	-144	15.0	0
QA Eb 157	QA-81-0475	Aquia	07-25-84	332	331	7.5	7.6	-149	15.0	0
QA Fa 39	QA-01-1712	Aquia	12-20-54	507	--	7.8	--	--	15.5	--
QA Fa 50	QA-73-2309	Aquia	07-07-83	320	322	7.9	7.3	--	17.0	.2
QA Fa 60	QA-73-2330	Aquia	07-07-83	415	415	7.9	7.7	--	15.5	.6
QA Fa 64	QA-73-2736	Aquia	07-07-83	725	718	7.6	7.5	--	17.0	.2
QA Fa 67	QA-73-2158	Aquia	07-07-83	345	356	>7.7	7.4	--	16.5	0
QA Fa 68	QA-81-0069	Aquia	08-18-83	465	428	7.6	7.7	--	17.0	.1
QA Fb 1	QA-73-1517	Aquia	07-14-83	420	367	7.9	7.8	--	15.5	--

Table 9a. — Major dissolved constituents and nutrients in water from selected wells in the Kent Island area - Continued

[mv = millivolts; deg C = degrees Celsius; mg/L = milligrams per liter; µS/cm = microsiemens per centimeter at 25° Celsius; µg/L = micrograms per liter; -- = data not collected; > = greater than; < = less than]

Well number	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L $CaCO_3$)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity field (mg/L as $CaCO_3$)	Alkalinity, carbonate It-Fld (mg/L as $CaCO_3$)
QA Db 10	400	240	140	15	45	3.2	161	--
QA Db 10	440	240	150	17	43	3.9	200	--
QA Db 15	460	240	170	9.4	23	5.6	220	--
QA Db 23	220	22	81	4.6	7.7	3.9	200	--
QA Db 25	45	19	9.9	4.8	45	.7	26	--
QA Db 26	710	570	200	50	460	7.6	140	--
QA Db 27	590	370	210	17	13	4.4	220	--
QA Db 30	4,100	4,000	1,400	140	2,100	27	--	126
QA Db 31	4,400	4,200	1,500	160	2,800	18	--	179
QA Db 32	3,000	2,800	1,100	55	790	9.4	--	223
QA Db 34	190	--	61	8.6	30	4.0	--	280
QA Db 35	5,800	5,700	2,000	200	1,200	22	--	101
QA Db 36	3,900	3,700	1,300	160	3,400	17	--	175
QA Db 37	250	--	84	8.8	20	4.1	--	253
QA Ea 10	140	0	43	7.5	4.1	4.6	153	--
QA Ea 26	61	50	16	5.2	2.1	2.8	11	--
QA Ea 32	120	--	37	7.2	33	3.8	--	--
QA Ea 36	750	590	270	19	56	4.4	160	--
QA Ea 37	150	--	54	3.9	8.1	2.0	160	--
QA Ea 41	590	430	210	15	40	3.1	160	--
QA Ea 45	150	--	48	7.7	15	6.8	190	--
QA Ea 61	--	--	--	--	--	--	--	--
QA Ea 77	6,500	6,400	2,100	300	510	29	--	60
QA Ea 78	130	--	41	7.3	11	3.6	--	169
QA Ea 79	53	--	18	1.9	63	7.4	--	160
QA Ea 80	110	--	34	6.8	27	4.3	--	196
QA Ea 81	140	16	45	6.2	70	5.4	--	122
QA Eb 110	17	0	3.6	1.8	36	7.2	76	--
QA Eb 110	15	--	3.1	1.8	36	6.7	--	--
QA Eb 111	33	21	7.2	3.5	1.9	3.1	12	--
QA Eb 112	41	6	8.6	4.5	3.6	6.5	35	--
QA Eb 113	160	0	43	13	6.5	5.6	180	--
QA Eb 117	3	--	.72	.24	100	1.3	230	--
QA Eb 132	190	--	60	9.1	38	4.0	270	--
QA Eb 135	130	--	33	12	15	9.5	180	--
QA Eb 136	2	--	.37	.21	100	.9	230	--
QA Eb 144	140	--	48	6.0	38	2.4	220	--
QA Eb 152	100	--	25	9.3	48	10	--	--
QA Eb 155	140	--	35	13	8.8	9.9	--	185
QA Eb 156	7,100	7,100	2,100	450	160	26	--	51
QA Eb 157	150	--	55	3.7	6.5	1.7	--	167
QA Fa 39	77	0	23	4.7	85	6.2	237	--
QA Fa 50	100	--	30	6.0	30	5.4	110	--
QA Fa 60	68	--	21	3.7	68	4.4	200	--
QA Fa 64	210	63	62	14	52	6.5	150	--
QA Fa 67	130	--	37	9.7	20	7.1	160	--
QA Fa 68	170	--	51	11	22	6.6	220	--
QA Fb 1	78	--	21	6.3	44	10	200	--

Table 9a. — Major dissolved constituents and nutrients in water from selected wells in the Kent Island area - Continued

[mv = millivolts; deg C = degrees Celsius; mg/L = milligrams per liter; μS/cm = microsiemens per centimeter at 25° Celsius; μg/L = micrograms per liter; -- = data not collected; > = greater than; < = less than]

Well number	Sulfate dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Bromide dis-solved (mg/L as Br)	Iodine, dis-solved (mg/L as I)	Silica, dis-solved (mg/L as SiO_2)	Nitro-gen, NO_2+NO_3 dis-solved (mg/L as N)	Phos-phorus, ortho, dis-solved (mg/L as P)
QA Db 10	220	80	0.4	--	--	38	--	--
QA Db 10	230	88	.3	--	--	39	<0.10	<0.01
QA Db 15	170	100	< .1	--	0.02	45	< .10	< .01
QA Db 23	7.9	21	.1	--	< .01	39	< .10	.02
QA Db 25	19	66	.1	--	< .01	27	2.90	.06
QA Db 26	82	1,100	.2	--	< .01	31	< .10	< .01
QA Db 27	17	320	.2	--	--	30	< .10	< .01
QA Db 30	670	6,000	.2	--	.06	20	< .10	< .01
QA Db 31	740	7,100	< .1	--	.063	25	< .10	< .01
QA Db 32	390	3,200	< .1	--	.042	18	< .10	< .01
QA Db 34	.5	11	.1	--	.013	46	< .10	.13
QA Db 35	470	5,700	.6	--	.056	18	< .10	< .01
QA Db 36	810	7,400	< .1	--	.10	29	< .10	< .01
QA Db 37	58	14	< .1	--	.007	31	< .10	.02
QA Ea 10	0.1	3.1	0.2	--	--	27	--	--
QA Ea 26	54	.8	.4	--	--	7.4	--	--
QA Ea 32	15	3.8	.2	< .01	.001	21	< .10	< .01
QA Ea 36	8.0	560	.1	--	.01	24	< .10	< .01
QA Ea 37	1.9	4.4	.2	--	< .01	30	< .10	.03
QA Ea 41	9.7	360	< .1	--	--	29	< .10	< .01
QA Ea 45	2.1	4.7	.2	--	--	31	< .10	.03
QA Ea 61	--	370	--	--	--	--	--	--
QA Ea 77	430	6,000	< .1	--	.013	19	< .10	< .01
QA Ea 78	12	4.1	.1	--	.008	23	< .10	.04
QA Ea 79	45	3.0	.3	--	.004	14	< .10	< .01
QA Ea 80	.4	2.6	.1	--	.008	17	< .10	.05
QA Ea 81	38	110	.2	--	.004	14	< .10	< .01
QA Eb 110	13	13	.2	--	.00	14	.00	--
QA Eb 110	14	15	.2	--	--	14	--	--
QA Eb 111	27	.9	.2	--	.01	9.7	.02	--
QA Eb 112	13	1.1	.2	--	.01	12	.03	--
QA Eb 113	0	2.5	.2	--	--	14	--	--
QA Eb 117	8.6	7.9	.2	--	--	33	< .10	.07
QA Eb 132	2.2	9.3	< .1	--	--	26	< .10	.06
QA Eb 135	.4	2.0	1.0	--	--	18	< .10	.01
QA Eb 136	5.5	2.5	1.0	--	--	17	< .10	.01
QA Eb 144	7.6	6.3	.2	--	--	21	< .10	.05
QA Eb 152	4.5	1.5	.9	< .01	.001	16	< .10	< .01
QA Eb 155	2.7	2.2	.8	--	.011	16	< .10	< .01
QA Eb 156	410	5,600	< .1	--	.018	22	< .10	< .01
QA Eb 157	10	28	.2	--	.008	30	< .10	.05
QA Fa 39	7.0	18	1.1	--	--	18	--	--
QA Fa 50	.9	2.9	.5	--	< .01	15	< .10	.05
QA Fa 60	5.3	11	1.1	--	.01	19	< .10	.03
QA Fa 64	1.2	130	.3	--	< .01	18	< .10	< .01
QA Fa 67	5.2	15	.3	--	< .01	16	< .10	< .01
QA Fa 68	17	4.3	.2	--	--	21	< .10	.03
QA Fb 1	.9	2.2	.8	--	--	14	< .10	.02

Table 9a. — Major dissolved constituents and nutrients in water from selected wells in the Kent Island area – Continued

[mv = millivolts; deg C = degrees Celsius; mg/L = milligrams per liter; μS/cm = microsiemens per centimeter at 25° Celsius; μg/L = micrograms per liter; -- = data not collected; > = greater than; < = less than]

Well number	Aluminum, dissolved (μg/L as Al)	Barium, dissolved (μg/L as Ba)	Iron, dissolved (μg/L as Fe)	Manganese, dissolved (μg/L as Mn)	Strontium, dissolved (μg/L as Sr)	C-13/C-12 stable isotope ratio per mil	Carbon organic dissolved (mg/L as C)
QA Db 10	--	--	--	--	--	--	--
QA Db 10	<100	--	4,800	26	--	--	5.5
QA Db 15	<100	130	4,200	18	170	-13.6	2.5
QA Db 23	<100	210	890	8	110	-13.7	1.2
QA Db 25	<100	35	73	69	34	-21.8	1.0
QA Db 26	<100	100	3,700	5,700	440	-14.9	1.0
QA Db 27	<100	--	4500	150	--	--	4.0
QA Db 30	<10	300	150,000	930	4,100	-13.5	1.8
QA Db 31	<100	200	23,000	80	2,200	-13.2	2.1
QA Db 32	<100	200	13,000	170	1,100	-13.1	1.3
QA Db 34	<10	110	--	--	140	--	3.4
QA Db 35	<100	300	44,000	170	3,500	--	1.0
QA Db 36	<10	300	25,000	50	2,300	--	1.3
QA Db 37	<10	160	940	42	220	--	2.5
QA Ea 10	--	--	--	--	--	--	--
QA Ea 26	--	--	--	--	--	--	--
QA Ea 32	10	170	280	12	200	--	1.9
QA Ea 36	100	600	4,600	70	550	-16.1	1.6
QA Ea 37	100	72	600	8	73	-17.8	1.9
QA Ea 41	<100	--	3,400	100	--	--	1.8
QA Ea 45	<100	--	660	4	--	--	3.3
QA Ea 61	--	--	--	--	--	--	--
QA Ea 77	<100	1,000	15,000	630	7,000	-12.3	.6
QA Ea 78	<100	90	1,500	29	130	-18.4	1.1
QA Ea 79	30	45	30	3	220	--	.9
QA Ea 80	<10	98	520	6	130	--	2.2
QA Ea 81	<100	140	840	57	300	-9.4	.7
QA Eb 110	10	40	890	70	120	--	--
QA Eb 110	--	--	1,500	70	--	--	--
QA Eb 111	0	100	14,000	240	200	--	--
QA Eb 112	40	300	3,200	200	300	--	--
QA Eb 113	--	--	630	2	--	--	--
QA Eb 117	100	--	21	<1	--	--	2.3
QA Eb 132	<100	--	560	6	--	--	3.3
QA Eb 135	100	--	370	2	--	--	1.5
QA Eb 136	<100	--	7	2	--	--	1.4
QA Eb 144	<100	--	440	3	--	--	1.9
QA Eb 152	30	6	220	160	430	-13.5	1.8
QA Eb 155	30	140	410	3	860	-16.1	--
QA Eb 156	<100	1,000	15,000	50	5,600	-11.3	.7
QA Eb 157	<100	72	1,400	10	78	-15.7	1.8
QA Fa 39	--	--	--	--	--	--	--
QA Fa 50	<100	110	190	2	230	-16	2.1
QA Fa 60	<100	66	350	4	200	-11.4	1.0
QA Fa 64	<100	180	770	5	440	-16	2.1
QA Fa 67	<100	47	300	5	490	-12.5	1.3
QA Fa 68	<100	--	360	8	--	--	1.9
QA Fb 1	<100	--	300	2	--	--	1.3

Table 9b. — Dissolved metals in water from selected wells in the Kent Island area

[μg/L = micrograms per liter; < = less than]

Well number	Date	Aluminum, dissolved (μg/L as Al)	Antimony, dissolved (μg/L as Sb)	Arsenic dissolved (μg/L as As)	Beryllium, dissolved (μg/L as Be)	Cadmium dissolved (μg/L as Cd)
QA Db 30	08-27-84	<10	<1	<1	<10	<1
QA Db 34	08-29-84	<10	<1	<1	<0	<1

Well number	Chromium, dissolved (μg/L as Cr)	Cobalt, dissolved (μg/L as Co)	Copper, dissolved (μg/L as Cu)	Lead, dissolved (μg/L as Pb)	Mercury dissolved (μg/L as Hg)
QA Db 30	<1	1	<1	11	1.2
QA Db 34	1	1	<1	3	.3

Well number	Molybdenum, dissolved (μg/L as Mo)	Nickel, dissolved (μg/L as Ni)	Selenium, dissolved (μg/L as Se)	Silver, dissolved (μg/L as Ag)	Zinc, dissolved (μg/L as Zn)
QA Db 30	<1	3	<1	<1	40
QA Db 34	<1	2	<1	<1	<3

Table 10a. — Brief biostratigraphic analyses of test-well samples using palynomorphs

[Modified from (G.J. Brenner, State University of New York at New Paltz, written commun., 1984)]

Well Number	Location	Depth, feet	Formation	Age	Paleoecology	Diagnostic Species and Discussion
QA DB 31	Love Point	170.0-170.3	---	---	---	BARREN
QA DB 31	Love Point	275.5-275.9	---	---	---	BARREN
QA DB 31	Love Point	314.2-314.9	---	---	---	BARREN Discussion: Plant debris in this sample have a higher thermal maturation index than the samples above. This characteristic continues below in the core at 368.3-368.7 feet, which can be dated with palynomorphs as Santonian-Campanian. A disconformity between 275.9 and 314.2 feet is suspected.
QA DB 31	Love Point	368.3-368.7	Magothy or Matawan	Upper Cretaceous (Santonian to Campanian)	Nonmarine	Diagnostic Spores and Pollen — Range ACP* — Frequency[1] *Todisporites major* — Cretaceous — R *Plicapollis sp.* — Santonian-Campanian — R *Podocarpidites sp.* — Cretaceous — R *Rugubivesiculites rugosus* — L.Albian-Maastrichtian — A Discussion: Although *R. bivesiculites* is found in the Monmouth[2] Group, it is much more abundant in samples from older levels. In a study of well AA-De 100 (Brenner, 1974) this species was not found above the Campanian. The genus *Plicapollis* is typical of the Magothy-Matawan horizons. The absence of dinoflagellate cysts and the large amount of wood debris in this sample suggests a non-marine environment of deposition. The paucity of specimens prevents a more precise dating.
QA DB 34	Cloverfields	90.7-90.1	Calvert	Miocene	Nonmarine to nearshore marine	Diagnostic Spores and Pollen — Frequency[1] *Betula sp.* — A *Carya sp.* — A *Liquidamber sp.* — R Nymphaceous type — O *Osmunda sp.* — C *Pterocarya* — A *Quercus sp.* — A *Tilia sp.* — R *Tsuga sp.* — C *Ulmus sp.* — R Discussion: Typical oak-hickory-birch assemblage of the Maryland Miocene. Nymphaceous grains constitute the occasional exotic element. The grasses and composites, so typical of the Plio-Pleistocene, are absent. The presence of a few non-diagnostic acritarchs suggest the proximity of the marine environment.
QA DB 34	Cloverfields	155.0-155.4	---	---	---	BARREN
QA DB 34	Cloverfields	156.6-157.0	---	Miocene	Nonmarine	Diagnostic Palynomorphs — Frequency[1] *Betula sp.* — C *Fagus sp.* — C *Quercus sp.* — C *Pinus sp.* — C *Tsuga sp.* — C Discussion: This sample contains a well preserved assemblage of modern forest tree pollen. Typical nonarboreal pollen common to the post-Miocene Neogene was not found.
QA DB 35	Mylander Farm	231.0-231.4	Brightseat or Hornerstown	Lower Paleocene (Danian)	Offshore marine	Diagnostic Dinoflagellates — Range ACP* — Frequency[1] *Danea californica* Whitney — Danian — O *Spiniferits ramosus* — Maastrichtian-Danian — R Silicoflagellates *Distephanus sp.* — Paleocene-Holocene — R Discussion: There are no land derived plant microfossils in this assemblage. Specimens of dinoflagellates are rare but those found are good index forms.

*ACP = Atlantic Coastal Plain

[1]A = abundant; C = common; O = occasional; R = rare; VA = very abundant

[2]The Monmouth Group or Formation may be equivalent to the Severn Formation referred to in this report.

Table 10a. — Brief biostratigraphic analyses of test-well samples using palynomorphs - Continued

Well Number	Location	Depth, feet	Formation	Age	Paleoecology	Diagnostic Species and Discussion		
QA EA 77	Matapeake	340.0-340.5	Severn	Maastrichtian-Paleocene(?)	Marine	Diagnostic Spores and Pollen	Range ACP*	Frequency[1]
						Platycarya sp.	Upper Paleocene-Holocene	R
						Dinoflagellates		
						Deflandrea sp.	Cretaceous-Cenozoic	R
						Exochosphaeridium complex	Maastrichtian-Paleocene	O
						Discussion: This sample contains very few palynomorphys. The few grains that were found have been reported from the Monmouth[2] and Aquia Formations.		
QA EA 77	Matapeake	396.2-396.4	---	Upper Cretaceous	Marine	Discussion: Palynomorphs are extremely rare. However, several specimens of *Rugubivesiculites rugosus* were found. This form is typical of the Upper Cretaceous in the Atlantic Coastal Plain. Fragments of a few centric diatoms and a chitinous lining of a foraminiferal cyst indicate a marine environment of deposition.		
QA EA 79	Mowbray Park	60.5-61.0	Nanjemoy	Lower Eocene (Ypresian)	Marine	Diagnostic Spores and Pollen	Range ACP*	Frequency[1]
						Carya sp. <29 um	Danian-Ypresian	R
						Castanea types		A
						Casuarinidites sparsus Frederiksen	Danian-Ypresian	O
						Nudopollis terminalis Pflug	Late Cretaceous-Ypresian	O
						Nuxipollenites psilatus Frederiksen	Ypresian	R
						Dinoflagellates		
						Leptodinium sp.	?	R
						Silicoflagellates		
						Distephanus sp.	Paleocene-Holocene	O
						Discussion: Palynomorphs are very rare in this sample; however, those that were found were good index forms. The presence of *Nuxipollenites psilatus* restricts the age of this sample to the Ypresian stage (Frederiksen, 1979).		
QA EA 80	Mowbray Park	131.0-131.4	---	---	---		BARREN	
QA EA 81	Matapeake	267.6-268.0	---	---	---		BARREN	
QA EA 81	Matapeake	268.0-268.5	Brightseat or Hornerstown(?)	Lower Paleocene (Danian)	Marine	Diagnostic Palynomorphs	Range ACP*	
						Paleocystodinium golzowense	Danian	
						Systematophora placantha	Monmouth[2]-Brightseat	
						Discussion: In a dinoflagellate study of the Severn-Brightseat boundary, Whitney (1984) found *P. golzowense* restricted to the Brightseat Formation.		
QA EB 153	Piney Creek	70.0-70.4	---	Pleistocene	Nonmarine, cool temperate	Diagnostic Spores and Pollen		Frequency[1]
						Carya sp.		A
						Picea spp.		VA
						Pinus spp.		VA
						Tsuga sp.		C
						Discussion: The palynomorph assemblage is very rich in grains but low in diversity. The assemblage reflects a spruce, pine, hickory forest complex, and is suggestive of cool temperate conditions.		
QA EB 153	Piney Creek	130.0-130.4	---	Neogene (possibly Miocene)	Nonmarine	Diagnostic Spores and Pollen	Range ACP*	Frequency[1]
						Betula spp.		C
						Carya sp. >29 um	Middle Eocene-Holocene	C
						Caryophllaceae	Neogene	R
						Fagus sp.	Neogene	R
						Ulmus sp.	Paleocene-Recent	O
						Discussion: Palynomorphs are poor; however, the above types have been found in the Calvert Formation.		

*ACP = Atlantic Coastal Plain

[1]A = abundant; C = common; O = occasional; R = rare; VA = very abundant

[2]The Monmouth Group or Formation may be equivalent to the Severn Formation referred to in this report.

Table 10a. — Brief biostratigraphic analyses of test-well samples using palynomorphs - Continued

Well Number	Location	Depth, feet	Formation	Age	Paleoecology	Diagnostic Species and Discussion
QA EB 157	Sewage Plant	45	Nanjemoy	Lower Eocene (Ypresian)	---	**Diagnostic Spores and Pollen** / **Range ACP*** / **Frequency**[1] *Momipites tenuipolus* — Maastrichtian-Ypresian — R *Castanea* type — Paleocene-Holocene — A *Platycaryapollenites swasticoidus* — Ypresian (Lower Eocene) — R Discussion: Although few in number the forms restrict this sample to the Ypresian Stage. The form *P. swasticoidus* has been found in the upper Marlboro Clay and Nanjemoy Fm. of Maryland by this author. It has also been reported from the Oak Grove well of Virginia in beds of Ypresian age (Frederiksen, 1979).
QA EB 157	Sewage Plant	46	---	Eocene	Marine	**Diagnostic Palynomorphs** / **Range ACP*** *Momipites tenuipolus* — Cretaceous-Lower Eocene *Distephanus sp.* — Paleocene-Holocene Centric diatom — Cretaceous-Holocene Discussion: Palynomorphs are extremely rare. The few forms found are consistent with the Upresian age previously determined at 45 ft in this well.

*ACP = Atlantic Coastal Plain

[1] A = abundant; C = common; O = occasional; R = rare; VA = very abundant

Table 10b. — Brief biostratigraphic analyses of test-well samples using foraminiferal species

[Modified from (R.K. Olsson, Rutgers University, written commun., 1984)]

Well Number	Location	Depth, feet	Sample Description	Depositional Environment	Age	Species	
QA Db 31	Love Point	110-120	Medium to coarse glauconitic sand (cuttings)	Middle Shelf (320 ft)	Late Paleocene (Lower P4 Zone)	*Alabamina midwayensis*	C[1]
						Cibicides marylandicus	C
						Cibicidoides alleni	F
						Gavelinella compressa	F
						Gavelinella neelyi	C
						Gavelinella umbonifera	F
						Globulina gibba	C
						Guttulina hantkeni	F
						Gyroidinoides subangulata	F
						*Morozovella acutispira**	R
						*Morozovella aequa**	R
						Oolina rancocasensis	R
						Pararotalia perclara	F
						*Planorotalites imitata**	R
						*Planorotalites pseudomenardii**	R
						*Planorotalites pusilla laevigata**	R
						Spiroplectammina wilcoxensis	R
						*Subbotina velascoensis**	R
						Textularia portenta	R
						Vaginulina crosswicksensis	R
						* planktonic markers	
QA Db 31	Love Point	170	Dark green, medium glauconitic sand	Inner Shelf	Paleocene (?)	*Anomalinoides acuta**	X
						Trochammina sp.	X
						* common in Paleocene, but not restricted	
QA Db 31	Love Point	275.5	Yellowish brown, clayey medium glauconitic sand; highly weathered	--	--	BARREN	
QA Db 31	Love Point	314.2	Yellowish brown, fine to medium glauconitic sand; weathered	--	--	BARREN	
QA Db 31	Love Point	368.3	Light gray silty very fine sand; lignitic and micaceous	--	--	BARREN	
QA Db 33	Cloverfields	311.4-311.7	Clayey, silty, glauconitic sand with abundant forams	Outer Shelf (500-600 ft)	Early Paleocene (P1B Zone)	*Alabamina midwayensis*	C
						Cibicidoides howelli	F
						Dentalina arkansasanum	R
						Dentalina basiplanata	R
						Dentalina naheolensis	R
						Dentalina pseudo-obliquistriata	R
						Dentalina virginiana	R
						Fursenkoina wilcoxensis	F
						Gavelinella cf. compressa	A
						Gavelinella danica	R
						Gavelinella neelyi	A
						Gavelinella umbonifera	A
						*Globoconusa daubjergensis**	A
						Globulina gibba	C
						Gyroidinoides octacameratus	A
						Lagena sp.	R
						Lenticulina midwayensis	F
						Nodosaria latejugata	R
						Oolina rancocasensis	F
						Pararotalia reissi	X
						Pulsiphonina prima	R
						Pulvinulinella minuta	R
						Rectonodosaria tenuistrata	F
						Siphogenerinoides eleganta	R
						*Subbotina edita**	C
						*Subbotina fringa**	R
						*Subbotina pseudobulloides**	C
						Tappanina selmensis	F
						Vaginulina sp.	R
						Vaginulinopsis echinata	R
						* planktonic markers	

[1]A = abundant F = few X = very rare
C = common R = rare

Table 10b. — Brief biostratigraphic analyses of test-well samples using foraminiferal species - Continued

Well Number	Location	Depth, feet	Sample Description	Depositional Environment	Age	Species	
QA Db 34	Cloverfields	90.7	Greenish brown silt; lignitic	--	--	BARREN	
QA Db 34	Cloverfields	155.0	Light brown, sandy silt with occasional glauconite and diatoms	--	--	BARREN	
QA Db 34	Cloverfields	186.0	Brown, fine to medium sand; slightly glauconitic	--	--	BARREN	
QA Db 35	Mylander Farm	231.0	Yellowish brown, medium glauconitic sand; slightly weathered	--	--	BARREN	
QA Ea 77	Matapeake	340.0	Greenish gray, clayey medium glauconitic sand with gypsum	Inner to Middle Shelf	Early Paleocene	*Cibicidoides alleni*	X[1]
						*Subbotina fringa**	X
						* age diagnostic	
QA Ea 77	Matapeake	395.6	Dark green clayey, fine glauconitic sand	--	--	BARREN	
QA Ea 78	Matapeake	134.3	Greenish gray, medium to coarse glauconitic sand with shells	Inner to Middle Shelf	Early Eocene (?)	*Alabamina midwayensis*	X
						*Cibicides cf. westi**	X
						Gavelinella cf. burlingtonensis	X
						Globulina gibba	X
						*Pararotalia sp.**	X
						* more common in Eocene, but not restricted	
QA Ea 79	Mowbray Park	60.5	Dark green sandy greensand with gypsum	--	--	BARREN	
QA Ea 79	Mowbray Park	160-180	Medium to coarse glauconitic (cuttings)	Inner to Middle Shelf (160-320 ft)	Middle to Late Paleocene	*Alabamina midwayensis*	C
						Cibicides marylandicus	C
						Cibicides succedens	C
						Cibicidoides alleni	F
						Gavelinella compressa	C
						Gavelinella neelyi	A
						Globulina gibba	C
						*Morozovella aequa**	X
						*Morozovella angulata**	X
						Pararotalia perclara	R
						Spiroplectammina wilcoxensis	F
						*Subbotina velascoensis**	?
						Textularia portenta	F
						Vaginulina marginata	R
						* planktonic markers	
QA Ea 79	Mowbray Park	280.0	Greenish gray medium glauconitic sand	Inner to Middle Shelf	Middle Paleocene (P3 Zone)	*Acarinina strabocella**	C
						Alabamina midwayensis	C
						Arenobulimina cuskleyae	X
						Bolivinopsis emmendorferi	F
						Bulimina hornerstownensis	X
						*Chiloguembelina midwayensis**	X
						Cibicidoides alleni	C
						Eponides sp.	X
						Gavelinella burlingtonensis	C
						Gavelinella compressa	F
						* age diagnostic	

[1]A = abundant F = few X = very rare
C = common R = rare
? = questionably present

Table 10b. — Brief biostratigraphic analyses of test-well samples using foraminiferal species - Continued

Well Number	Location	Depth, feet	Sample Description	Depositional Environment	Age	Species	
QA Ea 79 (cont'd)	Mowbray Park	280.0	Greenish gray medium glauconitic sand	Inner to Middle Shelf	Middle Paleocene (P3 Zone)	*Gavelinella danica*	C[1]
						Gavelinella umboniferous	C
						Globulina gibba	R
						Gyroidinoides subangulata	X
						Lenticulina midwayensis	R
						Loxostomoides applinae	X
						Marginulina sp.	X
						*Morozovella angulata**	C
						*Planorotalites compressa**	R
						Pullenia quinqueloba	X
						Pulsiphonina prima	X
						Stilostomella plummerae	X
						*Subbotina triloculinoides**	X
						Tappanina selmensis	X
						* age diagnostic	
QA Ea 80	Mowbray Park	131.0	Yellowish brown, medium to coarse glauconitic sand with shell; weathered	Middle Shelf	Early Eocene (P9 Zone)	*Acarinina cf. pentacamerata**	X
						*Acarinina soldadoensis angulosa**	X
						Alabamina midwayensis	R
						Cibicides cf. westi	X
						Cibicidoides cf. alleni	X
						Gavelinella cf. danica	R
						Globulina gibba	X
						Guttulina cf. communis	X
						Guttulina sp.	X
						Kolesnikovella elongata	X
						*Morozovella bullbrooki**	X
						Pararotalia sp.	R
						* age diagnostic	
QA Ea 81	Matapeake	267.6	Greenish gray, clayey, medium glauconitic sand	Middle to Outer Shelf	Early Paleocene (P1B Zone)	*Alabamina midwayensis*	F[1]
						Bolivinopsis emmendorferi	R
						Bulimina hornerstownensis	X
						Bulimina quadrata	X
						Chiloguembelina midwayensis	X
						Cibicidoides alleni	C
						Dentalina colei	X
						Gavelinella danica	C
						Gavelinella umboniferous	A
						*Globoconusa daubjergensis**	C
						Globulina gibba	F
						Guttulina hantkeni	X
						Gyroidinoides subangulata	C
						Lagena pseudocostata	X
						Lenticulina midwayensis	F
						Loxostomoides applinae	X
						Nodosaria latejugata	X
						Nodosaria sp.	X
						Pararotalia reissi	X
						Pulsiphonina prima	X
						Rectonodosaria tenuistrata	F
						Siphogeneroides eleganta	X
						Stilostomella plummerae	X
						*Subbotina edita**	R
						*Subbotina fringa**	C
						*Subbotina pseudobulloides**	R
						*Subbotina triloculinoides**	C
						Valvulineria sp.	X
						*Woodringina hornerstownensis**	X
						* age diagnostic	
QA Eb 153	Piney Creek	70.0	Gray clay	--	--	BARREN	
QA Eb 153	Piney Creek	130.0	Gray clay with diatoms	Inner Shelf to lagoonal	Probably Miocene	*Elphidium gunteri**	X
						* Miocene to Holocene range	

[1]A = abundant F = few X = very rare
C = common R = rare

Table 10b. — Brief biostratigraphic analyses of test-well samples using foraminiferal species - Continued

Well Number	Location	Depth, feet	Sample Description	Depositional Environment	Age	Species	
QA Eb 153	Piney Creek	240-260	Medium glauconitic sand (cuttings)	Middle Shelf (320 ft)	Middle to Late Paleocene	*Alabamina midwayensis*	F[1]
						Cibicides succedens	F
						Cibicidoides alleni	F
						Dentalina basiplanata	R
						Eponides cf. lotus	X
						Gavelinella compressa	F
						Gavelinella neelyi	C
						Globulina gibba	C
						Guttulina hantkeni	R
						Lenticulina jenningsi	R
						Nonion graniferum	X
						Osangularia plummerae	X
						Pararotalia perclara	X
						Spiroplectammina wilcoxensis	R
						*Subbotina velascoensis**	X
						Tappanina selmensis	X
						Textularia portenta	R
						* planktonic markers	
QA Eb 156	Sewage Plant	140-160	Medium to coarse glauconitic sand with abundant forams (cuttings)	Inner to Middle Shelf (160-320 ft)	Late Paleocene (P4 Zone)	*Gavelinella danica*	X
						Gavelinella neelyi	R
						Gavelinella umbonifera	X
						Globulina gibba	R
						*Morozovella aequa**	X
						Pararotalia perclara	X
						Spiroplectammina wilcoxensis	X
						*Subbotina velascoensis**	X
						Textularia portenta	X
						* planktonic markers	
QA Eb 156	Sewage Plant	220.4	Gray fine to medium glauconitic sand	Inner to Middle Shelf	Middle Paleocene (P3 Zone)	*Alabamina midwayensis*	C
						Bolivinopsis emmendorferi	X
						Cibicidoides alleni	C
						Dentalina colei	X
						Epistominella minuta	X
						Fissurina oslatus	X
						Gavelinella burlingtonensis	C
						Globulina gibba	F
						Guttulina hantkeni	X
						Gyroidinoides subangulata	X
						*Morozovella angulata**	C
						*Morozovella similatilis**	X
						Pulsiphonina prima	X
						*Subbotina triloculinoides**	X
						* age diagnostic	
QA Eb 157	Sewage Plant	45.0	Dark greenish gray clayey greensand	--	--	BARREN	

[1] A = abundant F = few X = very rare
C = common R = rare

Table 11. — Geologist's logs of cutting samples from test wells

Description	Depth, in feet below land surface
QA Db 31 - Love Point	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Silt, mottled light gray (10YR 7/2) and very pale brown (10 YR 7/5), micaceous; sandy; yellow-stained, fine-grained quartz, subangular	0- 10
Silt, as above.	10- 20
Sand, pale brown (10YR 6/3), silty, fine to coarse; quartz, clear and frosted; colorless and yellow-stained; angular (fine-medium fraction) to sub-rounded (coarse fraction); common dark, fine grain minerals present; some gravel.	20- 30
Sand, as above.	30- 40
Gravel, sandy; mostly quartzite, subangular to sub-rounded, some highly polished; a few sandstone and lithic grains; sparse, fine black, glauconite grains.	40- 50
Gravel, sandy; as above; fine gravel to coarse sand; sparse, coarse, black, glauconite grains.	50- 60
AQUIA AQUIFER	
Lower Eocene sand	
Sand, dark yellowish-brown (10YR 4/5), fine- to coarse-grained, poorly sorted; quartz stained yellow and orange; frosted, some clear; subangular (fine) to rounded (coarse); glauconite abundant (30%), dark green to black, botryoidal; some fine, calcareous material.	60- 70
Sand, as above; sparse foraminifera; echinoid spines.	70- 80
Sand, as above; glauconite, medium green to black; some coarse, brown, limonitized grains; abundant foraminifera, sparse shell fragments.	80- 90
Sand, as above; a few unstained quartz grains; abundant foraminifera.	90-100
Aquia Formation	
Sand, as above.	100-110*
Sand, light olive-brown (2.5Y 5/4), fine- to medium-grained; quartz frosted, yellow; clear, colorless subangular to rounded; glauconite abundant (30%), fine, green to black, botryoidal; some smooth, brown grains; foraminifera very abundant (25%); sparse bryozoans, shell material, echinoid spines cemented intervals at 113-115 ft and 116-117 ft.	110-120

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Db 31 - Love Point (continued)	
Aquia Formation (continued)	
Sand, olive (5Y 4.5/3), fine- to medium-grained, moderately well sorted; quartz, clear and frosted, colorless, some yellow; orange-stained, subangular to subrounded; glauconite abundant (30%), greenish-black, botryoidal; some iron oxide cement; abundant calcite cement.	120-140
Sand, grayish-brown, (2.5Y 4.5/2), fine- to coarse-grained; quartz frosted, colorless; some orange- and green-stained, subangular to subrounded; glauconite abundant (40%); medium greenish-black, botryoidal; common calcite cement; rare pyrite.	140-160
Sand, dark greenish-gray (5GY 4/1), medium grained; quartz colorless, frosted, and clear, subangular; glauconite very abundant (60%), greenish-black botryoidal, coarse grained.	160-180*
Sand, as above; abundant shell material; green-tinted calcite with green, hair-like inclusions; thin (0.5'), cemented layer at 184 ft.	180-200
Hornerstown (?) Sand	
Sand, olive-gray (5Y 4/2), fine- to medium-grained; quartz frosted, yellowish-gray, some clear, colorless, subrounded to subangular; glauconite (30%) dark greenish-black, botryoidal; abundant shell material, as above; gray (5Y 5/1) clay matrix.	200-220
Sand, dark gray (5Y 4/1), fine- to medium-grained, clayey; quartz frosted, colorless, some clear, subangular to subrounded; glauconite abundant (20%), medium green to black, subrounded to botryoidal; clay is dark gray (5Y 4/1) and medium green, mottled; rare clusters of fine, colorless, radiating acicular crystals (gypsum, calcite ?).	220-240
Sand, olive-gray (5Y 4/2), fine to medium, clayey; quartz clear, colorless, some green, subangular to subrounded; glauconite abundant (25%), medium green to black, subrounded to slightly botryoidal; clay, dark gray (5Y 4/1); abundant shell fragments.	240-260

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Db 31 - Love Point (continued)	
LOWER CONFINING BED	
Brightseat (?) Formation	
Sand, dark yellowish-brown (10YR 3/3); fine- to medium-grained; quartz, clear, colorless, some frosted, stained yellowish-brown, subrounded to subangular; glauconite abundant, yellowish-brown, subrounded to botryoidal, some accordion-shaped; and clay, dark yellowish-brown, with abundant iron oxide.	260-280
Severn and Matawan Formations (Undifferentiated)	
Sand, dark gray (5Y 4/1), fine- to medium-grained; quartz clear, colorless, some yellow-stained, subangular to subrounded; glauconite common (20%), medium to dark green, subrounded to slightly botryoidal; gravel-size grains (from previous intervals?) includes shell fragments, calcite and iron oxide-cemented sand, yellow and gray-stained quartz.	280-300
Sand, clayey, very dark grayish-brown (2.5YR 3/2), fine grained; quartz clear, colorless, subangular; glauconite common (20%), medium to dark green, subrounded to slightly botryoidal; clay dark gray (5Y 4/1), micaceous.	300-320
Sand, clayey, as above.	320-340
MAGOTHY (?) AQUIFER	
Sand, silty, mottled gray (N 4.5/) and light yellowish-brown (2.5Y 6/4), very fine grained, well sorted; quartz frosted, colorless and yellow-stained, angular to subangular; no glauconite; abundant mica (muscovite, chlorite) and carbonaceous matter (lignite).	340-368*

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Db 33 - Cloverfields	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Silt, clayey, mottled light gray (10YR 7/2) and very pale brown (10YR 7/5), micaceous; peat, dark brown, from 15-20 ft.	0- 20
Silt, sandy, clayey, light brownish-gray (10YR 6/2), micaceous; quartz clear, colorless, some frosted, subangular to subrounded; abundant organic matter (lignite).	20- 40
UPPER CONFINING BED	
Calvert Formation	
Silt, clayey, as above; abundant shell fragments - oysters.	40- 60
Clay, sandy, dark gray (10YR 4/1); quartz sand, medium-grained, frosted, colorless, subangular to subrounded; sparse glauconite; abundant lignite interspersed throughout clay; abundant shell fragments (oysters).	60- 80
Clay, light gray (10YR 6.5/1), silty, micaceous; sparse bluish vivianite, abundant lignite.	80-100*
Clay, silty, as above; some coarse gravel.	100-120
Clay, silty, as above.	120-140
Clay, silty, as above; abundant bluish vivianite.	140-160*
AQUIA AQUIFER	
Aquia Formation	
Sand, light brownish-gray (10YR 6/2), medium- to coarse-grained; quartz, clear and frosted, colorless, sparse yellow, pink, green-stained, subangular to subrounded; sparse glauconite (1%), medium green to black, subrounded to botryoidal.	160-180
Sand, as above; glauconite (5-10%); cemented 182-186 ft, 190-196 ft.	180-200
Sand, as above (2.5Y 6/2); glauconite (30%), black, botryoidal, coarse grained cemented, 200-204 ft, 206-208 ft.	200-220
Sand, as above; cemented 222-224 ft, 225-229 ft.	220-240
Hornerstown (?) Sand	
Sand, as above (2.5Y 6/3); abundant yellow-stained quartz grains; glauconite (30%) black, botryoidal, medium grained, few yellowish-green and brown grains; rare green, fibrous, calcitic material.	240-260
Sand, as above.	260-280

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Db 33 - Cloverfields (Continued)	
Hornerstown (?)Sand (Continued)	
Sand, dark gray (5Y 4.5/1), clayey, fine- to medium-grained; quartz, clear and frosted, colorless and yellow-stained, subangular to subrounded; glauconite (30%) light green to black, subrounded to botryoidal; clay dark gray (5Y 4/1); few foraminifera (Nodosaria?, coiled forms); sparse green, fibrous, calcitic material.	280-300
LOWER CONFINING BED	
Brightseat (?) Formation	
Clay, gray (5Y 5/1), silty, sandy; glauconite (20%) light to medium green, subrounded to slightly botryoidal; foraminifera very abundant (30%); abundant pyritized lignite.	300-320*
Severn and Matawan Formations (Undifferentiated)	
Clay, gray, as above; abundant shell material; abundant foraminifera (10%)	320-340
Clay, gray (5Y 5/1), as above; abundant, very coarse quartz grains, yellow and orange-stained, rounded; glauconite (10%), medium to dark green, subrounded to botryoidal; foraminifera abundant (5%); abundant shell fragments.	340-360

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Db 35 - Mylander Farm	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Sand, silty, very pale brown (10YR 7/3), fine-grained; quartz, frosted, colorless, subangular to sub-rounded; common lignite.	0- 10
Sand, silty, very pale brown (10YR 7/4), fine to coarse; quartz, frosted, yellow-stained, some clear, sub-angular to subrounded; abundant lignite, mica.	10- 20
Sand, light gray (10YR 6.5/1), fine- to medium-grained; quartz, frosted, colorless, subangular; few fragments iron oxide cemented sand.	20- 30
Sand and gravel, light brownish-gray (10YR 6/3), coarse sand to medium gravel; quartz frosted, clear, stained yellow, gray, mostly rounded, some subangular; abundant lithic grains.	30- 40
Sand and gravel, as above; sparse glauconite, medium green, slightly botryoidal.	40- 50
AQUIA AQUIFER	
Lower Eocene sand	
Sand, yellowish-brown (10YR 5/6), fine- to medium-grained, moderately well sorted; quartz, frosted, yellow-stained, iron oxide coatings, subangular to subrounded; glauconite abundant (30%), light green to dark greenish-black, subrounded to botryoidal; abundant shell material, calcite-cemented sand; cemented 52-60 ft.	50- 60
Sand, as above; cemented 60-64 ft.	60- 70
Sand, light brownish-gray (2.5Y 6/2), medium-grained; quartz clear and frosted, colorless, yellow and green stained, subangular to subrounded; glauconite, abundant (30%), medium green to black, botryoidal; abundant shell material, common foraminifera, bryozoans; cemented 70-80 ft.	70- 80
Sand, light brownish-gray (2.5Y 6/2), medium- to coarse-grained; quartz, clear and frosted, colorless and yellow and green-stained; glauconite abundant (20%), medium green to black, some brown, botryoidal; abundant foraminifera (10%).	80- 90
Aquia Formation	
Sand, as above.	90-100
Sand, as above.	100-110

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Db 35 - Mylander Farm (Continued)	
Aquia Formation (Contiued)	
Sand, light brownish-gray (2.5Y 6/2), medium- to coarse-grained; quartz, clear, colorless, frosted, yellow-stained, subangular to subrounded; glauconite abundant (20%), dark green to black, some brown, botryoidal; abundant coarse, well rounded limonite grains, yellowish-brown (10YR 5/6); abundant shell material, echinoid spines, calcite-cemented sand fragments; foraminifera abundant (10%); cemented 110-120 ft.	110-120
Sand, as above.	120-140
Sand, olive-gray (5Y 5/2); fine- to medium-grained, well sorted; quartz, clear, colorless and green-stained, subangular; glauconite (30%), dark green to black, botryoidal, few brown, accordion-shaped grains; foraminifera common.	140-160
Sand, medium- to coarse-grained; quartz clear, colorless, some green to yellow-stained, subangular; glauconite dark green to black, botryoidal; foraminifera rare; cemented in thin layers at 170 ft, 174 ft, and 179 ft.	160-180
Sand, as above.	180-190
Hornerstown (?) Sand	
Sand, olive-gray (5Y 5/2); medium-grained, well sorted; quartz clear, colorless, some yellow-stained, sub-angular to rounded; glauconite (20%), dark green to black, botryoidal; few shell fragments, fibrous.	190-200
Sand, as above; more fibrous shell material.	200-220
Sand, clayey, dark gray (5Y 4/1), fine-grained; quartz, clear, colorless, subangular; glauconite abundant (30%), medium to dark green, subrounded to slightly botryoidal; clay dark gray (5Y 4/1).	220-240*
Sand, as above; few iron oxide and pyrite-cemented sand fragments.	240-250
LOWER CONFINING BED	
Brightseat (?) Formation	
Sand, clayey, dark gray and clay, dark gray (5Y 4/1); abundant shell fragments (bryozoans?).	250-260
Sand, as above.	260-280
Severn and Matawan Formations (Undifferentiated)	
Sand, clayey, dark gray (5Y 4/1), fine- to medium-grained; quartz, clear, colorless, some yellow-stained, sub-angular to subrounded; glauconite (20%), medium to dark green, subrounded to slightly botryoidal, few brown grains; pyrite common.	280-300
Sand, clayey, as above; micaceous.	300-320

Description	Depth, in feet below land surface
QA Ea 77 - Matapeake	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Clay, brown, gray; slightly silty.	0- 10
Clay, blue-gray; not silty; some gravel.	10- 30
Clay, blue-gray; silty; some pink clay; lignite.	30- 31
Sand, pinkish-gray; poorly sorted, medium- to coarse-grained; abundant lithic grains.	31- 36
Sand, gravel; very hard; some shell material.	36- 60
UPPER CONFINING BED	
Nanjemoy Formation	
Clay, light gray, some brown; very soft.	60- 70
Clay, light gray, some brown; abundant shell material.	70- 90
Sand, gray (5Y 5/1); medium grained, poorly sorted; quartz mostly clear, colorless and frosted, abundant coarse, well rounded, polished, green-stained grains, also, dark gray and yellow-stained; glauconite abundant (30%), dark greenish-black, botryoidal, fine grained; cement mostly light gray (10YR 7/2), enclosing fine quartz and black glauconite grains; some reddish-yellow; cemented 117-125 ft.	90-125
AQUIA AQUIFER	
Lower Eocene sand	
Sand, as above; cemented 125-129 ft, 130-132 ft, 133-134 ft.	125-140*
Sand, as above, but higher percentage (50%) of glauconite, medium green, and yellowish-brown (5%); abundant foraminifera (10%), cemented 140-141 ft.	140-160
Sand, light olive gray (5Y 6/2); medium grained, well sorted; quartz clear, colorless, abundant yellowish-brown grains, few green-stained; glauconite abundant (30%), botryoidal, mostly greenish-black; some medium green; abundant foraminifera (20%), partly recrystallized calcite; cemented in thin layers, 161 ft, 162 ft, 169-170 ft, 170-172 ft.	160-180
Aquia Formation	
Sand, as above; foraminifera abundant (30%), cemented 185 ft, 191 ft.	180-200
Sand, olive (5Y 5/3); coarse grained; well sorted; quartz colorless, stained brown and green, mostly frosted, some clear; glauconite abundant (30%), coarse grained, black, botryoidal and brown, limonitized, rounded grains; abundant shell fragments (clam, oyster?); rare foraminifera, echinoid spines and ostracods.	200-220

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Ea 77 - Matapeake (Continued)	
Aquia Formation (Continued)	
Sand, light brownish-gray (2.5Y 6/2); medium grain; well sorted; quartz mostly clear, colorless, some stained brown, green, yellow; glauconite abundant (30%), botryoidal, black and medium green; few coarse grains (limonitized glauconite?), rounded, polished dark brown (7.2YR 4/4), some with green core; abundant shell fragments (clams, oysters); rare foraminifera, echinoid spines, cheilostome bryozoans.	220-240
Sand, as above; cemented 256-257 ft.	240-260
Hornerstown (?) Sand	
Sand, dark greenish-gray (5GY 4/1); fine grained; clayey (dark gray clay); well sorted; quartz sub-angular to subrounded, mostly clear, colorless, some frosted, rare green-stained; glauconite abundant (40%), mostly botryoidal, rare accordion-shaped, greenish-black; foraminifera abundant; abundant green and gray fibrous, calcareous material (bryozoans?).	260-280*
Sand, olive-gray (5Y 4.5/2); fine to medium grained; poorly sorted; clayey (light gray clay); quartz frosted, some clear, colorless, yellow-stained; glauconite (30%) dark green-black, botryoidal.	280-300
Sand, clayey, olive-gray (5Y 5/2); medium grained, well sorted; quartz mostly frosted, colorless, some yellow-stained, some clear; glauconite abundant (30%), mostly black, some medium green, botryoidal, few accordion-shaped; some shell fragments; gravel (from higher interval?); rare phosphate pebbles.	300-320
LOWER CONFINING BED	
Brightseat (?) Formation	
Sand, dark greenish-gray (5GY 4/1), very clayey; and clay, greenish-gray (5GY 6/1) and dark gray (5Y 4/1); common clusters of radiating acicular crystals (gypsum?).	320-340
Severn and Matawan Formations (Undifferentiated)	
Clay, light gray (5Y 7/1), silty; some fine sand, clear, colorless quartz; rare carbonaceous matter; common muscovite.	340-365
Sand, medium dark greenish-gray (5GY 4/1); very clayey; some reddish-yellow (7.5YR 7/8) patches of limonitized glauconite mostly medium green.	365-397*

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Ea 79 - Mowbray Park	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Silt, sandy, very pale brown (10YR 7.5/4), abundant muscovite.	0- 10
Sand, silty, light yellowish-brown (10YR 6/4), fine- to medium-grained; poorly sorted; quartz subangular, frosted, yellow-stained, some clear, colorless.	10- 20
Sand, light brownish-gray (10YR 6/2), medium grained; moderately sorted; quartz frosted, colorless, some yellow-stained, pink, sub- and well rounded; sparse glauconite, botryoidal, black, some medium green; abundant lithic grains, some gravel.	20- 35
UPPER CONFINING BED	
Nanjemoy Formation	
Sand, greenish-gray (5GY 5/1), clayey; coarse grain to fine gravel to medium grain; poorly sorted; quartz clear, colorless, abundant frosted, green-stained grains, subangular to subrounded, some highly polished; abundant glauconite (40%); botryoidal, greenish-black; clay matrix, dark gray (5Y 4/1), some bright green (5G 5/2).	35- 50
Sand, dark greenish-gray (5G 4/1), clayey, fine grain to medium gravel, very poorly sorted; quartz color-less, frosted, some clear, some green-stained, many coarse grains highly polished; highly glauconitic (50%), greenish-black, botryoidal; clay matrix dark gray (5Y 4/1) and bright green (5G 5/2).	50- 60
Sand, dark greenish-gray (5G 4/1), clayey, fine- to medium-grained, poorly sorted; quartz frosted, green-stained, some clear, some colorless, subangular to subrounded; glauconite abundant (60%), black, medium green, botryoidal; clay matrix dark gray (5Y 4/1) and green (5G 5/2) in layers 1 cm thick.	60 - 70*
Sand, olive (5Y 5/3), medium- to coarse-grained, poorly sorted; quartz clear, frosted, abundant yellow-stained, subrounded, very coarse grains; glauconite abundant (40%), botryoidal, black, some green.	70- 80

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Ea 79 - **Mowbray Park** (Continued)	
Nanjemoy Formation (Continued)	
Sand, olive-gray (5Y 5/2), medium- to coarse-grained, poorly sorted; quartz clear and frosted, colorless, abundant yellow-stained, subrounded, very coarse grains; glauconite (40%) botryoidal, medium green-black; abundant clay, light brownish-gray (10YR 6.5/2), highly micaceous with sparse organic matter; some clasts of pure clay, some in matrix containing glauconitic sand; abundant shell fragments (clams).	80- 90
Sand and clay, as above; some glauconite, mostly medium green; common yellow-brown limonitized grains.	90-100
Sand, grayish-brown (10YR 5/2), medium- to coarse-grain, moderately sorted; quartz generally frosted, yellow-stained, some colorless; glauconite abundant (40%), some medium green, some reddish-brown and yellow, some variegated yellow and green, brown grains are more rounded than green, rare black grains; abundant shell (clams?) fragments, foraminifera; most calcite material has a reddish hue; cemented in thin (0.5 ft. layers 100-108 ft.	100-120
AQUIA AQUIFER	
Lower Eocene sand	
Sand, grayish-brown (2.5Y 5.5/2), medium- to coarse-grained, moderately sorted; quartz, colorless, yellow and green-stained, frosted, some clear; glauconite abundant (40%), botryoidal, shades of green, yellow and brown, some black; abundant shell fragments, partially recrystallized, clams, foraminifera, echinoid spines, bryozoans; fragments of calcite-cemented sand; glauconite in these fragments tends to be fine grained and black, unlike uncemented glauconite in sample; some cement is tinted green; cemented 120-130 ft, thin layers 130-140 ft.	120-135*
Sand, grayish-brown (2.5Y 5/2), as above, glauconite predominantly black, fine grained, abundant foraminifera; cemented thin layers 140-160 ft.	135-160
Aquia Formation	
Sand, grayish-brown (2.5Y 5.5/2), fine to medium grained, moderately sorted; quartz, frosted, colorless, some coarse yellow-stained grains, glauconite (30%), botryoidal, black, some green, few accordion-shape; foraminifera very abundant (30%); rare pyrite.	160-180*

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Ea 79 - **Mowbray Park** (Continued)	
Aquia Formation (Continued)	
Sand, grayish-brown (2.5Y 5.5/2), fine to medium grained; quartz frosted, colorless, yellow-stained, some clear; glauconite botryoidal, black, some green, generally fine grained; abundant shell fragments; chalky cement; clams, foraminifera, bryozoans (coral?), partially recrystallized; cemented 184-192 ft, 198-199 ft.	180-200
Sand, olive-gray (5Y 5/2), medium-grained, quartz mostly clear, colorless, some coarser yellow-stained grains; glauconite (50%) various shades of green, yellow, black, brown, many green grains yellow in crevices between lobes, common accordion-shape; few shell fragments.	200-220
Sand, olive-gray (5Y 5/2), fine- to medium-grained, moderately sorted; quartz clear, frosted, colorless, some green-stained, rare yellow, angular to sub-angular; glauconite (40%), greenish-black, some brown, botryoidal; common elongate accordion-shaped; few shell fragments; foraminifera.	220-240
Hornerstown (?) Sand	
Sand, olive-gray (5Y 5/2), as above; a little light gray clay matrix, abundant, brown, limonitized rounded glauconite grains.	240-260
Sand, as above.	260-280
Sand, olive-gray (5Y 5/2); fine- to medium-grained, well sorted; quartz clear, frosted, colorless, slightly green-stained, angular to subrounded; glauconite abundant (40%), dark green to black, mostly botryoidal, rare accordion-shape; common foraminifera.	280-300*
Sand, very dark gray (5Y 3/1); very clayey, fine, poorly sorted; quartz clear, colorless, some frosted, subangular to subrounded; glauconite abundant (40%), dark green to black, botryoidal; few foraminifera; clay matrix dark gray (5Y 4/1); rare phosphate pellets.	300-320
LOWER CONFINING BED	
Brightseat (?) Formation	
Sand and clay, as above.	320-340

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Eb 153 - Piney Creek	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Silt, sandy, clayey, mottled, very pale brown (10YR 7/5) and light gray (10YR 7/2), micaceous; sand is quartz, frosted, colorless and yellow-stained, fine- to medium-grained, subangular; sparse lignite, carbonized leaf fragments.	0- 10
Silt, sandy, clayey, gray (5Y 6/1), micaceous; sand is quartz, frosted, colorless, some yellow-stained, pink-stained, fine- to coarse-grained, subangular to well rounded; sparse lignite.	10- 20
Clay, silty, sandy, gray (5Y 5.5/1), micaceous; sand is quartz, frosted, colorless and yellow-stained, fine-grained, angular; sparse lignite, carbonized leaf fragments; rare diatoms.	20- 40
Clay, silty, gray (5Y 5.5/1), micaceous; abundant lignite, leaf fragments; sparse, coarse sand grains.	40- 50
Clay, as above; common bluish vivianite.	50- 60
Clay, as above.	60- 70*
Clay, slightly silty, gray (5Y 6.5/1), micaceous, sparse lignite, common bluish vivianite.	70- 80
UPPER CONFINING BED	
Calvert Formation	
Clay, light gray (5Y 7/1); sparse lignite.	80-100
Clay, light gray (5Y 7/1).	100-130*
AQUIA AQUIFER	
Lower Eocene sand	
Sand, light brownish-gray (2.5Y 6/2), fine- to medium-grained; quartz clear and frosted, colorless and yellow-stained, subangular to rounded; glauconite abundant (25%), medium to dark green, botryoidal; rare foraminifera (coiled).	130-140
Sand, clayey, gray (5Y 6/1), medium-grained; quartz frosted, colorless, some yellow-stained, subangular to subrounded; glauconite abundant (25%), medium to dark green, botryoidal; clay is light gray (5Y 7/1); sparse shell fragments, mica.	140-150
Sand, light olive-gray (5Y 6/2), medium-grained, well sorted; quartz, clear, colorless and frosted, yellow, green, pink-stained, subangular to subrounded; glauconite abundant (25%), light to dark green, botryoidal.	150-160

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Eb 153 - Piney Creek (Continued)	
Lower Eocene sand (Continued)	
Sand, light brownish-gray (2.5Y 5.5/3), medium-grained; quartz frosted, some clear, colorless, some yellow-stained, subangular to subrounded; glauconite (25%) medium green to black, few brown, subrounded to botryoidal, few accordion-shaped; rare foraminifera; cemented 160-164 ft, 165-175 ft, 175-180 ft, cemented partially.	160-180
Sand, pale olive (5Y 6/3), medium-grained; quartz frosted, some clear, yellow-stained, some colorless, green-stained, subangular to subrounded; glauconite (30%), medium green to black, greenish-brown, botryoidal, subrounded; common foraminifera (coiled).	180-200
Sand, olive (5Y 5/3), medium- to coarse-grained; quartz frosted, some clear, yellow-stained, some colorless, subangular to subrounded; glauconite abundant (15%), medium green to black, brown, botryoidal to rounded; common foraminifera (coiled).	200-220
Aquia Formation	
Sand, olive-gray (5Y 5/2), fine- to medium-grained; quartz frosted, stained yellow, green, some clear, colorless, subangular; glauconite (25%), dark green to black, some brown, botryoidal to subrounded; foraminifera very abundant (30%).	220-240
Sand, light olive-gray (5Y 6/2), medium to coarse grained; quartz frosted, colorless and yellow-stained, subangular to subrounded; glauconite (25%) light green to black, botryoidal to subrounded, some coarse, brown, rounded grains; foraminifera very abundant (30%); ostracodes(?); thin (0.5 ft), cemented layer at 272 ft.	240-260*
Sand, light yellowish-brown (2.5Y 6/4), medium- to coarse-grained; quartz frosted, yellow-stained, some clear, colorless, subrounded to subangular; glauconite (30%), medium green to black, subrounded to botryoidal, some brown, rounded grains; foraminifera abundant (10%).	260-280
Sand, olive-gray (5Y 4/2), medium- to coarse-grained; quartz clear, colorless, frosted, stained yellow and green, subangular to rounded; glauconite abundant (40%), black, botryoidal, coarse grained, some medium green, brown, subrounded to botryoidal, few accordion-shaped; few foraminifera; common shell fragments.	280-310

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Eb 153 - Piney Creek (Continued)	
Aquia Formation (Continued)	
Sand, light olive-gray (5Y 6/2), fine- to medium-grained; quartz clear, colorless, some frosted, yellow and green-stained, subangular to subrounded; glauconite abundant (30%), dark green to black, subrounded to botryoidal, few brown grains; few foraminifera, rare fibrous shell material (bryozoans?).	310-320
Hornerstown (?) Sand	
Sand, as above; glauconite (40%).	320-340
Sand, as above; glauconite (40%).	340-360
Sand, light olive-brown (2.5Y 5/4), medium- to coarse-grained; quartz frosted, yellow-orange-stained, some green, some clear, colorless, subangular to sub-rounded; glauconite abundant (20%), light green to black, botryoidal, abundant reddish-brown, subrounded to slightly botryoidal grains; few shell fragments.	360-380
Sand, as above; abundant shell fragments, few green, fibrous, calcareous fragments (bryozoans?); calcite-cemented sand.	380-400

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Eb 156 - Sewage Plant	
UNCONFINED AQUIFER	
Talbot and Kent Island Formations (Undifferentiated)	
Silt, mottled light gray (10YR 7/2) and very pale brown (10YR 7/5); micaceous; few admixed, coarse grains.	0- 10
Silt, as above.	10- 20
Silt, gray (10YR 6/1), sandy; gravel, coarse, well rounded, yellow-stained quartz, and subangular, lithic grains; few grains glauconite, medium green to black, fine grained, rounded.	20- 30
UPPER CONFINING BED	
Nanjemoy Formation	
Clay, gray (5Y 5.5/1), sandy, highly glauconitic; quartz subangular to subrounded, clear colorless, some frosted, some green-stained; glauconite very abundant (40%), greenish-black, botryoidal, rounded.	30- 40
Clay, dark greenish-gray (5GY 4/1), sandy, micaceous; clay matrix gray (5Y 5.5/1), some brownish-yellow (10YR 6/6) portions; sand, quartz clear and frosted, colorless and green-stained; subangular to well rounded; glauconite very abundant (60%), dark greenish-black, botryoidal, few well rounded, light yellowish-green grains.	40- 50*
Sand, grayish-brown (2.5Y 5/3); fine- to coarse-grained, poorly sorted; quartz medium grained, colorless and green-stained, subangular and abundant, very coarse, yellow-stained, rounded grains; glauconite fine to medium grained, dark green to black, botryoidal, some gray; micaceous clay matrix enclosing glau-conitic sand.	50- 60
Sand, grayish-brown (2.5Y 5/3); medium to coarse, moderately well sorted; quartz mainly coarse, sub-rounded, polished, frosted, yellow and green-stained, some clear, colorless; glauconite abundant (30%), fine grained, medium to dark green, botryoidal, carbonate cement, mostly white (10YR 8/2), etched; some dusky red (2.5YR 3/2); clay matrix, some bright green, some dark gray, some shell fragments (clams) and rare foraminifera (Nodosaria) cemented 60-70 ft.	60- 70

* Biostratigraphic data available. See tables 10a and 10b.

Table 11. — Geologist's logs of cutting samples from test wells - Continued

Description	Depth, in feet below land surface
QA Eb 156 - Sewage Plant (Continued)	
Nanjemoy Formation (Continued)	
Sand, olive-gray (5Y 4/2), medium- to coarse-grained; quartz frosted, yellow-stained, some colorless, green-stained; glauconite, dark green, black, botryoidal; some clay, gray (5Y 5/1), micaceous; carbonate cement and shell fragments as above.	70- 80
Sand, olive (5Y 4/3), medium to coarse, as above; carbonate cement; various shades of yellow, green, orange; highly weathered; rare bryozoans; a few coarse, well rounded, weathered glauconite grains.	80- 90
AQUIA AQUIFER	
Lower Eocene sand	
Sand, olive-gray (5Y 5/2), medium- to coarse-grained, as above; carbonate cemented, white (10YR 8/2); fragments of smooth surfaced clam-shell molds; cemented 97-100 ft.	90-100
Sand, olive-gray (5Y 5/2), as above; a few bryozoans, coral(?), foraminifera (Nodosaria(?)); cemented thin layers 104 ft, 108 ft, 109 ft, 114 ft.	100-120
Sand, olive-gray (5Y 4/2), medium grained; quartz, yellow-stained, frosted, subrounded, some green-stained; glauconite abundant (30%), medium green to black, botryoidal, some brown; common foraminifera, bryozoans, echinoderm spines, shell fragments.	120-140
Aquia Formation	
Sand, olive (5Y 5/3), medium-grained, well sorted; quartz, yellow-stained, frosted, some colorless, clear, subangular; glauconite mostly dark reddish-brown (5YR 3/2), rounded, slightly botryoidal, some greenish-black, botryoidal; foraminifera very abundant (10-20%).	140-160*
Sand, olive (5Y 5/3), medium-grained, as above; glauconite half reddish-brown, rounded grains, half greenish-black botryoidal grains; foraminifera very abundant (20%); cemented 160-170 ft, 176-180 ft.	160-180
Sand, olive-gray (5Y 4/2), medium-grained; quartz mostly clear, colorless, subangular, many yellow-stained, frosted, subrounded grains; glauconite predominantly greenish-black, botryoidal, many reddish-brown, rounded grains, a few accordion-shaped grains.	180-200

* Biostratigraphic data available. See tables 10a and 10b.

Description	Depth, in feet below land surface
QA Eb 156 - Sewage Plant (Continued)	
Aquia Formation (Continued)	
Sand, olive (5Y 4.5/2), medium-grained; quartz clear, frosted, green-stained, subangular to subrounded; glauconite greenish-brown, a few elongate accordion-shaped; abundant well preserved foraminifera and shell fragments; a few coarse, well rounded grains of limonite.	200-220
Sand, greenish-gray (5Y 6/1), fine to medium grains; quartz mostly clear, colorless, some green-stained, frosted, subangular to rounded; glauconite various shades of green to black, botryoidal; abundant fragments of light green (5GY 7/2), clayey calcite cement enclosing medium grained, glauconitic sand; abundant fragments of translucent light green (5GY7/2) to greenish-gray (5G 6/1), carbonate shell material, containing numerous minute, bright green, hair-like inclusions in subparallel orientation, giving a brush-like appearance (punctate brachiopods?); abundant foraminifera, shell material.	220-240*
Hornerstown (?) Sand	
Clay, gray (5Y 5/1), sandy, micaceous; sand, as above; abundant phosphate pellets.	240-260
Clay, sandy, as above.	260-280
Clay, as above; common yellow-stained, quartz grains; common greenish-brown glauconite, and common black grained weathered orange in crevices; rare foraminifera, cement, shell material.	280-300
LOWER CONFINING BED	
Brightseat (?) Formation	
Clay, gray (5Y 5/1), sandy, micaceous; sand, quartzose, clear, colorless, angular; glauconite, medium green to black, fine botryoidal; abundant foraminifera.	300-320
Clay, dark gray (5Y 4/1), sandy; sand, as above; foraminifera very abundant.	320-340

* Biostratigraphic data available. See tables 10a and 10b.

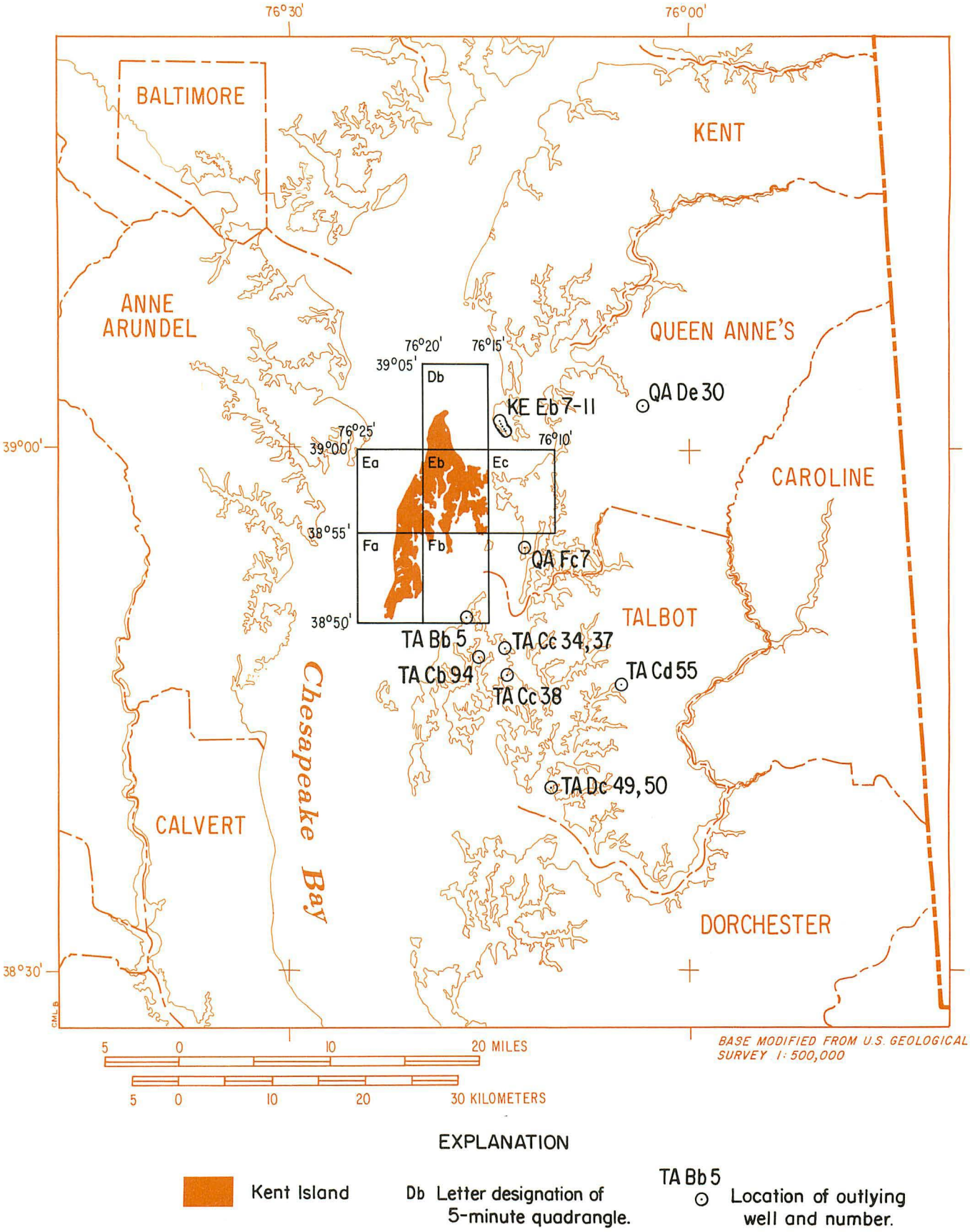


Figure 63. — Locations of 5-minute quadrangles and outlying wells.

MAPS SHOWING WELL LOCATIONS

Quadrangle QA Db

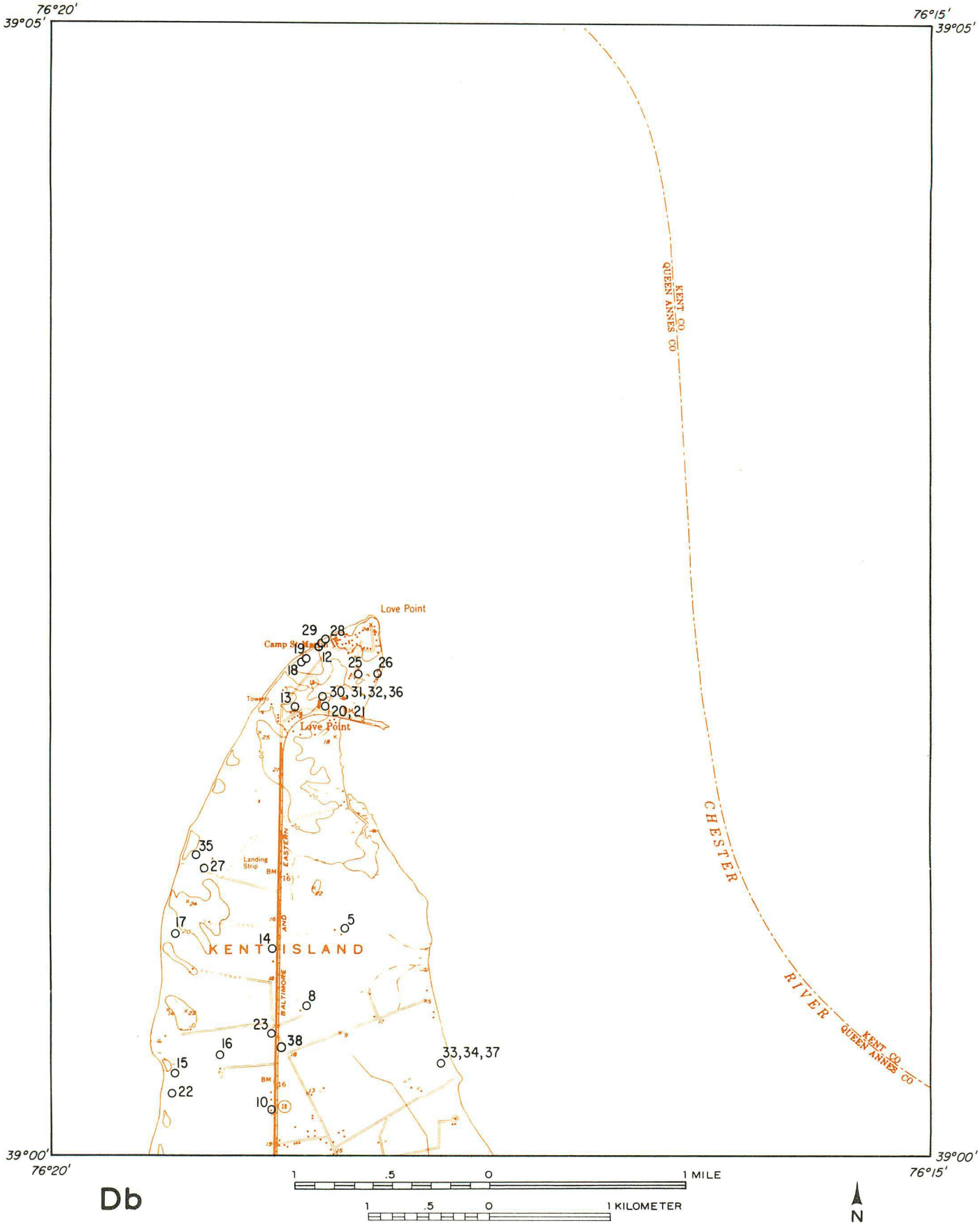
Quadrangle QA Ea

Quadrangle QA Eb

Quadrangle QA Ec

Quadrangle QA Fa

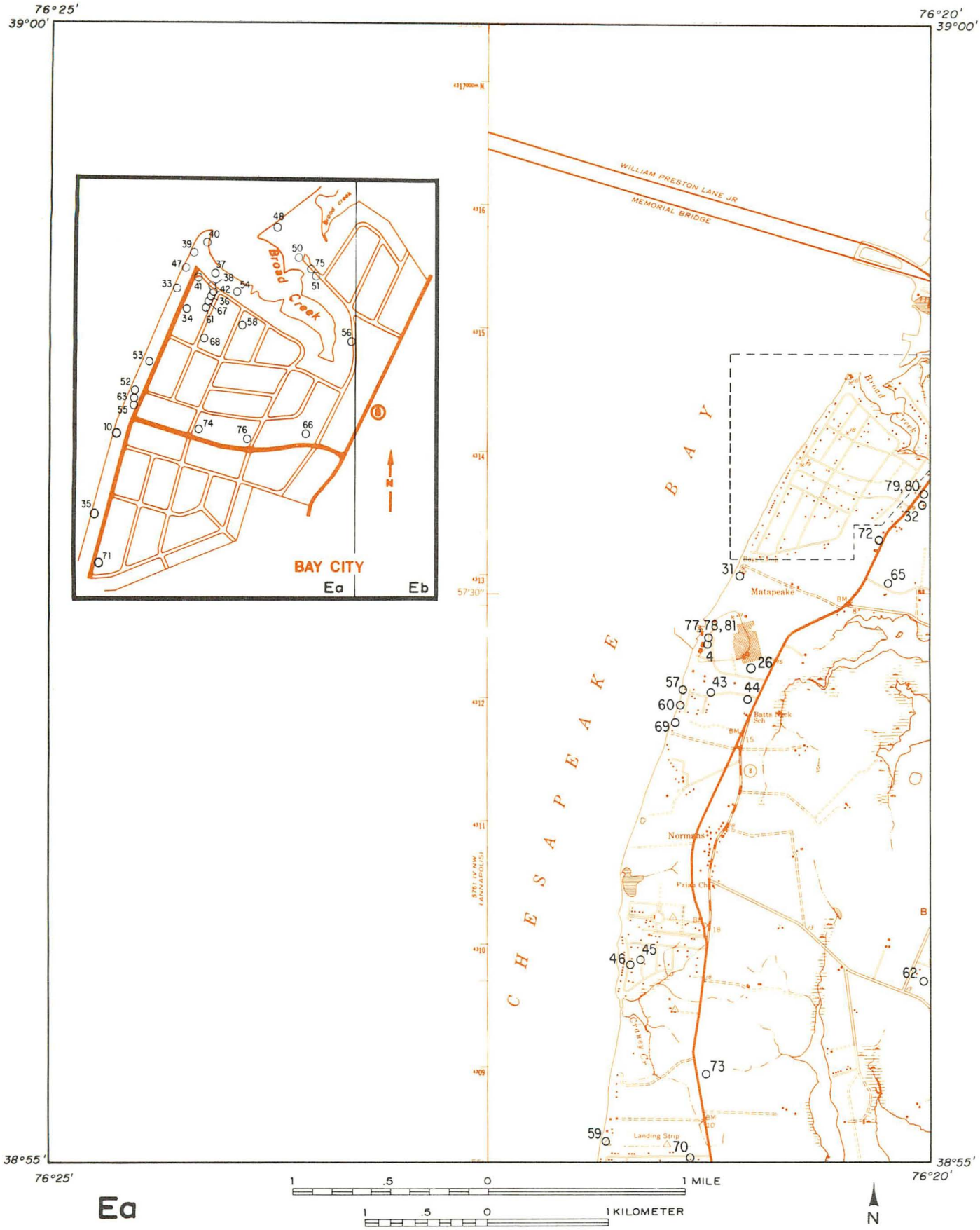
Quadrangle QA Fb



Db

38 ○ Well location and number

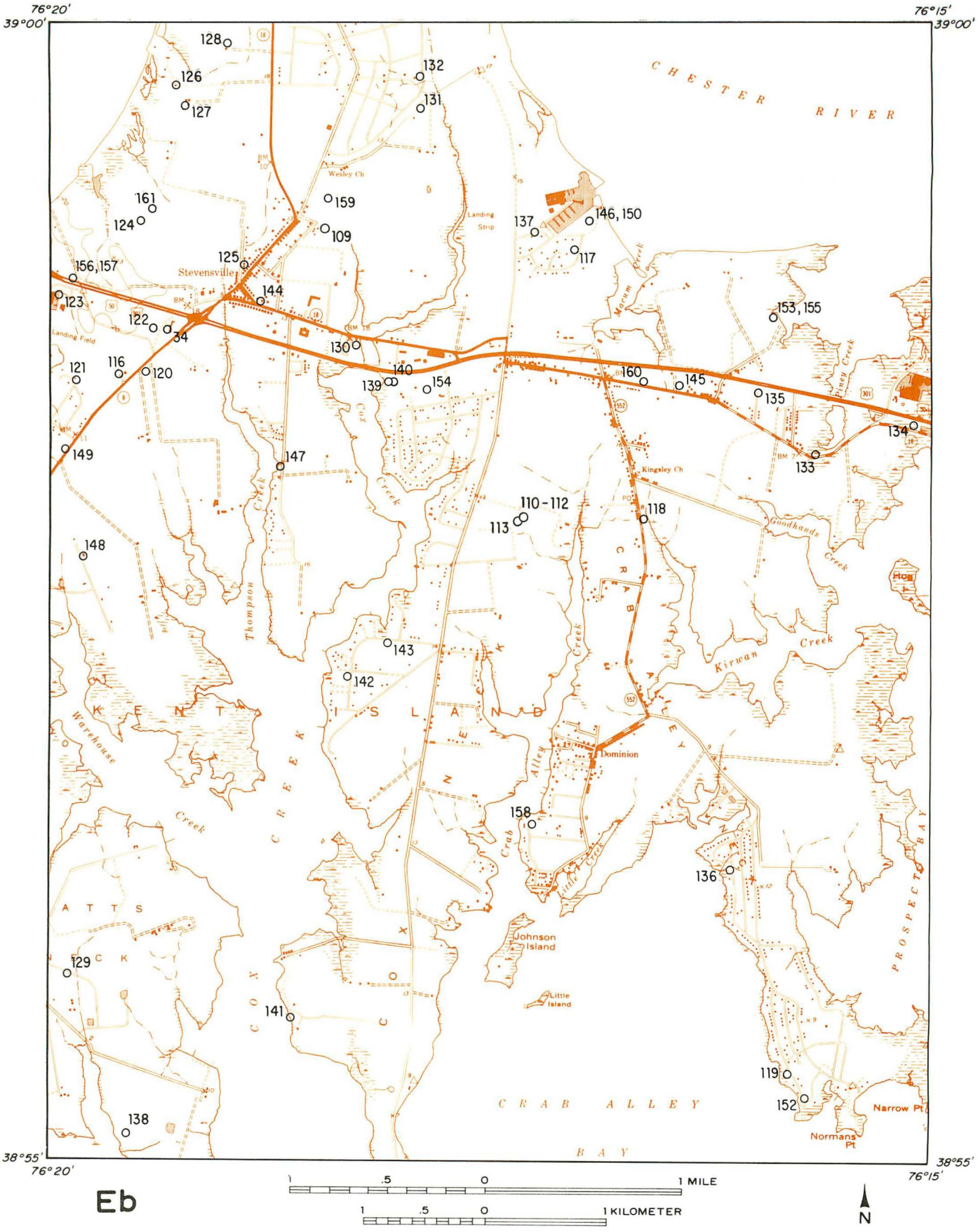
Base modified from U.S. Geological Survey 7.5 minute quadrangles 1:24,000



Ea

73 ○ Well location and number

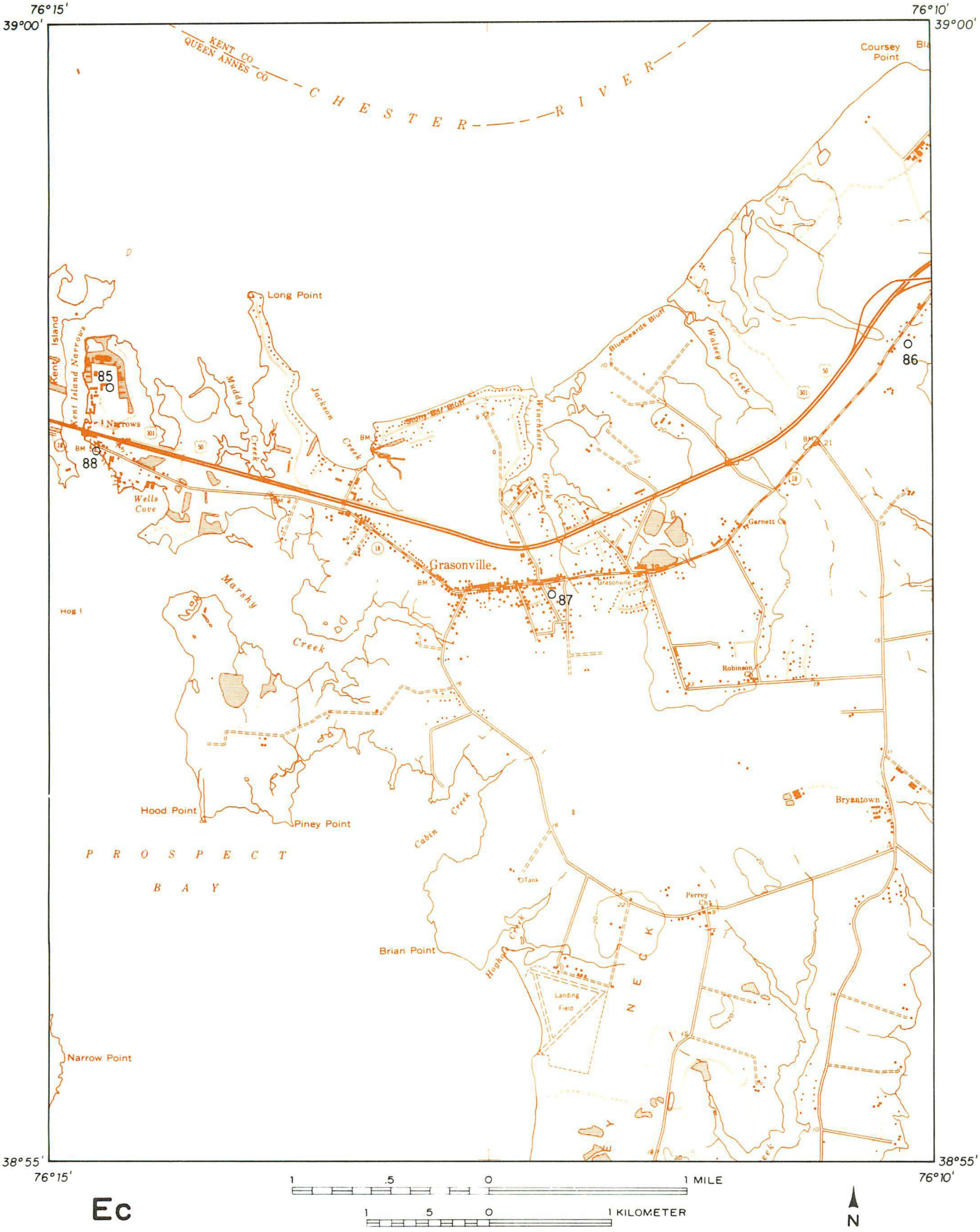
Base modified from U. S. Geological Survey 7.5 minute quadrangles 1:24,000



Eb

139
O Well location and number

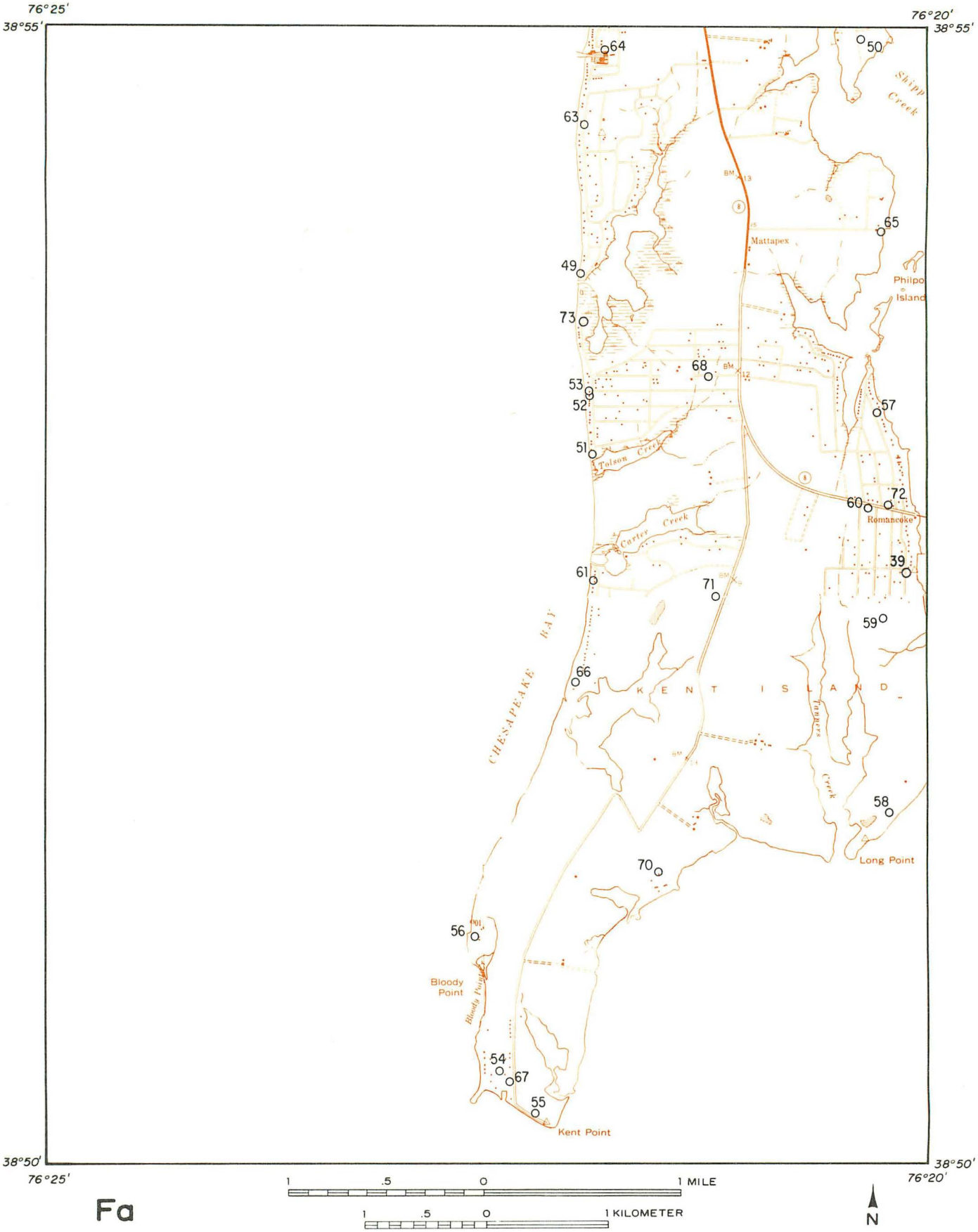
Base modified from U. S. Geological Survey 7.5 minute quadrangles 1 : 24,000



Ec

87
O Well location and number

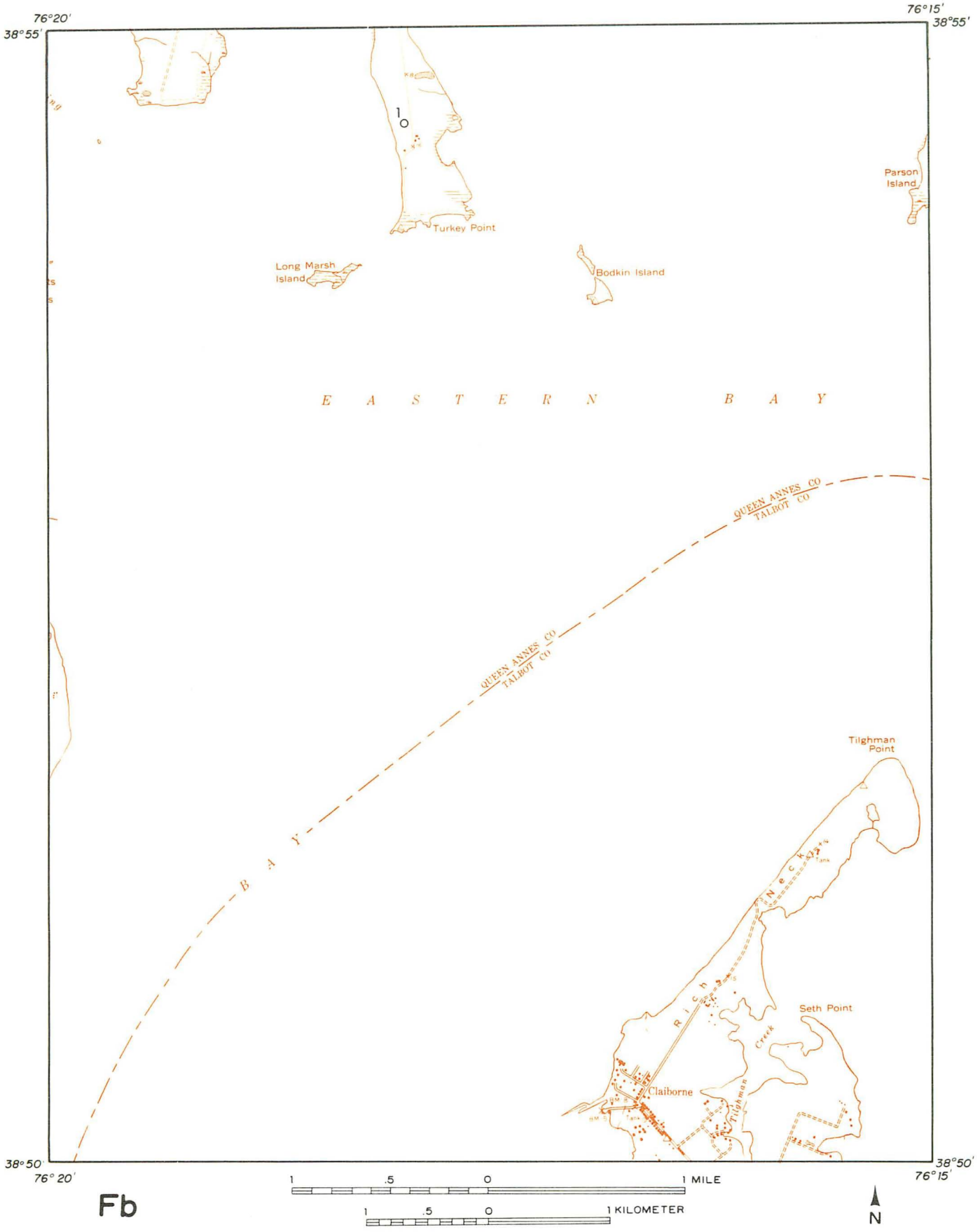
Base modified from U.S. Geological Survey 7.5 minute quadrangles 1:24,000



Fa

60 Well location and number

Base modified from U.S. Geological Survey 7.5 minute quadrangles 1:24,000



Fb

1 ○ Well location and number

Base modified from U.S. Geological Survey 7.5 minute quadrangles 1:24,000

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