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

REPORT OF INVESTIGATIONS NO. 37

GEOHYDROLOGY OF THE FRESH-WATER AQUIFER SYSTEM IN THE VICINITY OF OCEAN CITY, MARYLAND, WITH A SECTION ON SIMULATED WATER-LEVEL CHANGES

by
James M. Weigle and Grufron Achmad

Prepared in cooperation with the
Geological Survey
United States Department of the Interior
Town of Ocean City
and Worcester County

1982

CONVERSION OF MEASUREMENT UNITS

The following factors may be used by readers who wish to convert inch-pound units to metric (System International or SI) units.

To convert from	Multiply by	To obtain
foot (ft)	0.3048	meter (m)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch (in.)	2.54	centimeter (cm)
million gallons per day (Mgal/d)	3785	cubic meters per day (m^3/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

NOTE REGARDING VERTICAL DATUM

The National Geodetic Vertical Datum of 1929 (NGVD), the reference surface to which relief features and altitude data are related, and formerly called "mean sea level," is referred to as "sea level" throughout this report.

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GEOHYDROLOGY OF THE FRESH-WATER AQUIFER SYSTEM IN THE VICINITY OF OCEAN CITY, MARYLAND, WITH A SECTION ON SIMULATED WATER-LEVEL CHANGES

by

James M. Weigle[1] and Grufron Achmad

ABSTRACT

Fresh ground water in northeastern Worcester County, Maryland, is restricted to a series of sediments about 450 feet thick between the land surface and the top of the St. Marys Formation. Water occurs in the Pleistocene aquifer primarily under water-table conditions but locally under semiconfined conditions. In the Pocomoke, Ocean City, and Manokin aquifers, water occurs under confined conditions.

Recharge originates as precipitation which is intercepted by the Pleistocene deposits throughout the area. The underlying aquifers are recharged by vertical leakage from the overlying Pleistocene deposits in the western part of the area, where heads are lower in successively deeper aquifers. Under natural conditions, most discharge occurs by upward leakage primarily in the eastern part of the area and offshore, where the relative head conditions are reversed. Lateral movement of the ground water is generally east-southeastward.

A cone of depression in the potentiometric surface of the Ocean City and Manokin aquifers is the result of pumping at Ocean City. Pumpage averaged 3.45 million gallons per day in 1976 and 8.1 million gallons per day in August of that year. The cone attained a diameter of more than 12 miles during the summer of 1976; in mid-summer of 1976, the potentiometric surface was inferred to be below sea level as far as 6 miles offshore from Ocean City. In autumn and early winter, the cone decreases considerably in size because of reduction in withdrawal.

Water needs for Ocean City and the nearby mainland are expected to substantially increase and most of this water will probably be withdrawn from the fresh-water aquifers underlying the area. Simulation of alternate ground-water development plans was made using a multi-layer aquifer model calibrated against six years (1971–1976) of historical pumpage and water level data. The model showed that dispersal of pumping centers will reduce the amount of drawdown by spreading out the cones-of-depression. Simulated withdrawal of additional water needs from well fields at Gorman Avenue, the Isle of Wight, 100th Street, and 66th Street appears to produce more moderate drawdowns than the other pumping schemes that were run on the model. The results are considered only approximations, however, because some of the natural flow boundaries lie outside of the model area.

Excessive hydraulic stress in the aquifer system at Ocean City is of special significance because of the presence of salty water in the nearby ocean and back bays, and the possible occurrence of salty water offshore in the Manokin aquifer. During the past pumping conditions, no hard evidence of increasing saltiness was found in the Ocean City, Pocomoke, or Pleistocene aquifer. However, slightly salty water occurs in the basal part of the Manokin aquifer in the vicinity of Gorman Avenue, near the northern end of Ocean City. Salty water has apparently entered the basal part of the Manokin from the underlying St. Marys Formation, a clayey confining bed; however, the source of salty water could also be associated with an offshore salt-water front in the Manokin aquifer.

[1]U.S. Geological Survey (retired)

INTRODUCTION

This report presents the results of a cooperative water-resources investigation in the coastal region of Maryland by the U.S. Geological Survey, the Maryland Geological Survey, the Town of Ocean City, and Worcester County. The report includes: (1) A description of the hydrogeologic framework of the aquifer system, (2) a discussion of the occurrence of salty water in the Manokin aquifer in the vicinity of Ocean City, and (3) an evaluation of alternate ground-water development plans by using a digital simulation model to illustrate how potentiometric head losses could be minimized by dispersal of well fields or by pumping from more than one aquifer, or both.

LOCATION AND EXTENT OF STUDY AREA AND MODEL AREA

The area that was studied intensively during the investigation is about 205 mi^2 in northeastern Worcester County, Md., and is bordered on the north by Delaware and on the east by the Atlantic Ocean (fig. 1). The model was developed to study this area; however, the total model area (fig. 1), or grid area, is larger (about 875 mi^2) in order to minimize the effect of the boundaries.

ACKNOWLEDGMENTS

The authors are indebted to the Assateague State Park Headquarters (Park Service, Maryland Department of Natural Resources); to District No. 1 of the Highway Administration (Maryland State Department of Transportation); and to individual landowners for the cooperation that made possible collection of data by test drilling and associated means. Thanks are expressed to the Worcester County Sanitarian for assistance in locating the results of chemical ground-water analyses. Appreciation

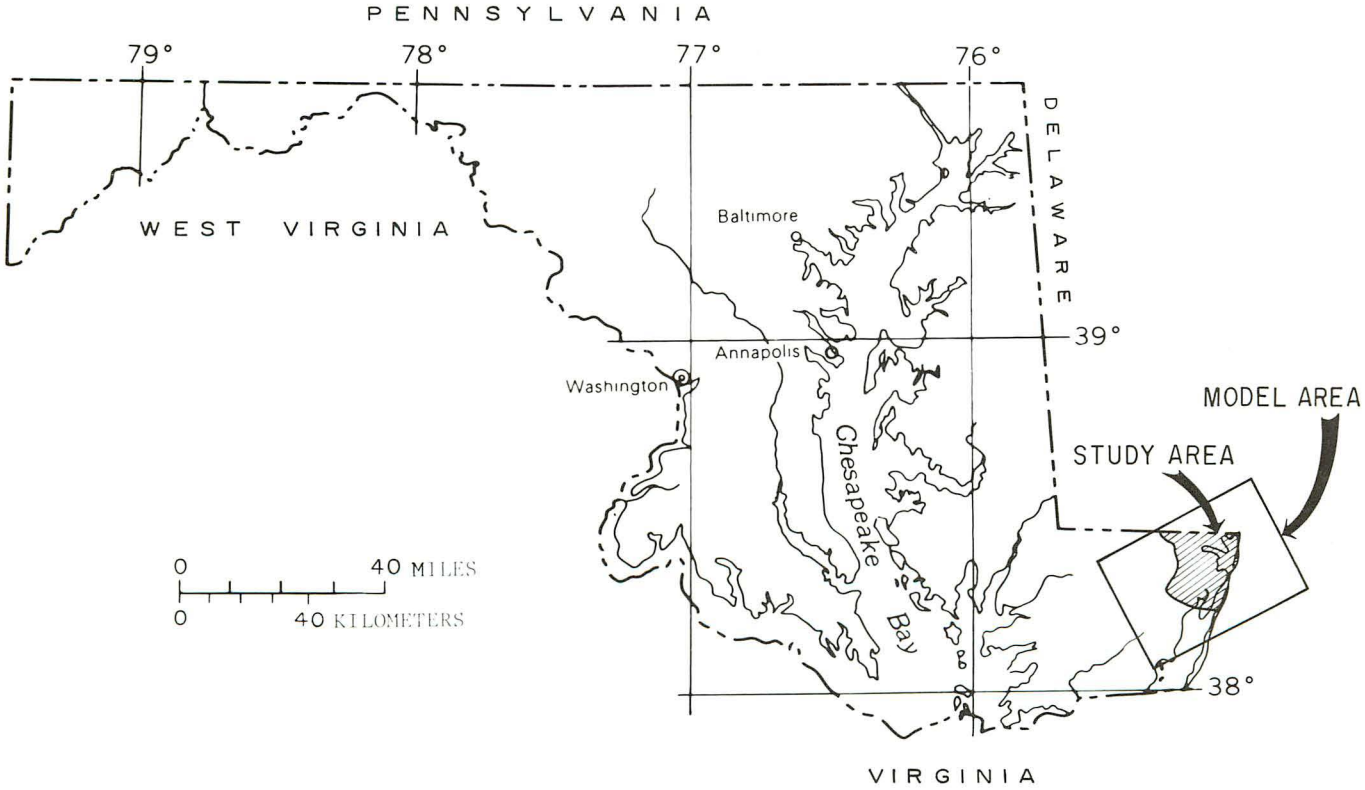


Figure 1.—Location of study area and model area.

is expressed to the Ocean City Engineer, to the Ocean City Water Department, and to the Worcester County Sanitary Commission at Ocean City for their cooperation during this investigation. The interest and assistance of Harry J. Hansen, Maryland Geological Survey, are gratefully acknowledged.

PREVIOUS INVESTIGATIONS

Rasmussen and Slaughter prepared a comprehensive report (1955) of ground-water resources of Somerset, Wicomico, and Worcester Counties. Subsequently, Slaughter (1962) prepared a brief report on water supplies at Ocean City, and adjacent Fenwick Island in Delaware. That report includes a discussion of the potential productivity of the aquifers at Ocean City and the danger of salt-water contamination. During 1967–68, E. F. Hollyday (U.S. Geological Survey) conducted a test-drilling program and collected hydrologic data at Assateague Island National Seashore in Maryland and Virginia; some of that information is pertinent to this study. A 1,200-ft test hole drilled at the north end of Ocean City was described by Kantrowitz (1969). In that report, determination of the base of fresh ground water at about 485 ft below land surface in the test hole was discussed; also, the possible occurrence of an unused fresh-water aquifer below what is now referred to as the Ocean City aquifer was considered. Considerable ground-water information in Worcester County was compiled by Lucas (1972). Cushing, Kantrowitz, and Taylor (1973) investigated the hydrology of the Delmarva Peninsula. The reader is referred to the results of that study for a regional view of the hydrology.

Weigle (1974) described the results of a detailed hydrologic investigation in northeastern Worcester County. During the course of that study (1969–71), the stratigraphic relationship and areal extent of the Ocean City and Manokin aquifers were determined, and the high potential productivity of the combined Ocean City-Manokin aquifer system was assessed. It was found that a cone of depression in the Ocean City-Manokin potentiometric surface at Ocean City fluctuates in size in response to seasonal changes in rates of withdrawal from that aquifer system at Ocean City. In mid-August, the cone is 12 mi or more in diameter, but by early winter water levels have recovered almost completely. During the same study it became apparent that interaquifer leakage is important in northeastern Worcester County.

No evidence of increasing salinity of ground water in northeastern Worcester County was reported by Weigle (1974); however, the potential for saline-water intrusion of the Ocean City-Manokin aquifer system at Ocean City was discussed.

GEOHYDROLOGY

Generally, each of the geologic units in northeastern Worcester County consists of one or more hydrologic units. Water occurs in all the hydrologic units, but it can be withdrawn in significant quantities only where the materials in the units are permeable enough to permit water to move fairly freely. Such units are termed "water-bearing" and are referred to as "aquifers." By contrast, some hydrologic units are made up predominantly of silt or clay and are relatively impermeable. Those units impede the movement of water, and are termed "confining beds" or "confining layers." In this report, attention is focused on the Pleistocene, Pocomoke, Ocean City, and Manokin aquifers (table 1), which are the fresh-water aquifers in northeastern Worcester County.

Ground water in northeastern Worcester County occurs in part under unconfined or water-table conditions, in which the water table is free to move up or down in response to fluctuations in recharge. More commonly, ground water in the study area occurs under confined conditions in aquifers bounded above and below by confining beds. Confined aquifers are a very important source of ground water in northeastern Worcester County.

Knowledge of the transmissivity of an aquifer is necessary in order to quantify the aquifer flow system. Transmissivity (T) is the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972). Maps showing transmissivity distributions for the major aquifers are presented in the section on Input Data, and the transmissivity values are summarized in table 1.

GEOLOGIC AND HYDROLOGIC UNITS

Northeastern Worcester County is underlain by a southeastward-thickening wedge of un-

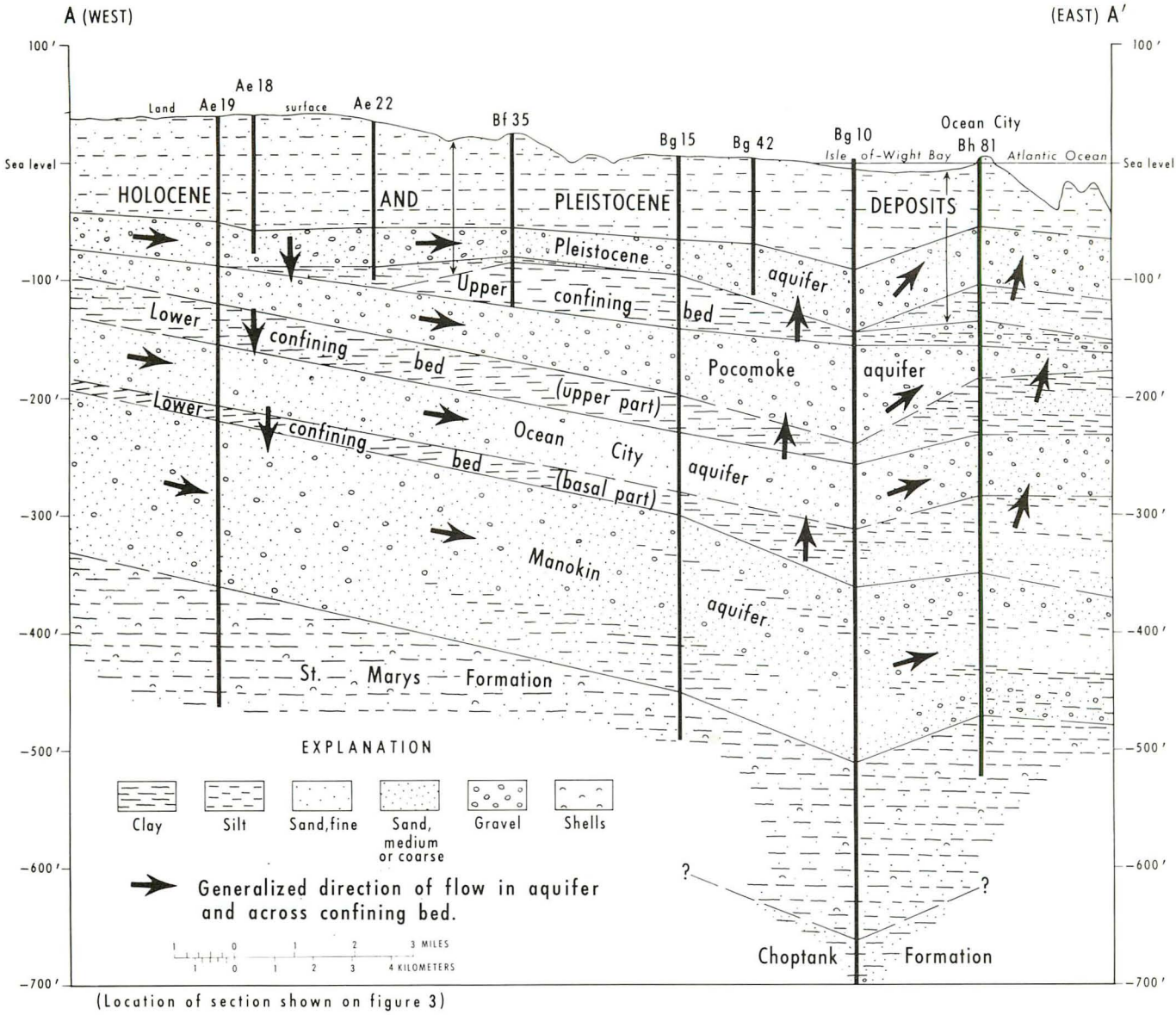


Figure 2.—Generalized geologic section trending east-southeastward across study area, and generalized directions of ground-water steady-state flow.

consolidated sediments. Successively older sediments subcrop northwestward under a mantle of Pleistocene deposits. The Miocene units, which include the most important fresh-water aquifers, occur at depths that increase southeastward (fig. 2).

The age, lithology, thickness, and water-bearing characteristics of the Miocene and Quaternary units are summarized in table 1 and are described in detail by Rasmussen and Slaughter (1955), and Weigle (1974). Maps of the tops of the Pocomoke and Manokin aquifers, and a map of the base of the Quaternary deposits are presented by Cushing, Kantrowitz, and Taylor (1973). Similar maps were presented also by Rasmussen and Slaughter (1955).

Holocene Deposits

The Holocene deposits are from 0 to 40 ft thick, but generally are less than 10 ft thick. They overlie the Pleistocene deposits disconformably, and consist chiefly of sand but contain some silt, clay, and more or less decomposed plant remains. Commonly, the Holocene deposits are unsaturated but permit water to percolate downward to underlying units.

Pleistocene Deposits

The Pleistocene deposits generally thicken eastward; but their thickness and basal contact are very irregular, owing to erosion of the underlying Miocene units before Pleistocene

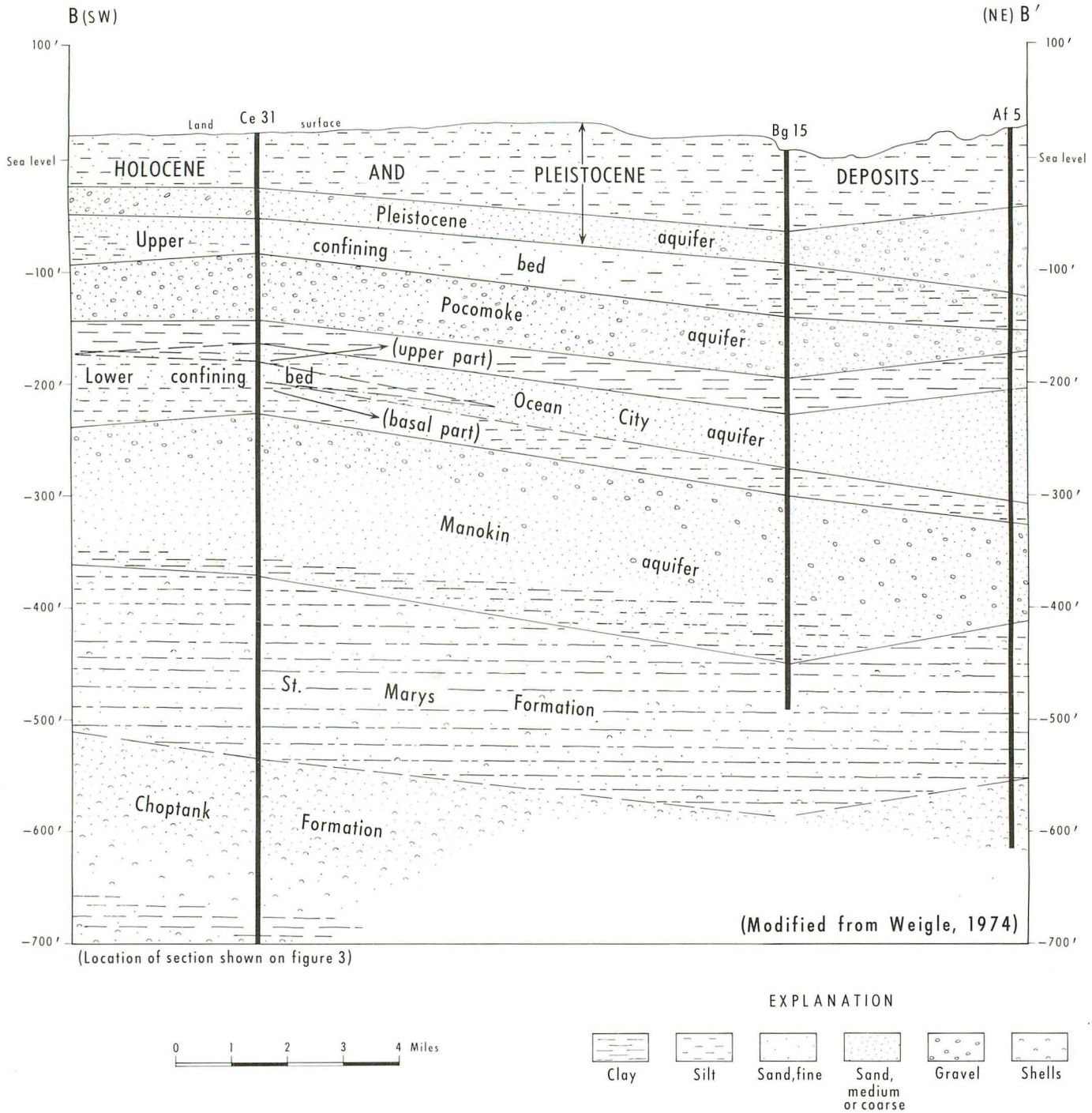


Figure 4.—Generalized geologic section trending northeastward across study area.

deposition. The Pleistocene deposits are stratigraphically complex, and within them are numerous discontinuous and nonparallel erosional surfaces. The thickness of the deposits ranges from 90 to 200 ft.

The upper Pleistocene sediments are primarily lenticular deposits of fine to medium sand, silt, clay, and peat, but some beds of coarse sand and fine gravel are included. The upper Pleistocene deposits are as much as 100 ft thick locally, and lie disconformably on lower Pleistocene deposits.

The lower Pleistocene deposits (in large part the Beaverdam Sand of Rasmussen and Slaughter, 1955) are composed of coarser materials. Generally, they are lensoidal or rudely stratified deposits of medium to very coarse sand and gravel. Water moves laterally in these deposits. This part of the Pleistocene deposits is referred to as the Pleistocene aquifer. Near the coast,

the basal 10 or 20 ft of these deposits contains interbedded clay and well-sorted fine or medium sand. Beds of clay, silt, and fine sand in the lower Pleistocene deposits increase in number and thickness toward the east.

The Berlin scarp, a prominent physiographic feature, traverses the middle of the area as shown in figure 3. The feature extends generally northeastward from Newark to Berlin and thence northward into Delaware. The face of the scarp slopes gently eastward, descending from 35 or 40 ft to 10 or 15 ft above sea level. It was formed by erosion during Pleistocene time and was partly buried by subsequent deposition. The entire process affected only the upper part of the Pleistocene deposits. The scarp serves as a geographic reference or landmark in this report.

Pleistocene Aquifer

The Pleistocene aquifer (principally the Beaverdam Sand) consists of the lower one-third to one-half of the Pleistocene deposits. The aquifer is from 25 to 50 ft thick in most of the area studied, but thickens toward the northeast and is from 60 to 90 ft thick beneath Ocean City.

Water in most of the Pleistocene aquifer occurs under water-table conditions. However, in many places (especially in the vicinity of the coast) strata of fine materials in the upper part of the Pleistocene deposits create local confining conditions.

Recharge to the Pleistocene aquifer is predominantly by direct infiltration and downward percolation of rainfall and snowmelt through the overlying Holocene deposits. Within the saturated zone below the water table the water moves laterally, generally in the direction of the land-surface slope. Discharge from the Pleistocene aquifer occurs by evapotranspiration; by discharge to the Pocomoke River, other streams, and widespread swamps; and by nearshore and offshore seepage upward into the bay and ocean. The Pleistocene aquifer also contributes some water to the underlying Pocomoke aquifer, especially where the two aquifers are in direct contact (fig. 2).

Miocene Deposits

The Miocene deposits generally dip and thicken southeastward in the study area, and strike northeasterly (somewhat more easterly than the trend of the shoreline). The deposits are of marine origin, although toward the top of the deposits indications of an estuarine or coastal depositional environment are increasingly common.

Fresh water in the Miocene deposits is restricted to the upper part of those deposits.

Upper Miocene Deposits

Upper Miocene deposits in this area include deposits of relatively coarse sands alternating with deposits of clay, silt, and fine sand. In general, the material composing the basal few tens of feet of the deposits grades upward from fine to coarse sand.

The Upper Miocene deposits are divided hydrologically into five units. They are: (1) The upper confining bed; (2) the Pocomoke aquifer; (3) the lower confining bed, which also contains (4) the Ocean City aquifer; and (5) the Manokin aquifer.

Upper Confining Bed

The upper confining bed (referred to as the upper aquiclude by Rasmussen and Slaughter, 1955) separates the Pocomoke and Pleistocene aquifers in most of the area. It consists of lenticular bodies of silt, clay, and fine sand. Silt and fine sand are most common. The bed averages 15 or 20 ft in thickness, but pinches out in the extreme northwestern part of the area and is absent locally elsewhere; for example, it is absent just north of Berlin, at well Wor-Bf 29. Where the upper confining bed is absent the Pleistocene deposits rest directly on the Pocomoke aquifer, and water can move freely from one unit to the other. Even where the confining bed is present, the vertical leakage ranges from good to poor because the materials in the confining bed vary from fine sand to clay.

Pocomoke Aquifer

The Pocomoke is an important aquifer in northeastern Worcester County. It is composed of sand, generally coarse and pebbly but locally fine. It is thickest (about 80 ft) near Berlin, but generally is from 30 to 60 ft thick. The aquifer pinches out under northern Ocean City and is partly eroded in the extreme northwestern part of the area studied. Ground water in the Pocomoke aquifer is confined except in the northwestern part of the area and elsewhere, where the upper confining bed is locally absent.

Recharge enters the Pocomoke aquifer in most of the western part of the area by percolation downward from the overlying Pleistocene deposits. This occurs where the upper confining

bed is absent or relatively ineffective as a confining layer, and where the head in the Pleistocene aquifer is greater than that in the Pocomoke aquifer.

From the principal area of recharge, water moves generally eastward in the aquifer. In most of the area east of the Berlin Scarp, the head in the Pocomoke aquifer normally exceeds that in the Pleistocene aquifer, and water discharges from the Pocomoke aquifer upward into the Pleistocene aquifer through permeable areas of the upper confining bed. Also, from Massey's Crossing southward in the Pocomoke River valley, similar head relations exist and some water discharges from the Pocomoke aquifer upward into the Pleistocene aquifer.

Lower Confining Bed

In northeastern Worcester County, the lower confining bed (referred to as the lower aquiclude by Rasmussen and Slaughter, 1955; and the lower confining bed by Weigle, 1974) is made up primarily of clayey silt and sand. The material in the upper part of this unit is mostly fine sand, silt, and clay. The middle and basal parts of the unit are generally sandy.

The lower confining bed partially separates the Pocomoke and Manokin aquifers hydraulically and is probably characterized by substantial leakage in a large part of the study area. The confining bed ranges from 15 ft to more than 100 ft in thickness, but in much of the study area only the upper part (15 to 20 ft thick) persists as a confining layer. In the northeastern part of the study area, the sandy middle part becomes the Ocean City aquifer (fig. 4). To the southwest, however, the Ocean City aquifer loses its identity, and at Snow Hill traces of it are difficult to detect.

Ocean City Aquifer

The Ocean City aquifer separates the upper and basal parts of the lower confining bed beneath approximately the northern two-thirds of the area of investigation. The aquifer is composed chiefly of fine to very coarse sand. Beneath Ocean City it ranges from 30 to 110 ft in thickness, and lies between approximately 240 and 300 ft below sea level at well Wor-Bh 81; the base of the unit deepens southward and shallows northward beneath Ocean City (fig. 5). All the public-supply wells in the southern half of Ocean City withdraw their water from the Ocean City aquifer. South of there, however, the aquifer becomes thinner and less productive.

The Ocean City aquifer is separated from the Manokin by the basal part of the lower confining bed (fig. 5), but is hydraulically connected by leakage through the confining layer. At Ocean City and westward in general, the transmissivity values for the Ocean City aquifer are approximately the same as those of the Manokin aquifer. Southwest of Ocean City, transmissivity decreases as the aquifer thins.

Manokin Aquifer

The Manokin is potentially a very important artesian aquifer in northeastern Worcester County. It was an untapped source of water at Ocean City prior to 1972. Since then, however, four public-supply wells (Wor-Ah 33, 34, 38, and 39) have been constructed in the Manokin aquifer at the northern end of Ocean City.

The Manokin aquifer is confined above by the basal part of the lower confining bed, and below by the St. Marys Formation. The Manokin ranges from less than 100 to 240 ft in thickness in the study area and occurs between 350 and 475 ft below sea level at well Wor-Bh 81, in Ocean City. In northeastern Worcester County the aquifer consists primarily of fine to very coarse sand, although beds of peat or lignite occur locally in the sand. The productive, sandy part of the aquifer is generally thickest in the northern and northwestern parts of the area. Southward and southeastward, however, beds of silty sand and clay, and beds or lenses of shells and shell fragments partly cemented by calcium carbonate occur in the middle of the Manokin, reducing the thickness of the productive part of the aquifer. Test drilling in the vicinity of Assateague State Park suggests that the thickness of the permeable sands in the aquifer ranges from 60 to 120 ft and that the rest of the aquifer is relatively nonproductive there.

The Manokin and Ocean City aquifers are hydraulically connected across the basal part of the lower confining bed and at Ocean City function as one hydrologic unit. Near Whaleysville (test hole Wor-Ae 19), hydraulic connection is poorer because the confining bed is less sandy, and the Ocean City aquifer perhaps should be considered as a hydrologic unit separate from the Manokin. In this report, the Ocean City and Manokin aquifers are treated as two aquifers separated by a leaky confining bed.

Under optimum conditions of well construction, the Ocean City-Manokin aquifer system is

capable of yielding very large supplies of water (several thousand gallons per minute) in most of the northern part of the area, although much less to the south and especially the southeast. (See section on ground-water yield in Weigle, 1974.)

The transmissivity of the Ocean City-Manokin aquifer system increases north-northwestward from a low in the southeastern corner of the study area to a high in the Berlin-Showell-Libertytown area. The increase is due to the presence of the Ocean City aquifer in the northern part of the area, and to increasing permeability of the materials in the Ocean City and Manokin aquifers toward the north and northwest, respectively.

The Manokin aquifer is recharged directly from overlying saturated sand and gravel of Pleistocene age along a belt several miles wide that trends northeastward across part of the Delmarva peninsula (Rasmussen and Slaughter, 1955; Boggess and Heidel, 1968; and Sundstrom and Pickett, 1969), about 20 to 50 mi northwest of Ocean City. However, most of the ground-water recharge received by the Manokin along that subcrop belt moves laterally away from rather than toward northeastern Worcester County, as indicated by an intervening ground-water high or divide shown by Cushing, Kantrowitz, and Taylor (1973). Additional recharge occurs by vertical leakage downward from the Pocomoke aquifer through the leaky lower confining bed, especially in the western and northern parts of the study area (fig. 2). That water then moves generally east-southeastward beneath northeastern Worcester County toward Ocean City and the ocean.

Under nonpumping conditions, water levels of the Ocean City-Manokin aquifer system are higher than those of the Pocomoke aquifer in the eastern part of the study area and presumably some distance offshore. Because of that head difference, water tends to discharge upward from the Ocean City-Manokin aquifer system into the Pocomoke aquifer through permeable places in the lower confining bed.

Large withdrawals of water from the Ocean City-Manokin aquifer system in response to summer demands at Ocean City lower the potentiometric surface extensively in the coastal part of the study area, reversing the head relation between the Ocean City-Manokin aquifer system and the Pocomoke aquifer. This creates a seasonal potential for movement of water from the Pocomoke aquifer downward into the Ocean City-Manokin aquifer system.

Figure 6 shows the seasonal change in the direction of vertical leakage. The area of potential summer leakage from the Pocomoke aquifer to the Ocean City-Manokin aquifer system is greater in years when summer withdrawals from the Ocean City-Manokin aquifer system are greater.

Offshore acoustical profiling of sub-bottom sediments done in the early 1970's by the Coastal Research Laboratory, U.S. Army Corps of Engineers, and cooperatively in 1976 by the U.S. Geological Survey, Maryland Geological Survey, and Delaware Geological Survey (see section on Hydrologic Information Obtained During this Study) indicated no abrupt structural or lithologic changes in the Upper Miocene deposits within several miles of shore. It is therefore assumed that the gradual southeasterly increase in content of fine materials in the Manokin continues seaward from Ocean City, and that lateral movement of water toward the east and southeast in the Manokin is increasingly retarded.

Middle and Lower Miocene Deposits

These deposits are of marine, near-shore and continental-shelf origin, and are saturated with brackish or salty water. The deposits are the St. Marys, Choptank, and Calvert Formations.

St. Marys Formation

The St. Marys Formation is a well-defined unit, from 160 to 190 ft thick in northeastern Worcester County. The formation is massive and varies little lithologically throughout its thickness; it is characteristically compact, tough, fossiliferous gray clay, silt, fine sand, and silty and sandy clay. It is an effective confining layer at the base of the Manokin aquifer, and prevents or effectively retards the movement of salt water from the underlying Choptank Formation into the Manokin aquifer. The St. Marys Formation is saturated with brackish or salty water throughout this area.

Choptank Formation

In northeastern Worcester County, the Choptank Formation ranges in thickness from 130 to 240 ft, and is composed of two parts. The upper part (the Frederica aquifer) consists of fine sand and thin beds of shell, calcite, and limestone capable of producing moderate supplies of salty water. The lower part consists of clay and fine sand, and thin beds of shell and calcite or limestone, and is a confining layer.

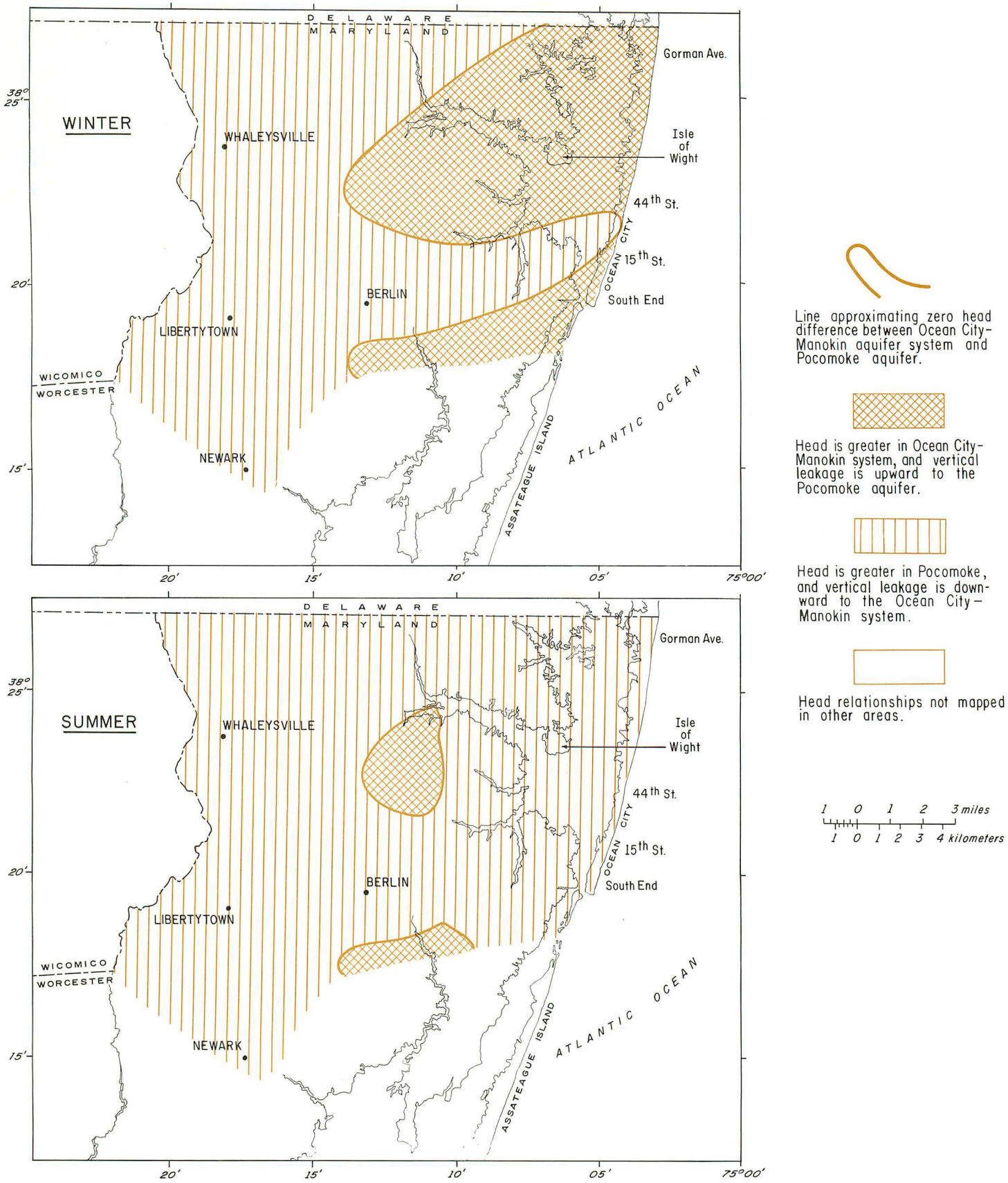


Figure 6.—Direction of vertical leakage between Ocean City-Manokin aquifer system and the Pocomoke aquifer in summer, 1971, and winter, 1971–1972.

Calvert Formation

The Calvert Formation is from 430 to 680 ft thick in northeastern Worcester County. It consists of alternating aquifers and confining layers made up of stratified sand, diatomaceous silt and clay, and shell beds. The aquifers could probably produce moderate to large (500 gal/min or more) supplies of water, but the water is salty.

FRESH-WATER AQUIFERS

In summary, fresh ground water in northeastern Worcester County is restricted to a block of sediments about 450 ft thick. The top of the block is the land surface, and the base is at or a few feet above the contact between the St. Marys Formation and the overlying Manokin aquifer. Within that block, water occurs under water-table and semi-confined conditions in the Pleistocene aquifer, and under confined conditions in the Pocomoke, Ocean City, and Manokin aquifers. Those four fresh-water aquifers comprise a leaky multiaquifer system.

VERTICAL LEAKAGE

Interaquifer leakage is extensive in northeastern Worcester County, and is potentially important in some places. In the vicinity of Ocean City, for example, the effectiveness of the several confining layers between the Manokin aquifer and the Pleistocene aquifer is inconsistent or poor. There, long-continued large-scale withdrawals from the Manokin aquifer probably would cause vertical leakage from the overlying units, thereby raising the possibility of sea-water intrusion from above.

GROUND-WATER FLOW

In northeastern Worcester County the water table (the top of the saturated zone) occurs in the Pleistocene deposits, and the dashed lines in figure 7 show its position. The dashed lines in figure 8 show the position of the potentiometric surface for the Pocomoke aquifer. Likewise, the dashed lines in figures 9 and 10 show the potentiometric surface for the Ocean City-Manokin aquifer system. Ground water moves generally perpendicular to the potentiometric contours; thus, paths of ground-water movement in northeastern Worcester County can be determined from these maps.

Lateral movement of water within the individual aquifer is slow, and down the hydraulic gradient toward areas of lower head. The gradients of the water table and the potentiometric surfaces in the study area generally slope east-southeastward. The average gradient of the water table in the Pleistocene deposits is much steeper than that of the potentiometric surfaces of the Pocomoke and Manokin aquifers. The steeper gradient and comparable or greater permeability of the materials in the Pleistocene aquifer indicate that water generally moves more rapidly in the Pleistocene aquifer than in the Pocomoke and Manokin aquifers.

Comparison of the maps shows head differences between the aquifers and therefore indicates the direction of vertical movement (leakage) between the aquifers: vertical movement is toward the aquifer that has the lower head. The vertical hydraulic conductivity values for the confining beds generally are much smaller than the lateral hydraulic conductivity values for the aquifers. The vertical movement of water through the confining beds between the aquifers, therefore, is much slower than the lateral movement of water within the aquifers.

Recharge to the aquifer system in northeastern Worcester County originates as precipitation. That part of the rainfall or snowmelt that does not immediately run off as overland runoff and that is not returned to the atmosphere through evapotranspiration, percolates downward to the water table as ground-water recharge. Ground water then moves laterally, discharging into streams as base flow; or recharges downward through confining beds to the underlying aquifers.

Water in the aquifer system generally moves slowly eastward or southeastward in northeastern Worcester County. In the western part of the area, some water leaks downward through confining beds into aquifers having lower hydraulic heads (fig. 2). In the eastern part of the area, the heads are higher in successively deeper aquifers. Under nonpumping conditions, water under this area leaks upward through confining beds and into the overlying aquifers.

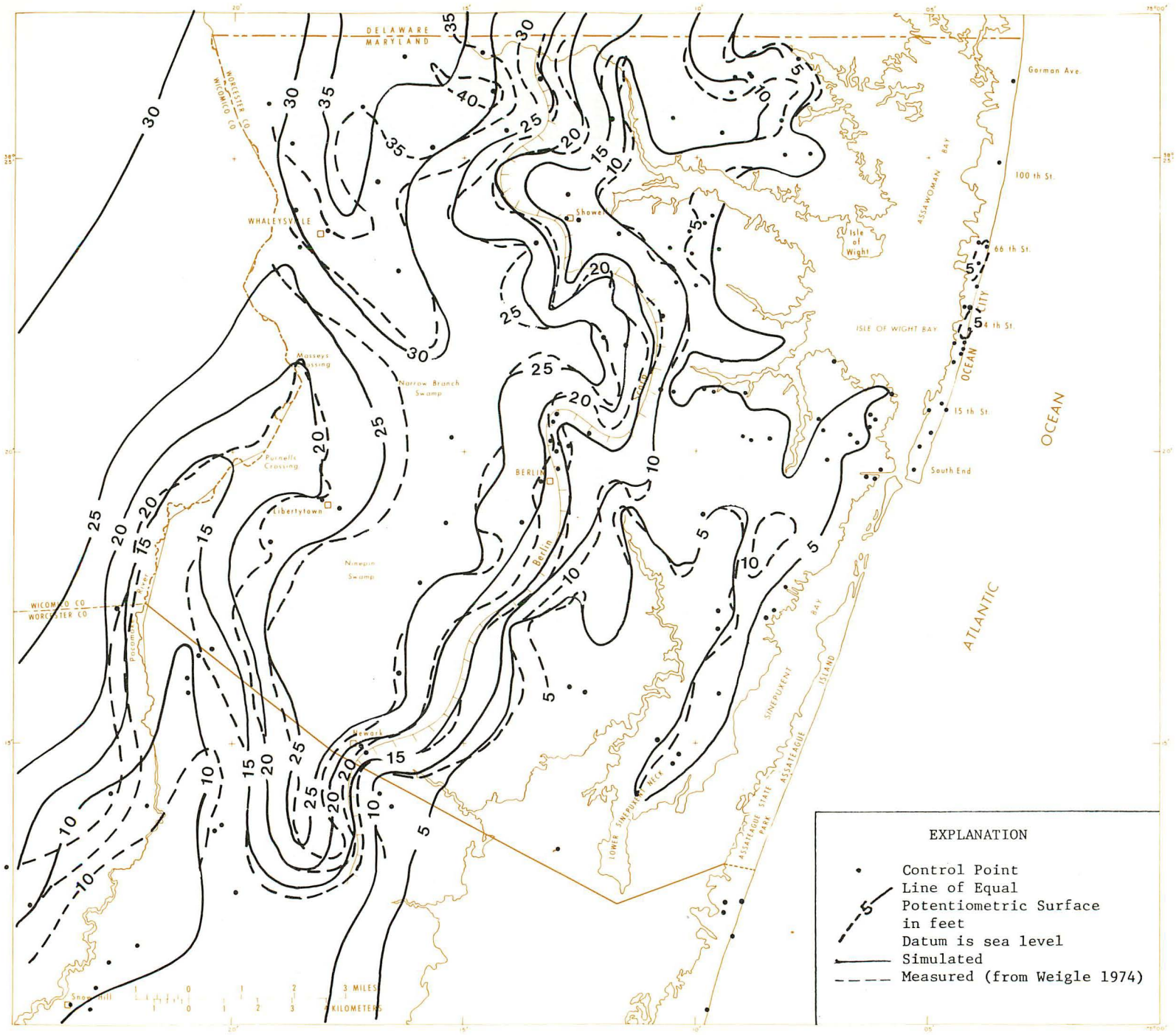


Figure 7.—Potentiometric surface of Pleistocene aquifer (1971) and initial conditions used in model.

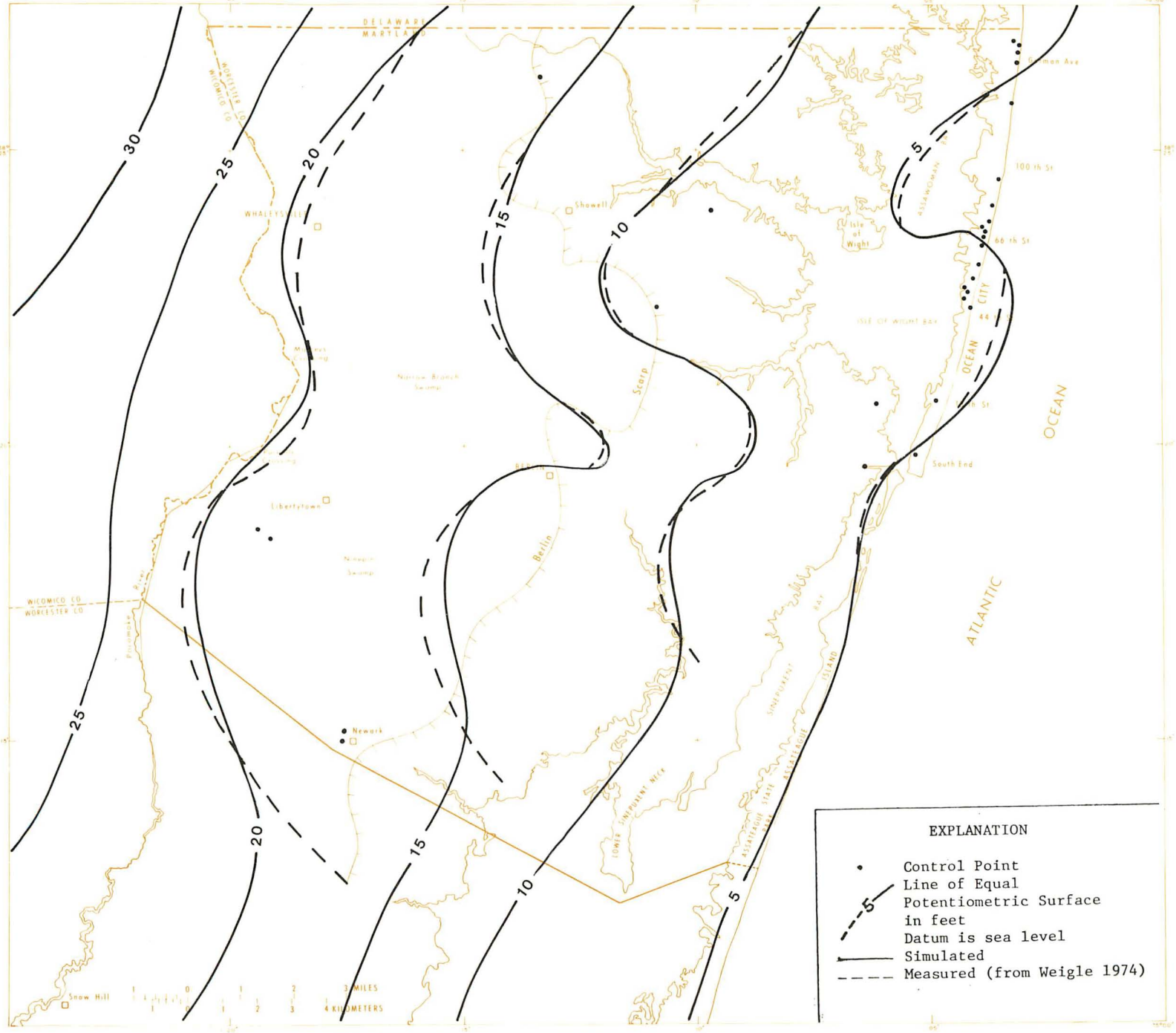


Figure 8.—Potentiometric surface of Pocomoke aquifer (1971) and initial conditions used in model.

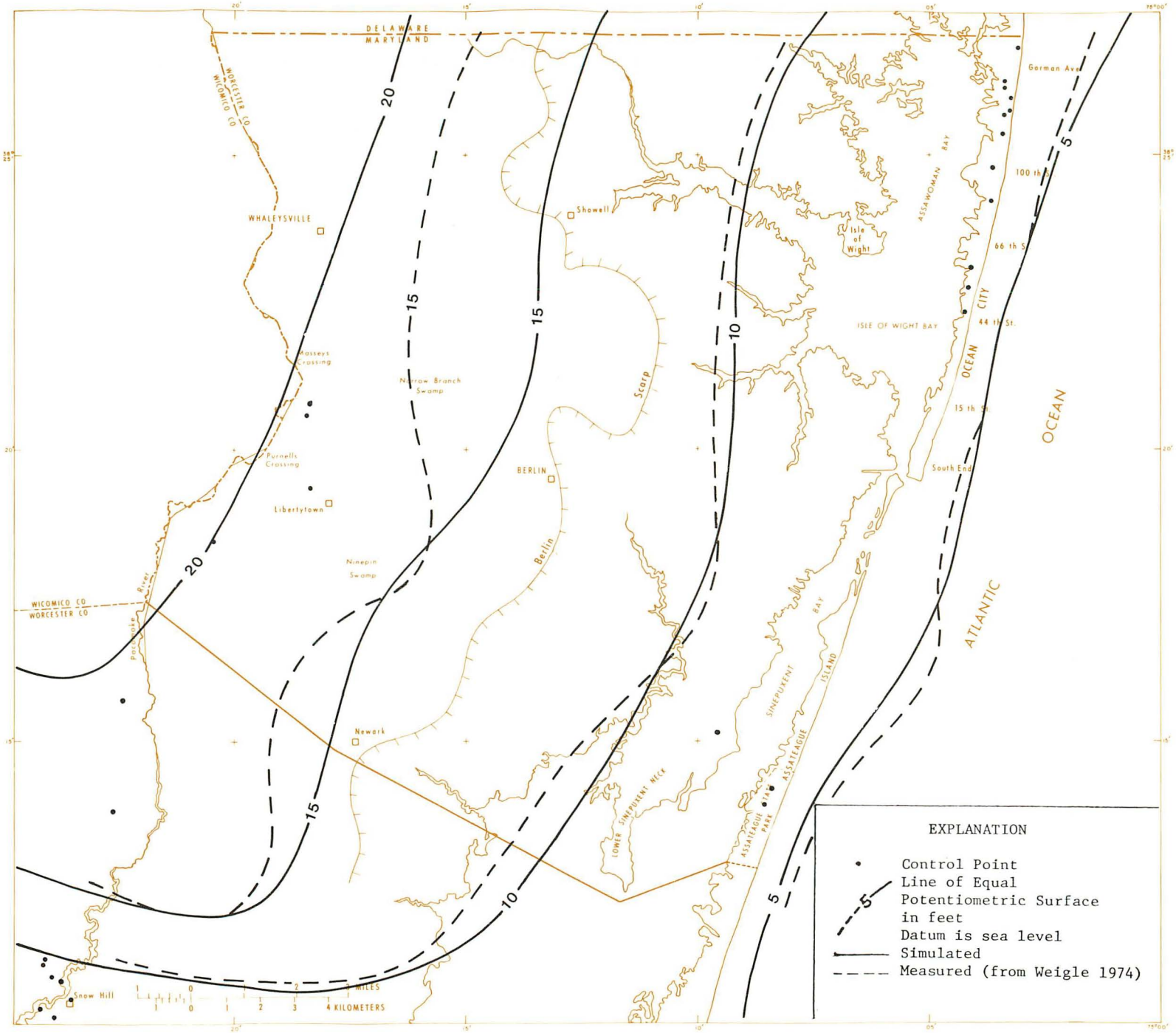


Figure 9.—Potentiometric surface of Ocean City aquifer (1971) and initial conditions used in model.

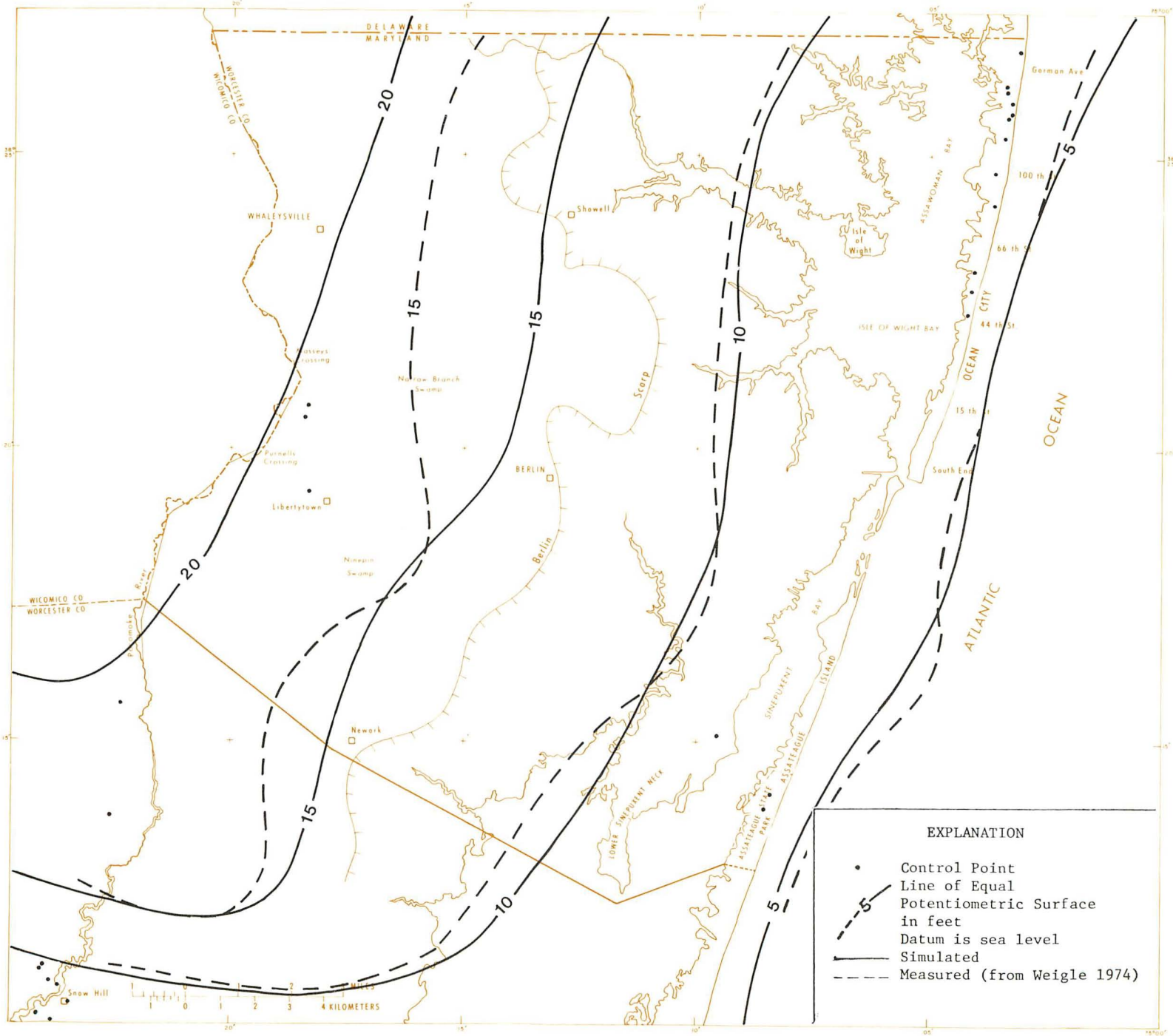


Figure 10.—Potentiometric surface of Manokin aquifer (1971) and initial conditions used in model.

Future ground-water development plans for northeastern Worcester County were simulated using a multi-layer digital ground-water flow model calibrated against six years (1971–1976) of historical pumpage and water-level data. The purpose of these simulations is to illustrate the effects of decentralizing pumping centers. The spreading out of pumpage reduces drawdowns which would minimize secondary effects such as salt-water intrusion. Thus, these simulations are a preliminary step in assessing future water needs and impacts, and further study is required for more definitive results.

The computer model and associated computer program used for this study have been developed and documented by Achmad and Weigle (1979). The model allows for simulation of multiaquifer systems with interaquifer leakage.

MODEL DEVELOPMENT

Grid Spacing and Boundary Conditions

The model area covers 875 mi^2 and is divided into 35 × 25 nodes of 1-square mile each (fig. 11). Because of data deficiency, the authors had to assign the model boundaries arbitrarily. No-flow boundaries roughly approximate the flow paths based on potentiometric-surface maps. Constant-head boundaries were assigned at the western corner of the recharge area and at the eastern corner of the discharge area. The upper Pleistocene deposits (table 1), which overlie the Pleistocene aquifer, and the St. Marys Formation, which underlies the Manokin aquifer, were assumed to be impervious boundaries. Although the assumed boundaries distort flow paths, particularly near the boundaries, trial runs with the assigned boundaries yield good results when compared with observed water levels. Another combination of model boundaries might also yield good results; however, there was no detailed information to justify which boundaries were the best ones to simulate the system. Because of these boundary uncertainties, the model cannot be fully calibrated and the model results should be interpreted accordingly.

Input Data

The following data were supplied to the model for each node: (1) Initial conditions in the form of hydraulic heads, (2) transmissivity of aquifers, (3) storage coefficients of aquifers, (4) vertical hydraulic conductivity of confining beds, and (5) specific storage of confining beds. In addition, pumpage must be specified for each node where pumping wells are located.

The data used for the model were derived mostly from published reports and personal communications. Information concerning the aquifer limits and other boundary conditions was obtained from Cushing, Kantrowitz, and Taylor (1973).

Head values were derived from maps prepared by Weigle (1974). Those maps were prepared using water levels in 1971 or earlier, and approximately represent steady-state conditions. Initial conditions for the transient model simulations were defined for all aquifers. Figures 7, 8, 9, and 10 show the water levels as reported by Weigle (1974) and those used for initial conditions in the model simulations.

The transmissivity matrices were also derived from maps prepared by Weigle (1974). An average transmissivity value was estimated from the maps for each node. Only minor adjustments were permitted in the aquifer transmissivity matrices because these values were considered the most reliable of the model input parameters. Aquifer transmissivities used in the model are presented in figures 12–15.

Aquifer storage coefficients were selected from values reported by Cushing, Kantrowitz, and Taylor (1973). The aquifers were regarded as having uniform storage coefficients, and a single storage (S) value was assigned to each aquifer.

Data on vertical hydraulic conductivity (K_v) and specific storage (S_s)were sparse. Values for a Miocene clay from Salisbury, Md., have been reported by Wolff (1970); vertical hydraulic conductivity ranged from 2.8×10^{-5} to 5.7×10^{-3} ft/d, and specific storage ranged from 0.3×10^{-4} to 1.8×10^{-4}(1/ft). Laboratory tests made on a Pleistocene clay sample from Ocean City in 1976 indicated a vertical hydraulic conductivity of 9.9×10^{-5} ft/d. Initial values used in the model were based on these data, but were adjusted. Simulation runs indicated that the best results were obtained by using the following values: K_v for confining bed on top of Pocomoke and Ocean City aquifers = 3.6×10^{-5} ft/d, and K_v for confining bed on top of Manokin = 1.9×10^{-3} ft/d.

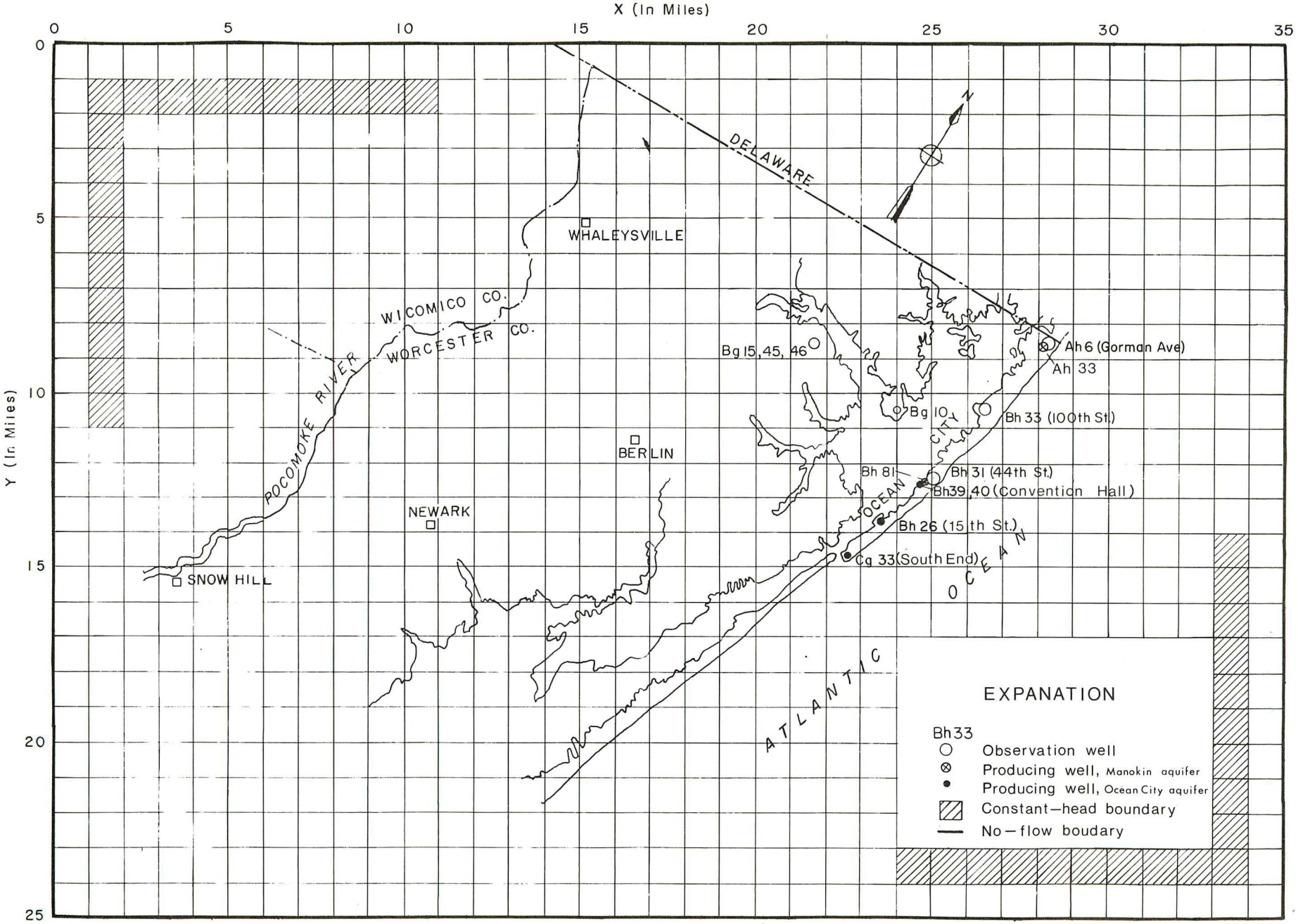


Figure 11.—Grid system of the model area.

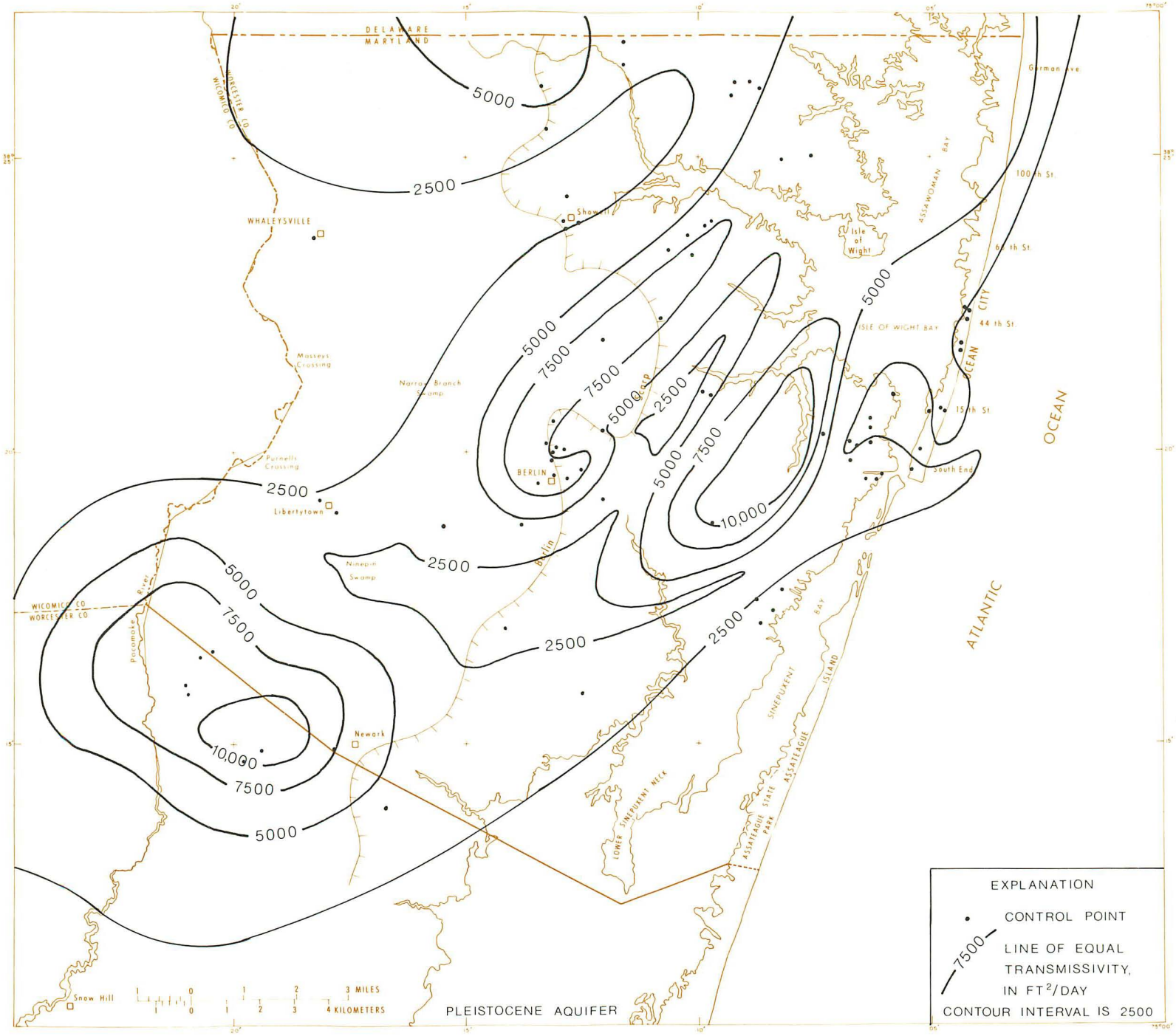


Figure 12.—Transmissivity of Pleistocene aquifer, used in model.

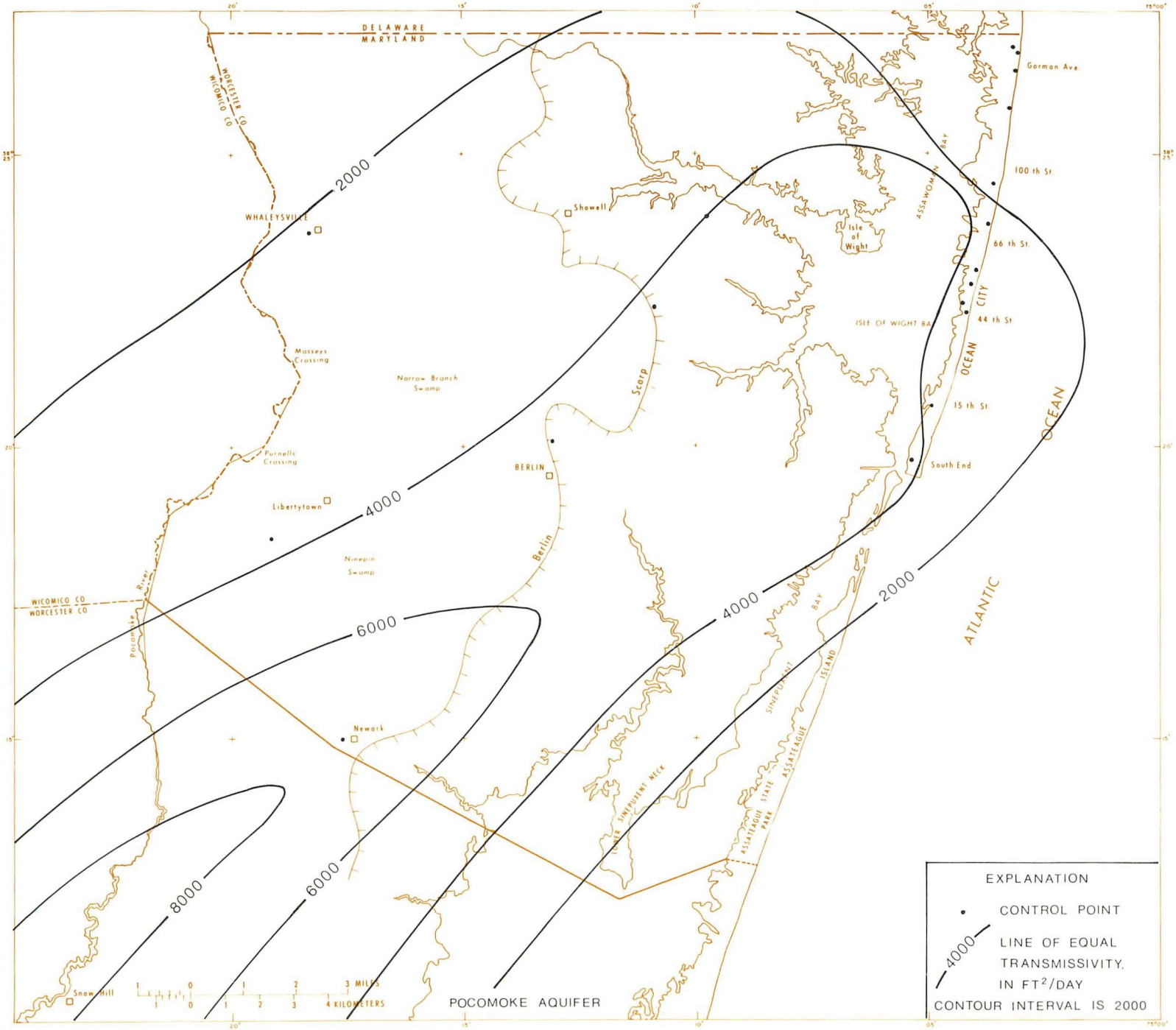


Figure 13.—Transmissivity of Pocomoke aquifer, used in model.

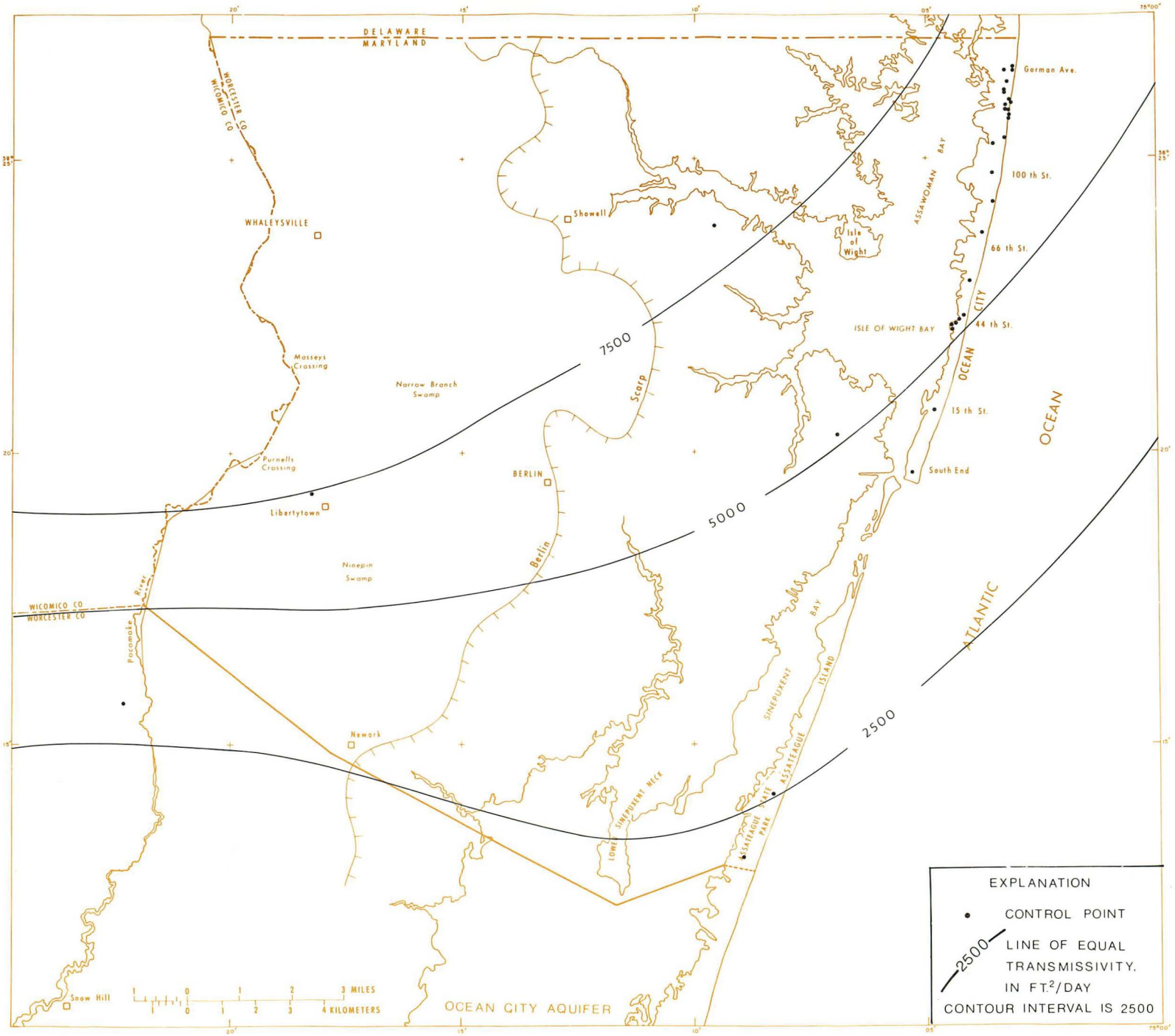


Figure 14.—Transmissivity of Ocean City aquifer, used in model.

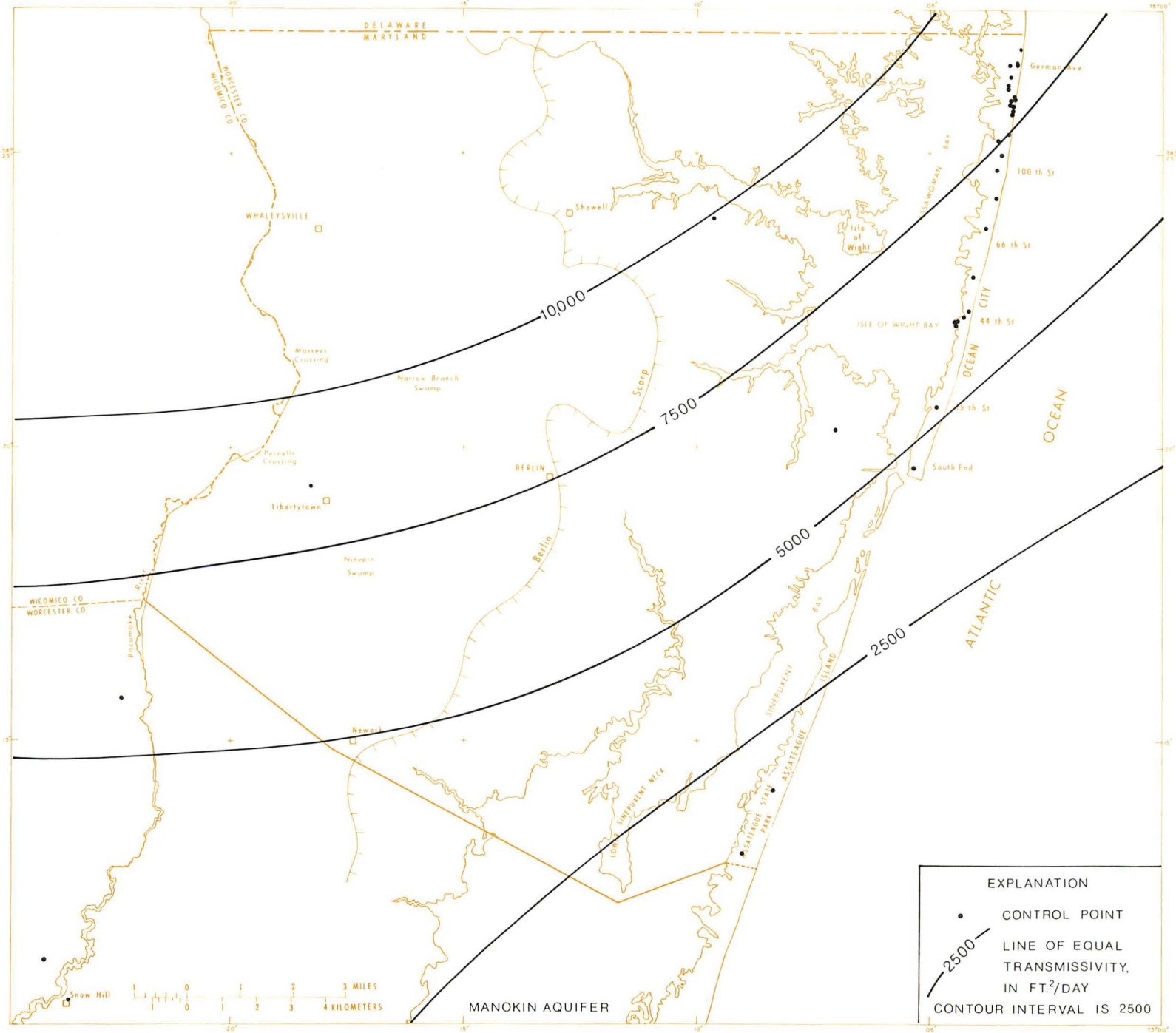


Figure 15.—Transmissivity of Manokin aquifer, used in model.

Parameter Adjustment

Although the model boundary conditions are artificial and no steady-state simulation was performed to reproduce initial conditions for the Pleistocene aquifer, 6 years of historical pumpage were simulated to insure that the model results are reasonable in showing the effects of present and future pumping centers. The effects of pumping on the water levels of the multiaquifer system at Ocean City were simulated for the 6-year period 1971 through 1976. The first 2-year period was used to adjust aquifer and confining-bed storage. The subsequent 4-year period was used to check whether the model could reproduce the observed water levels without further adjusting the aquifer parameters.

Adjustment of storage coefficients was based on the mass balance of the flow components, the overall head distribution in the aquifers, and the practical range of values reported for each aquifer. After several trial runs, it was found that aquifer storage coefficient values (S) that gave the best results were as follows: $S_{Manokin} = 0.00012$, $S_{Ocean\ City} = 0.00009$, $S_{Pocomoke} = 0.00012$, and $S_{Pleistocene} = 0.0015$. All confining beds were assigned the same specific storage value (S_s), and simulation runs indicated that the best results were obtained by using $S_s = 4 \times 10^{-4}$ (1/ft.)

Rates of withdrawal for the 6-year period are shown in table 2, and the locations of the pumping centers are shown in figure 16. From the simulated values, monthly head values at several locations were plotted in hydrograph form. The simulated hydrographs correspond well with the observed hydrographs (fig. 17). Both observed and simulated hydrographs show recovery of water levels.

The maximum difference between the simulated and observed hydrographs is less than 1 ft for 60 percent and less than 5 ft for 95 percent of the measurements.

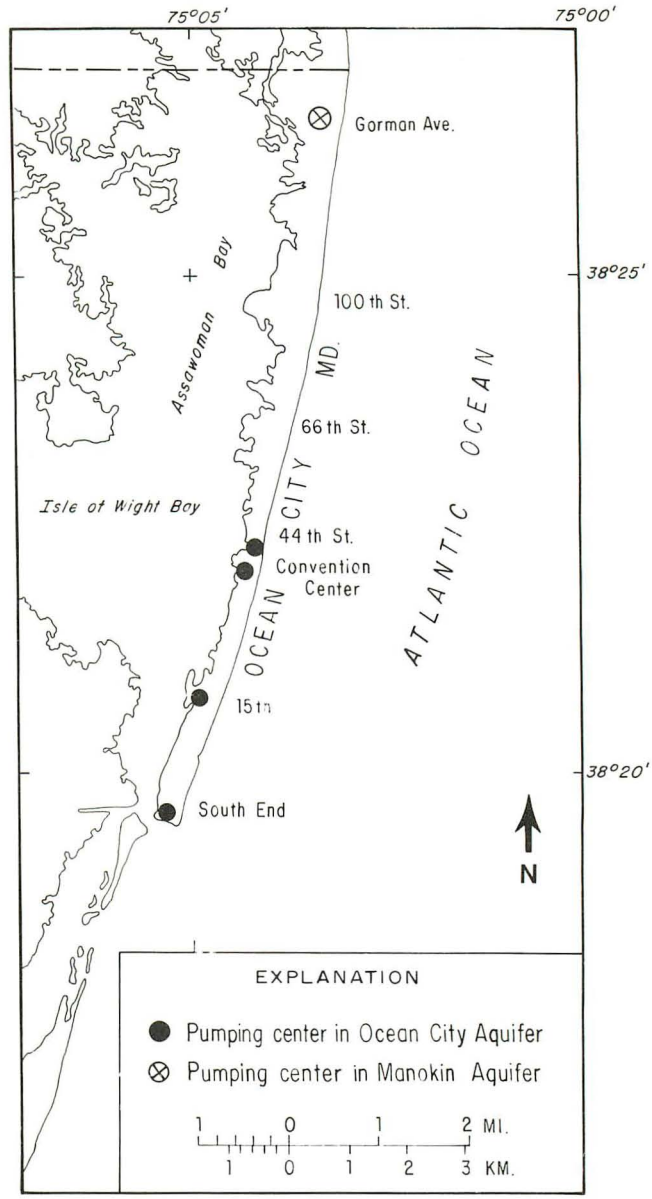


Figure 16.—Locations of centers of withdrawal of water from the Ocean City and Manokin aquifers at Ocean City.

LIMITATIONS

The model developed in this study has limitations for certain uses that are caused chiefly by the boundary assumptions, lack of steady-state calibration for the Pleistocene aquifer, and the size of the grid units.

The model assumes confined conditions. Except for the Pleistocene aquifer, this assumption is largely valid. In general, water in the Pleistocene aquifer in the immediate vicinity of Ocean City is confined. Westward, however, it occurs more commonly under water-table conditions.

Because the model area includes only a part of the aquifer system, some of the natural flow boundaries lie outside the model area. Consequently, representations of the boundaries in the model are artificial. (See section on boundaries.) For some of the simulations in figures 19, 20, 23, and 24, the effects of pumping intercept the constant-head nodes in the eastern part of the model. When pumping effects reach the eastern constant-head boundary, a larger flux may be provided to the aquifers than the actual conditions would permit.

Table 2—Withdrawal of water from the Ocean City and Manokin aquifers at pumping centers.

[Average rates in Mgal/d]

Month	Pumping center					Pumping center				
	1	2	3	4	5	1	2	3	4	5
			1971					1972		
Jan.	0.385	0.081	0.183	0.610	-	0.622	-	0.242	0.610	-
Feb.	-	.402	.226	.610	-	.553	-	.340	.610	-
Mar.	-	.444	.259	.920	-	.451	-	.318	.920	-
Apr.	-	.735	.441	.920	-	.675	-	.493	.920	-
May	.221	.874	.516	.920	-	1.041	0.146	.627	.920	-
June	.615	1.077	.907	.920	-	1.118	.578	.916	.920	-
July	1.089	1.289	1.408	.920	-	1.374	1.370	1.576	.920	-
Aug.	1.061	1.499	1.745	.920	-	1.510	1.423	1.915	.920	-
Sept.	.582	.814	.879	.920	-	.991	.799	.965	.920	-
Oct.	.161	.528	.414	.920	-	.818	-	.532	.920	-
Nov.	.263	.236	.367	.610	-	.601	-	.516	.610	-
Dec.	.447	-	.251	.610	-	.618	-	.518	.610	-
			1973					1974		
Jan.	0.600	-	0.605	0.610	-	-	0.709	0.552	0.610	-
Feb.	.530	-	.677	.610	-	0.044	-	.394	.610	-
Mar.	.633	-	.539	.920	-	.514	1.018	.501	.920	-
Apr.	.809	-	.888	.920	-	.479	1.702	.740	.920	-
May	.888	0.553	1.280	.920	-	2.193	1.720	.957	.920	-
June	1.106	1.498	1.209	.920	-	.905	1.371	1.475	.920	-
July	1.322	.617	1.649	.920	-	1.528	1.798	2.298	.920	1.109
Aug.	1.458	1.450	1.882	.920	-	1.505	1.340	2.483	.920	1.233
Sept.	1.475	1.912	1.944	.920	-	1.037	.456	1.567	.920	1.191
Oct.	.274	.875	.693	.920	-	.598	.169	1.139	.920	.311
Nov.	-	.761	.780	.610	-	.526	.037	.646	.610	-
Dec.	-	.524	.714	.610	-	.030	.287	.760	.610	-
			1975					1976		
Jan.	0.284	0.242	0.489	0.610	0.124	0.194	0.145	1.214	0.610	0.017
Feb.	.583	.319	-	.610	.332	.346	.256	.850	.610	.030
Mar.	.513	.292	.281	.920	.395	.529	.266	.498	.920	.307
Apr.	.447	.384	.635	.920	.640	.178	.641	.832	.920	.471
May	.643	.586	1.124	.920	.620	.610	.353	1.308	.920	.892
June	1.008	1.252	1.569	.920	.839	1.107	1.171	2.003	.920	1.230
July	1.320	1.388	2.337	.920	1.105	1.492	1.646	2.580	.920	1.630
Aug.	1.487	1.347	2.633	.920	1.343	1.579	1.852	2.608	.920	2.051
Sept.	.710	.654	1.317	.920	1.384	.839	1.085	1.142	.920	1.166
Oct.	.502	.226	1.142	.920	.023	.272	.687	.914	.920	.842
Nov.	.428	-	.888	.610	-	.325	-	1.265	.610	.416
Dec.	.361	.138	.699	.610	-	.590	-	.236	.610	.495

Explanation:

Pumping center 1 = South End (Ocean City aquifer)
Pumping center 2 = 15th Street (Ocean City aquifer)
Pumping center 3 = 44th Street (Ocean City aquifer)
Pumping center 4 = Convention Hall (Ocean City aquifer)
Pumping center 5 = Gorman Avenue (Manokin aquifer)

(See fig. 16 for location of pumping centers.)

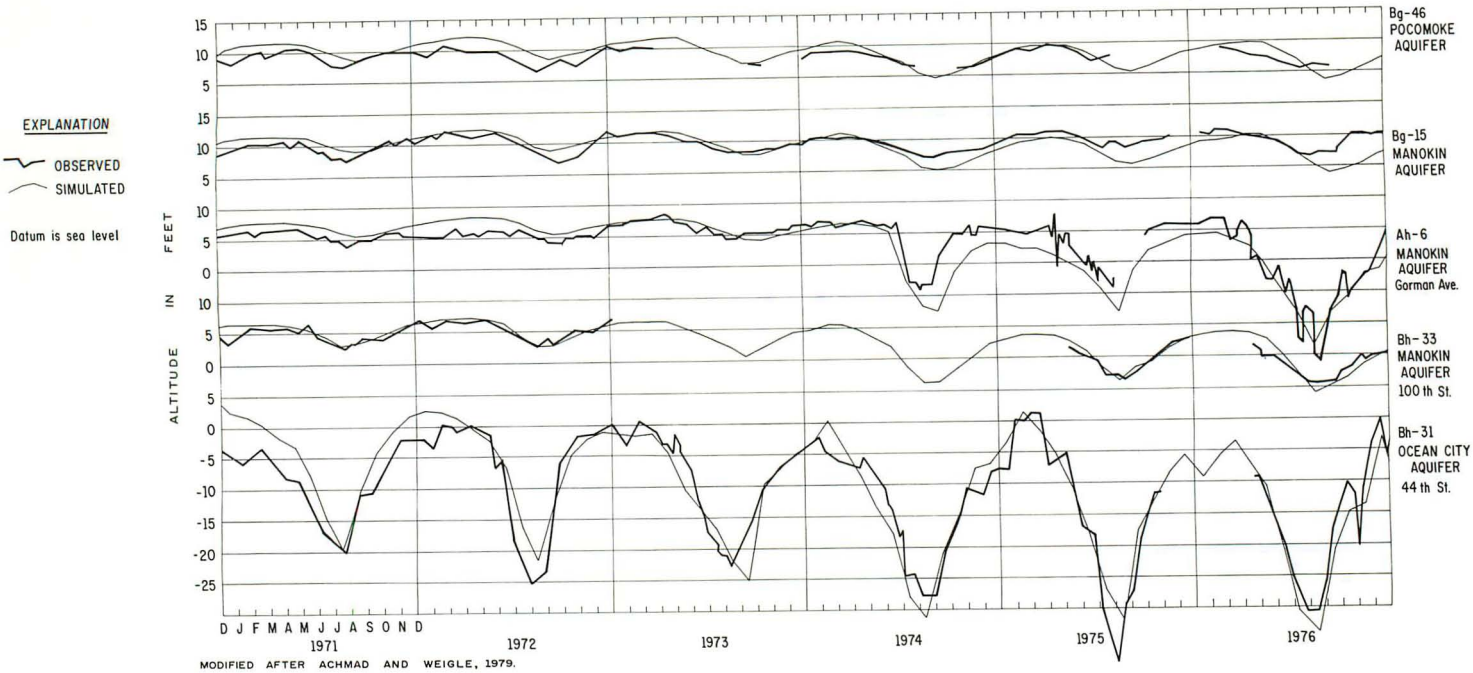


Figure 17.—Observed and simulated hydrographs compared.

In order to evaluate the effect of the constant head-boundary on the simulations, the model was tested using no-flow rather than constant-head conditions on the eastern boundary for the Pocomoke, Ocean City, and Manokin aquifers. Constant heads were retained for the Pleistocene aquifer. The change in boundary conditions caused less than 0.5-ft difference in head for the five observation wells (fig. 17) during simulation of the 1971–76 period. For a simulation using pumpage and conditions of figure 19, the boundary changes caused water levels in hypothetical wells to be 4 to 5 ft deeper than the levels for August 2000 shown in figure 19.

While boundary effects on the magnitudes of simulated water-level declines are probably moderate, the total effects are uncertain. Data, particularly offshore, were not sufficient to develop a fully calibrated model. The relative impacts of the different pumping schemes, however, probably are not significantly affected by the boundaries. The shapes and relative magnitudes of the analyses presented in figures 19, 20, 23, and 24 are probably valid for comparison.

Because no steady-state calibration was performed in simulating the Pleistocene aquifer, the initial conditions are not necessarily in equilibrium. For example, the surface expression of the streams is visible in the initial conditions (fig. 7) even though no streams were simulated. Thus, some of the drawdowns in the predictions may be due to the initial conditions not actually representing equilibrium conditions.

The model uses 1-mile-square grid units. Hydrologic data within each 1-square-mile area are averaged for model input; the model result is limited accordingly. If the grid units were one-tenth of 1 mile square, the potential detail would be much greater, but the cost of obtaining aquifer parameter information and the preparation and operation of the model would also be much greater.

Because of the relatively coarse grid used in the model the contour maps showing simulation results are generalized. The contours represent the average water levels for each 1-mile square in the grid. To assist in assessing detailed head conditions in the vicinity of withdrawal centers, water levels for hypothetical wells representing the well fields are also given on the maps. For that purpose, all the pumping in each well field is assumed to be combined in a hypothetical well which fully penetrates the aquifer, is 100 percent efficient, has a diameter of 24 in., and is located at the center of the node.

PUMPING SCHEMES FOR OCEAN CITY

Ocean City's water needs probably will continue to be supplied from local ground-water sources. Presumably, population and water demands at Ocean City will continue to increase. The sources of ground water most apt to be

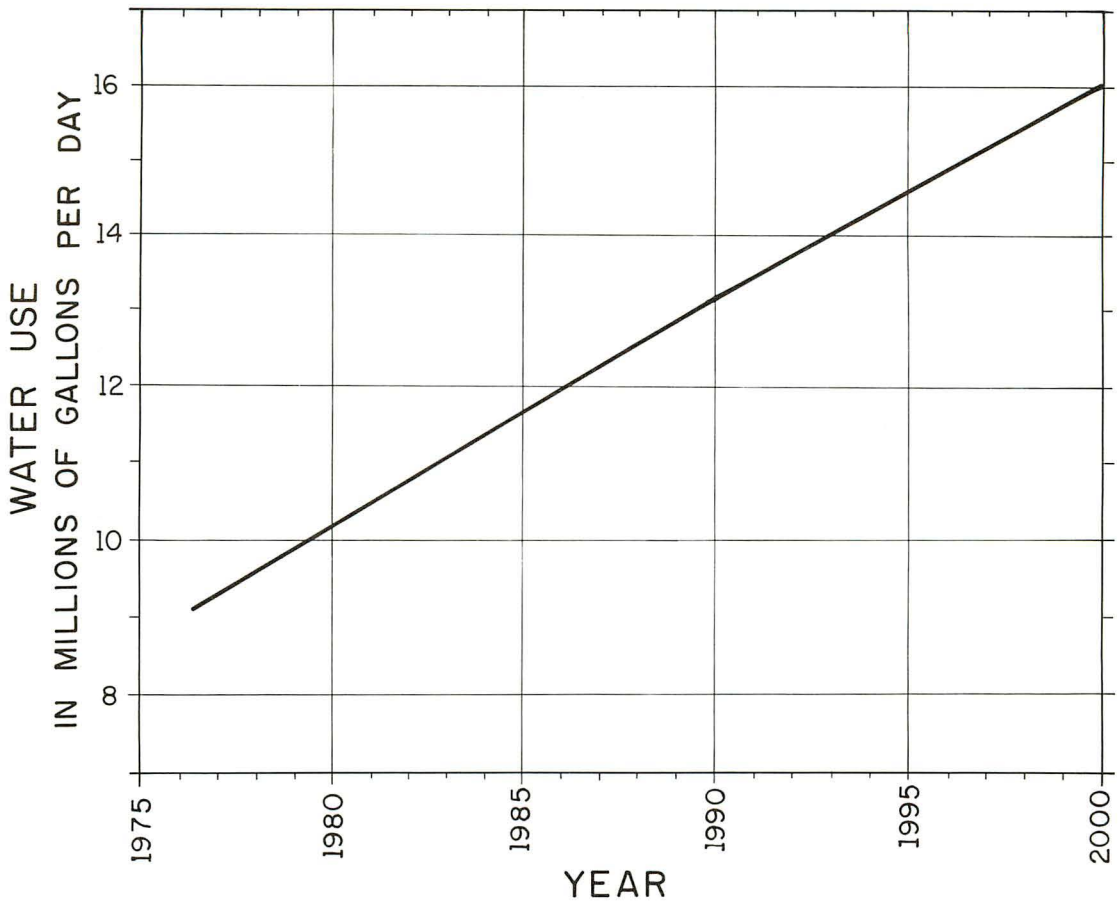


Figure 18.—Projection of water use for Ocean City, for maximum-use month, August. [Based on water-use of 57 gal/d per person in August 1976, and population estimates for 1985 and 2000 by Urban Pathfinders (1976)]

used are the Ocean City and Manokin aquifers, and possibly the Pocomoke aquifer. Simulations discussed in the following sections indicate the relative effects of various pumping schemes to supply these water needs.

Projected Water Needs

A straight-line projection of water needs (fig. 18) was used for the maximum-use month at Ocean City (August) in model simulations for the period 1976–2000. The projection was based on water use of 57 gal/d per person in August 1976, and population estimates for 1985 and 2000 by Urban Pathfinders (1976). Figure 18 indicates the water needs of Ocean City for August 2000 would be 7.0 Mgal/d greater than for August 1976.

The projected water need for August of each year is increased on the basis of the linear trend shown in figure 18. The projected water needs for the remaining months of each year are increased proportionately according to the monthly water-use percentage calculated on the basis of August 1976 water use (table 3) and the projected August water use for each year (fig. 18). Pumpage used in the simulations is updated by 1-month increments. The seasonal pattern of change in withdrawal is thereby incorporated, allowing seasonal recovery of water levels.

The water-use projections used in this study are probably reasonable, but may vary widely from the real future requirements of the area. Different projected water-use data supplied to the model would result in proportionately different results.

Pumping from the Manokin Aquifer at Gorman Avenue

The simulations of figure 19 assume that the additional water needs projected for Ocean City are pumped from the Manokin aquifer at Gorman Avenue, and no other changes are made in the 1976 pumping regimen at other pumping centers in Ocean City. The maps in figure 19 show the potentiometric surfaces for August 1976, and the simulated surfaces for August of

1985, 1990, 1995, and 2000. The withdrawal rate at Gorman Avenue simulated for August of 2000 was 9.0 Mgal/d (7.0 Mgal/d in addition to 2.0 Mgal/d pumped at Gorman Avenue in 1976).

The growth of the cones of depression results primarily from increased withdrawals. Most of the maps in this and the following sections indicate the simulated potentiometric surfaces for the peak of the pumping season during summer months. The potentiometric surfaces differ greatly during winter months, when pumping would be minimal and water levels would have recovered. Winter recovery would decrease in successive years as withdrawals increase. Winter (December) and summer (August) heads simulated for the year 2000 are compared in table 4.

The increased withdrawals for this simulation are assumed to be made only from the Manokin, but the potentiometric surfaces of both the Manokin aquifer and the Ocean City aquifer are affected because of vertical inter-aquifer leakage. The effects of the increased withdrawals at Gorman Avenue extend to southern Ocean City, where the cones of depression in the Manokin and Ocean City aquifers deepen in each successive map shown in figure 19. The figure indicates average heads at nodes representing the well fields; heads in the individual wells would be deeper yet, depending upon the number, spacing, and efficiency of the wells. Estimates of the heads in individual hypothetical wells representing each well field are given in the figure. These heads were estimated by use of a method described by Trescott and others (1976, p. 9), which is an adaptation of the Thiem formula.

It should be pointed out that in this simulation drawdown has reached some of the constant-head nodes on the eastern boundary of the model before the year 2000. As a result, water levels shown in the figure probably reflect minimum drawdowns. (See discussion on Limitations.)

Table 3.—Monthly distribution of total water use at Ocean City for 1976.

Month	1976[1] (Mgal/d)	1976 (percentage of Aug. needs)
January	0.072	0.008
February	.9	.01
March	1.35	.15
April	2.07	.23
May	3.96	.44
June	5.4	.60
July	7.2	.80
August	9.0	1.00
September	5.13	.57
October	3.69	.41
November	1.8	.20
December	2.16	.24

[1]Water use at Ocean City based on city records and on reported use at Convention Hall.

Table 4.—Simulated differences in water level between August and December 2000 at selected nodes. (Pumpage and conditions are those of figure 19.)

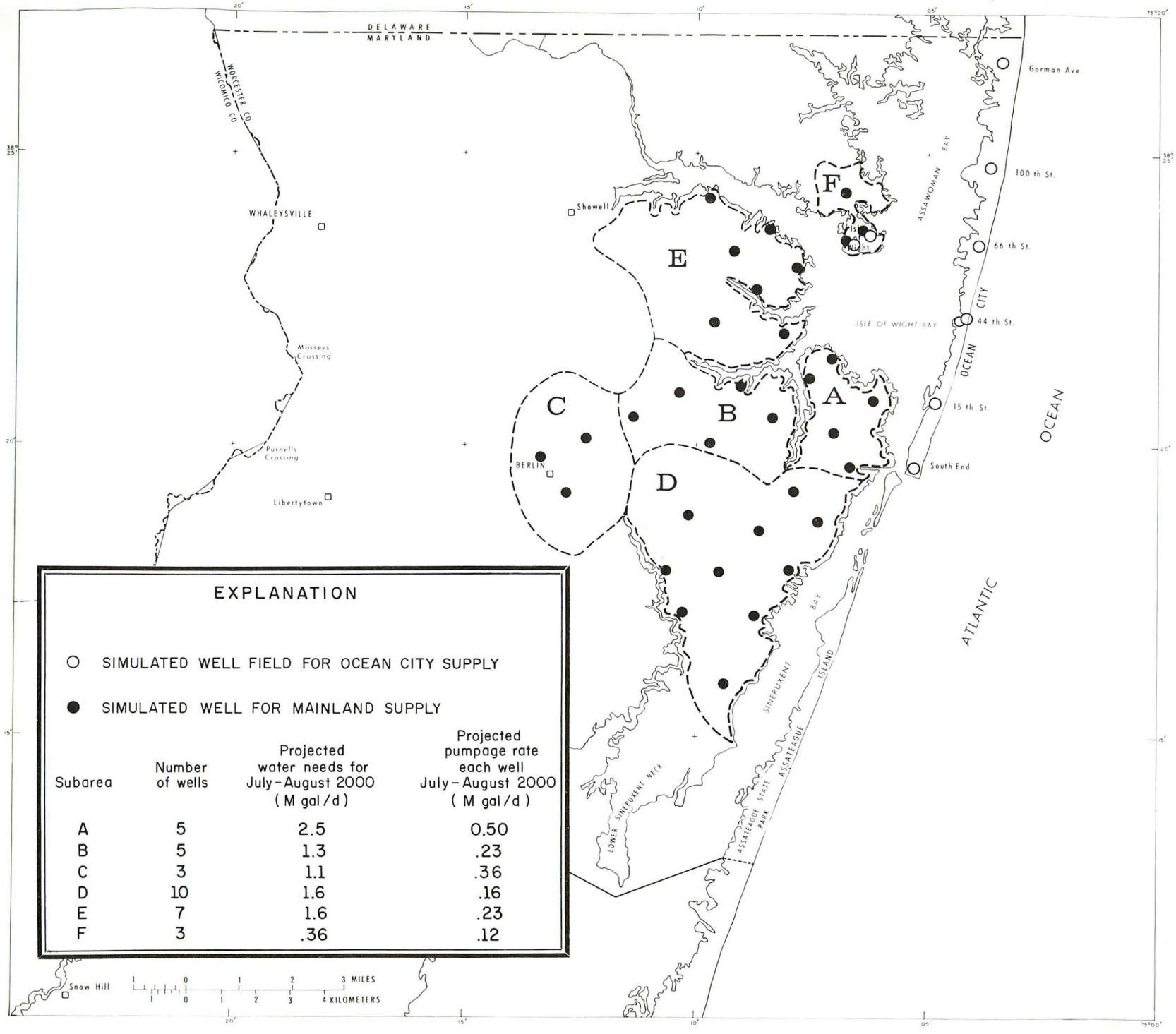
Well represented by node[1]	Aquifer	Difference in water level of August and December 2000 (ft)
Bg-46	Pocomoke	5
Bh-31	Ocean City	36
Bg-15	Manokin	6
Ah- 6	Manokin	54
Bh-33	Manokin	19

[1]Location on figure 3.

Dispersing Withdrawal Centers

Effects on potentiometric surfaces caused by withdrawal can be altered by dispersal of withdrawal centers or by withdrawals from more than one aquifer, or both, without changing the total pumpage. Simulated potentiometric surfaces of the Ocean City and Manokin aquifers for August 2000 are displayed in figure 20 for six different withdrawal schemes. The total pumpage in each scheme is identical and the same as that used for figure 19, but the aquifer source and withdrawal centers vary. Each set of maps shows the potentiometric surfaces resulting from one of the schemes. The location of well fields, aquifer source, and rate of withdrawal appear on the maps. Successive sets of maps correspond to increased dispersion of well fields southward and southwestward from Gorman Avenue and diversification of aquifer sources.

The simulated potentiometric-surface maps indicate that dispersal of sites for the additional withdrawals westward, and southward as far as 66th Street generally would be advantageous with respect to head changes. However, addi-



Subarea	Number of wells	Projected water needs for July-August 2000 (M gal/d)	Projected pumpage rate each well July-August 2000 (M gal/d)
A	5	2.5	0.50
B	5	1.3	.23
C	3	1.1	.36
D	10	1.6	.16
E	7	1.6	.23
F	3	.36	.12

Figure 21.—Well-field distribution plan postulated for the mainland subareas.

tional withdrawals from further south at 15th Street and the South End would cause undesirably large drawdowns in the Ocean City aquifer beneath the southern third of Ocean City (fig. 20b and c), even though the additional withdrawals were made from the Manokin. Presumably, this would be caused by a combination of vertical leakage from the Ocean City aquifer to the Manokin aquifer; preexisting large summer cones of depression associated with both aquifers; and a general southward decrease in transmissivity of those two aquifers beneath Ocean City.

A map of the simulated potentiometric surface of the Pocomoke aquifer for August 2000 is shown in figure 20g. Although little or no water is withdrawn from the Pocomoke aquifer at Ocean City, the map shows a cone of depression in its potentiometric surface. The cone indicates vertical leakage downward from the Pocomoke, in response to the lowered heads in the underlying Ocean City and Manokin aquifers. The Pocomoke would be affected to a similar degree by the other pumping schemes.

Results of two withdrawal plans as shown in figure 20d and f indicate the effects of relatively well-balanced arrangements of well fields and aquifer sources. In both plans, the Manokin aquifer cone of depression centered at Gorman Avenue is spread out and relatively shallow, signifying a corresponding relaxation in hydraulic stress. The pumping arrangements corresponding to figure 20d and f call for withdrawing the additional water at Gorman Avenue, the Isle of Wight, 100th Street, and 66th Street in the amounts and from the aquifers as noted in the maps.

The pumping schemes discussed in this section ignore the potential interference from increased pumping to satisfy mainland needs. Effects of this pumping are discussed in the following section.

Effects of Withdrawals for Mainland Needs

Population and associated water needs on the mainland near Ocean City will almost certainly increase, although the rates will probably be different from the rates for Ocean City. The effects of increased withdrawals for the mainland were combined in the model with those already illustrated for Ocean City, where pumping arrangements similar to those shown in figure 20d and f were used. Maps of the resulting potentiometric surfaces are shown in figures 23 and 24. These represent minimum drawdowns as discussed under "Limitations." They may be compared with corresponding maps in figure 20, to show the additional effects produced on the potentiometric surfaces when increased withdrawals for the mainland are also considered.

Present and future water needs of the mainland were estimated on the basis of the planning reports for Worcester County by George, Miles and Buhr (1975) and Urban Pathfinders (1976); and on the water-quality management plan for the Ocean Coastal Basin prepared by the Maryland Department of Natural Resources (1976).

In Worcester County, aside from Ocean City, the greatest increases in population and water needs through the year 2000 probably will occur in the areas adjacent to, west and southwest of Isle-of-Wight Bay. Those areas are divided into six subareas and shown in figure 21.

The water needs vary from one subarea to another, and between the summer peak (July-August) and the winter needs (mid-October thru mid-April). In general, the seasonal disparity increases with proximity to Ocean City. Because of that variation, water needs for each subarea were projected through the year 2000 (fig. 22). In each case, two projections were made: peak summer needs, and winter or off-season needs. Needs during the transitional months of May, June, September and October were assumed to be gradational between peak and off-season values. Those patterns served as guides for distributing the water needs proportionately among the individual months of any one year, once the peak and off-season values for the year were determined.

Hypothetical pumping sites for the nearby mainland (fig. 21) were arranged so that the projected water needs for each subarea could be met by withdrawals within that subarea. This is one of many possible arrangements. It permits some dispersal of withdrawal sites, thereby decreasing the likelihood of excessively concentrated drawdown and its attendant disadvantages. At the same time, it permits some concentration of pumping and treatment facilities, which is economically advantageous.

Figure 21 shows the nearby mainland wellfield distribution plan tested by the model and the projected July-August water needs for the year 2000 for each subarea. The total projected July-August need for the nearby mainland for the year 2000 is 8.51 Mgal/d.

Figure 23 illustrates the effects of providing all of the nearby mainland water needs from the Manokin aquifer. Pumping rates for mainland needs are as shown in figure 22 and pump-

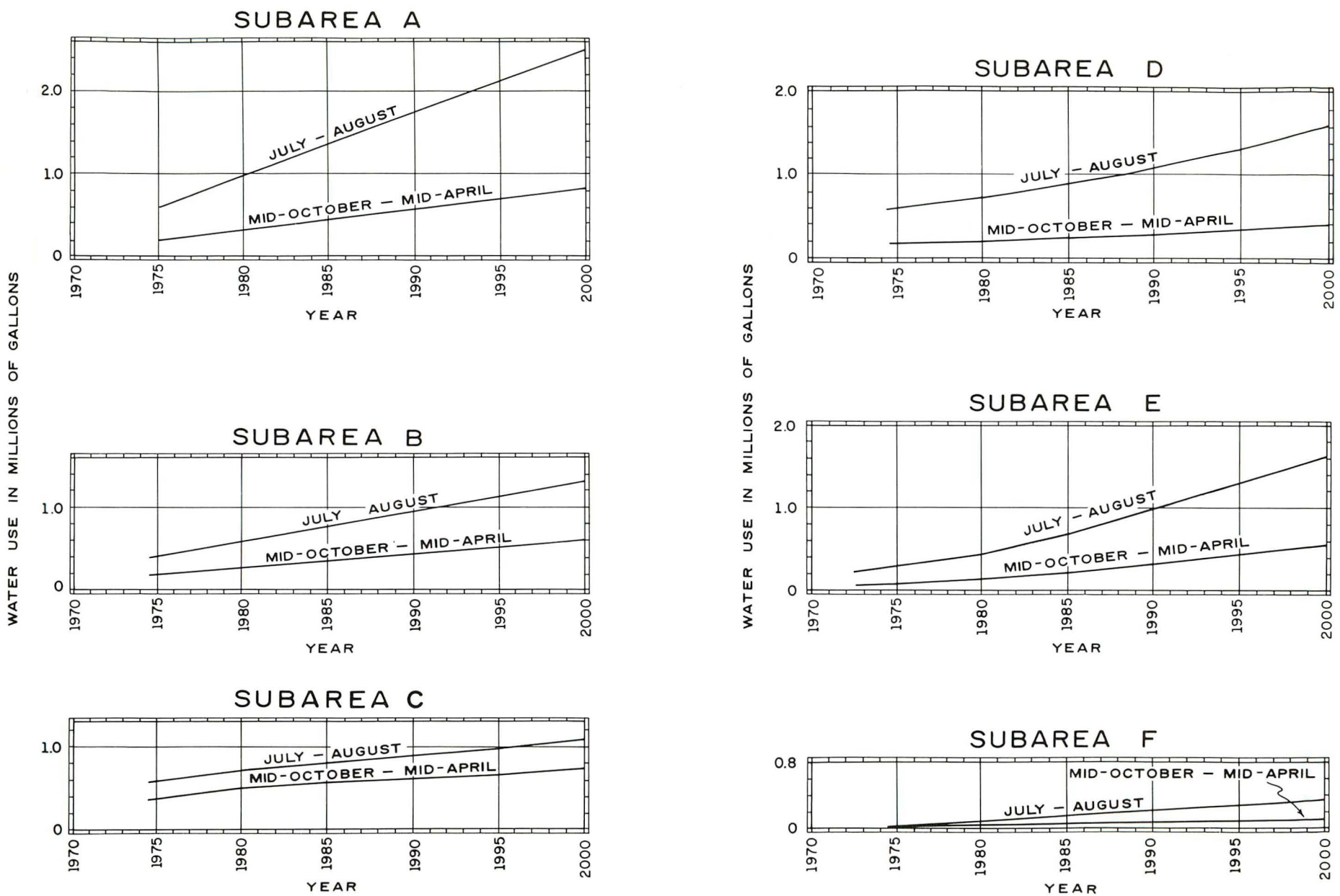


Figure 22.—Projected water-use trends in the mainland subareas near Ocean City.

ing rates for Ocean City needs are as shown in figure 20f (except that all Isle of Wight pumping is from the Ocean City aquifer). Results of this simulation show that the cone of depression in the Manokin aquifer is deeper and is shifted westward from Ocean City toward the mainland. The cones of depression in the Ocean City and Pocomoke aquifers are also deeper.

Figure 24 shows simulated effects of withdrawing all water for the nearby mainland needs from the Pocomoke aquifer. Pumping rates for mainland needs are as in figure 22 and pumping rates for Ocean City needs are the same as for figure 23.

Comparison of figures 8, 23, and 24 shows that satisfying mainland water needs from the Manokin or Pocomoke will cause water levels in the Pocomoke aquifer to be considerably lower than those in the Pleistocene aquifer in much of the area. As a result, water would move downward from the Pleistocene into the Pocomoke aquifer through the confining bed separating the aquifers, through discontinuities or permeable areas in the confining bed. One known discontinuity of the confining bed with undetermined shape and extent is located approximately one-half mile north of Berlin, Md. (Weigle, 1974). Salty water, which occurs locally in the Pleistocene aquifer, conceivably could enter the Pocomoke aquifer under those head conditions.

Hydraulic stress could be reduced by dispersing some of the withdrawal sites farther westward or northwestward, thereby reducing the possibility of salt-water intrusion.

Figures 23 and 24 show drawdown effects only for the summer (August), when water demand is greatest. Water levels recover during winter months, and maps for those months would show considerably less drawdown.

Because of the greater stress, boundary effects for these simulations are more severe than for the other simulations. Therefore, the model results should be interpreted with caution.

HYDROLOGIC INFORMATION OBTAINED DURING THIS STUDY

Much of the data necessary for modeling was already available and described by Lucas (1972) and Weigle (1974), but some additional information was obtained during this study. Seventeen test holes (table 5) ranging in depth from 118 to 728 ft were drilled and logged geophysically. Undisturbed cores taken during drilling provided information on the vertical hydraulic conductivity and other physical characteristics of the confining beds. Pore water was squeezed from the cores and analyzed. Results of chemical analyses of water obtained from the aquifers and confining beds are shown in table 6.

Of the 17 test wells, 11 were converted to observation wells. These and several other wells were used to extend the observation-well network.

Some of the observation wells were drilled close together in small clusters or nests, each nest including two or three wells drilled to different depths. Four such nests were drilled to serve as calibration points for vertical leakage between aquifers (fig. 3).

Some earlier observation wells, for which 2- or 3-year hydrographs have already been published, were maintained as observation wells during this study. Seven or more years of water-level records are available for those wells, with which the seasonal drawdown and recovery effects and long-term water-level fluctuations were observed.

In 1976, acoustical profiles of sediments were made offshore from Ocean City and Delaware (fig. 25) in cooperation with the Delaware Geological Survey. The profiles are on file at the offices of the U.S. Geological Survey in Towson, Md. and Woods Hole, Mass., and at the Delaware Geological Survey in Newark, Del. The marine acoustical results were used to determine the seaward extension of the onshore geologic structure (fig. 26).

Two profiles in particular (GD 1 and GD 2) were of help in that respect. They trend eastward and east-southeastward from Ocean City (fig. 25). Interpretation of those profiles, based on slope, continuity, and parallelism of acoustically reflective surfaces suggests that the Manokin and St. Marys units continue eastward and southeastward from Ocean City without major structural change. The reflective surfaces corresponding to the Ocean City aquifer and overlying beds suggest that a low, convex structure about 2¼ mi wide occurs 7.6 mi east of Ocean City, on the line of the profile.

As part of the U.S. Geological Survey Atlantic Continental Margin Coring Project in 1976, a test hole was drilled to a depth of 396 ft below sea bottom, 8.75 mi east of Ocean City (fig. 26) on the location line of one of the profiles (Hathaway and others, 1976; 1979). The test hole was abandoned because of a hurricane, but core samples from the test hole aided in interpreting the acoustical profiles.

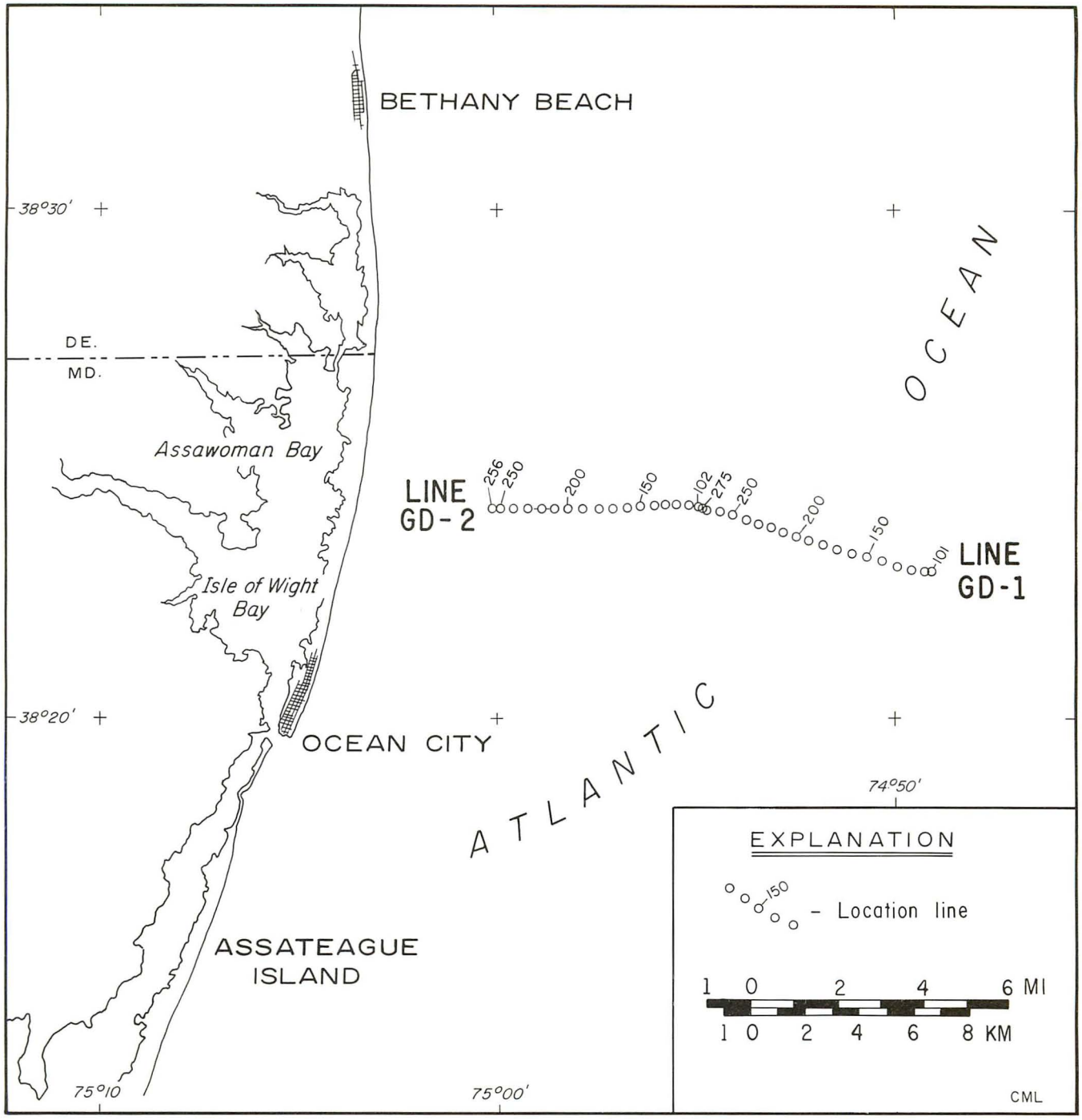


Figure 25.—Location lines of marine acoustical profiles run in 1976.

SALTY WATER IN THE MANOKIN AQUIFER

In this report, water having a chloride concentration of more than 250 mg/L is termed "salty water" and water with a lower chloride concentration is termed "fresh." In northeastern Worcester County, water from the base of the Pleistocene deposits down to the base of the Manokin aquifer is fresh except for that in the lowermost few feet of the Manokin in northern Ocean City. Ground water in the Pleistocene deposits, which are 90 to 160 ft thick, is also fresh in most of the area, but those deposits are susceptible to local salt-water contamina-

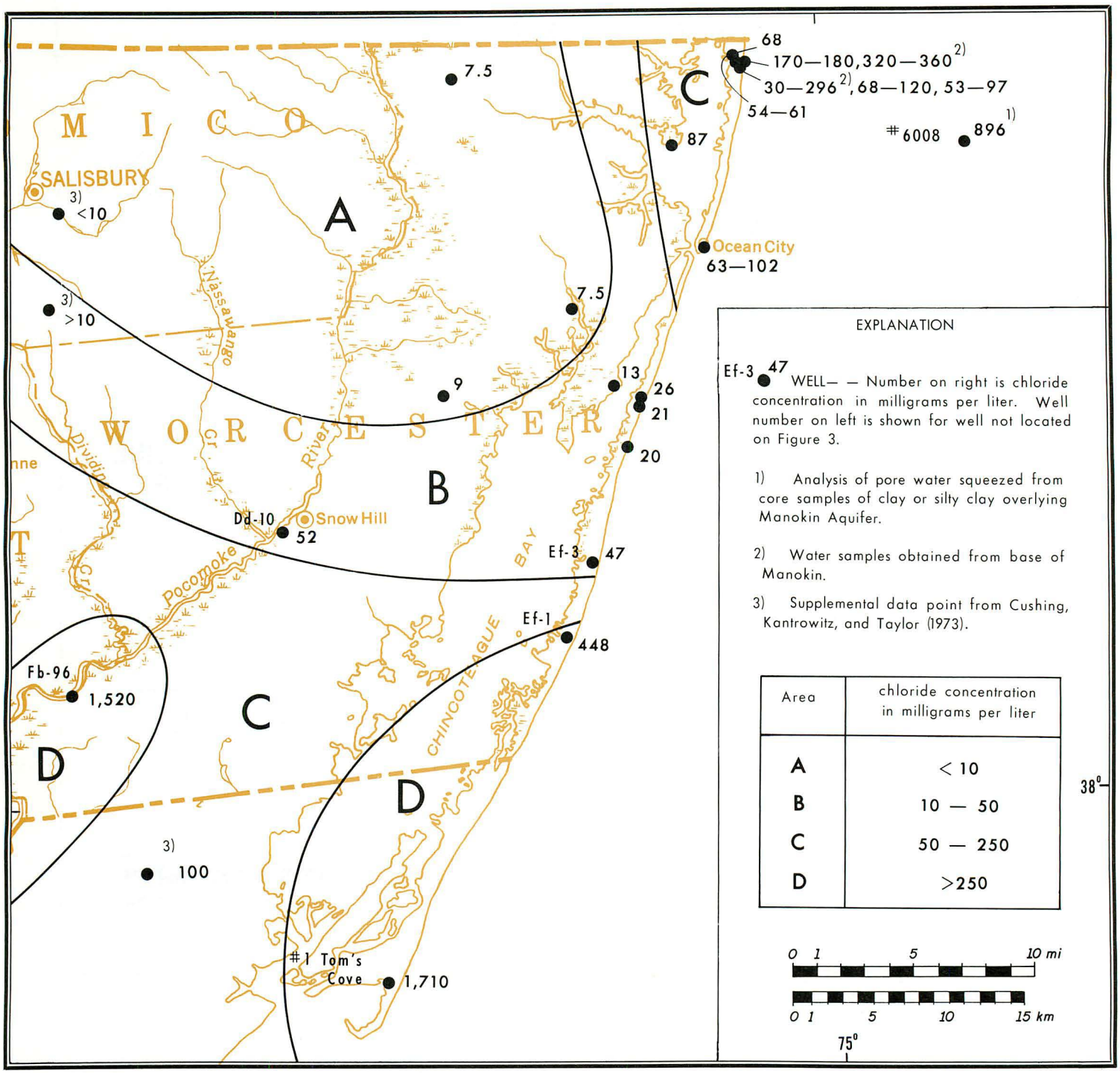


Figure 27.—Chloride concentration of water samples from the Manokin aquifer.

tion near the coast. Weigle (1974) presents more detailed discussion of salty water related to the individual aquifers in northeastern Worcester County. In the current report, attention is focused on salty water in the Manokin aquifer.

The salty water in the basal part of the Manokin aquifer at Ocean City may have two sources: (1) upward leakage from the underlying St. Marys Formation, which contains salty water; and (2) an offshore salt-water front in the Manokin aquifer. At Ocean City, salty water is not known to occur in the Manokin aquifer except in the basal part, and is not known to occur in the overlying Ocean City or Pocomoke aquifers. Salty water has been reported in parts of the Pleistocene aquifer at Ocean City (Weigle, 1974).

Figure 27 shows chloride concentrations in water in the Manokin aquifer at various locations where data are available. These data tend to show the highest values and do not show the variation of chloride concentration with depth in the aquifer at these locations. For instance, the 360 mg/L value at the northern Ocean City site represents only the bottom few feet of the aquifer at the site (fig. 5).[1] The 1,520 mg/L value near Pocomoke City is at a site where the full thickness of the aquifer is saturated with salty water.

During this study, test drilling (table 5), water sampling (table 6), and monitoring of chloride concentrations in selected wells were conducted in the vicinity of Gorman Avenue, in order to determine the extent of the salty water and possible changes in chloride concentrations in wells constructed in the Manokin aquifer. The results, when considered with information from earlier studies, indicate that the zone of salty water in the bottom part of the Manokin in northern Ocean City thins westward, and probably thickens eastward (fig. 27). The results also indicate that in the zone of salty water, the chloride concentration increases downward fairly rapidly; and that the concentration near the bottom is greater at sites where the zone of salty water is thicker. The chloride-concentration values for samples collected October 26–27, 1976, from wells Wor-Ah 36 and AH 37 (25 ft away) increased downward from 180 mg/L to 340 mg/L in a vertical distance of 26 ft (fig. 5).

Water samples collected weekly by the Ocean City Water Department, from wells (Wor-Ah 33 and 34) screened in the Manokin aquifer at Gorman Avenue, were analyzed chemically by the Worcester County Sanitary Commission at Ocean City. The chloride concentrations and the monthly combined pumpage at the Gorman Avenue well field were plotted against time, as shown in figure 28. During the winters of 1974–75 and 1975–76, the chloride concentrations decreased sharply, but the decreases were short-lived. The chloride concentration began to rise steeply even before pumping resumed, and soon rose to their previous levels when pumping continued. The chloride concentration at well Ah 33 attained higher levels during each of the two following summers, coinciding with increased pumpage. During the period 1974–77, the trend in chloride concetration in wells Ah 33 and Ah 34 was upward, owing to upconing of salty water in the basal part of the Manokin aquifer. Subsequently (1978 and 1979), the trend apparently leveled off although data are not conclusive.

Chloride concentrations were monitored also in wells in the Ocean City aquifer at 44th Street, 15th Street, and at the south end of Ocean City. From 1975 to 1978 the chloride concentrations in those wells fluctuated, but showed no general rise or decline. The concentration ranged from approximately 30 mg/L to 80 mg/L, and fluctuations were generally less than 10 mg/L.

A general depth-related change in the chemical character of water from the Frederica and Manokin aquifers and the St. Marys Formation is shown in figure 29. Water samples were obtained from the St. Marys Formation by squeezing cores.

The chloride-concentration values for water samples squeezed from clay cores obtained from offshore well 6008 (fig. 25) decreased downward from 15,352 to 896 mg/L in a vertical interval of 340 ft (table 6). The decreasing chloride concentrations in the clayey confining beds at this site located 8.75 miles due east of Ocean City are most probably related to upward leakage of fresh water from the underlying Manokin aquifer.

[1]Chloride values are for water samples obtained from material whose thicknesses ranged from about 1 in (squeezed core samples) to more than 100 ft (pumped wells). Refer to table 5 for screened thicknesses.

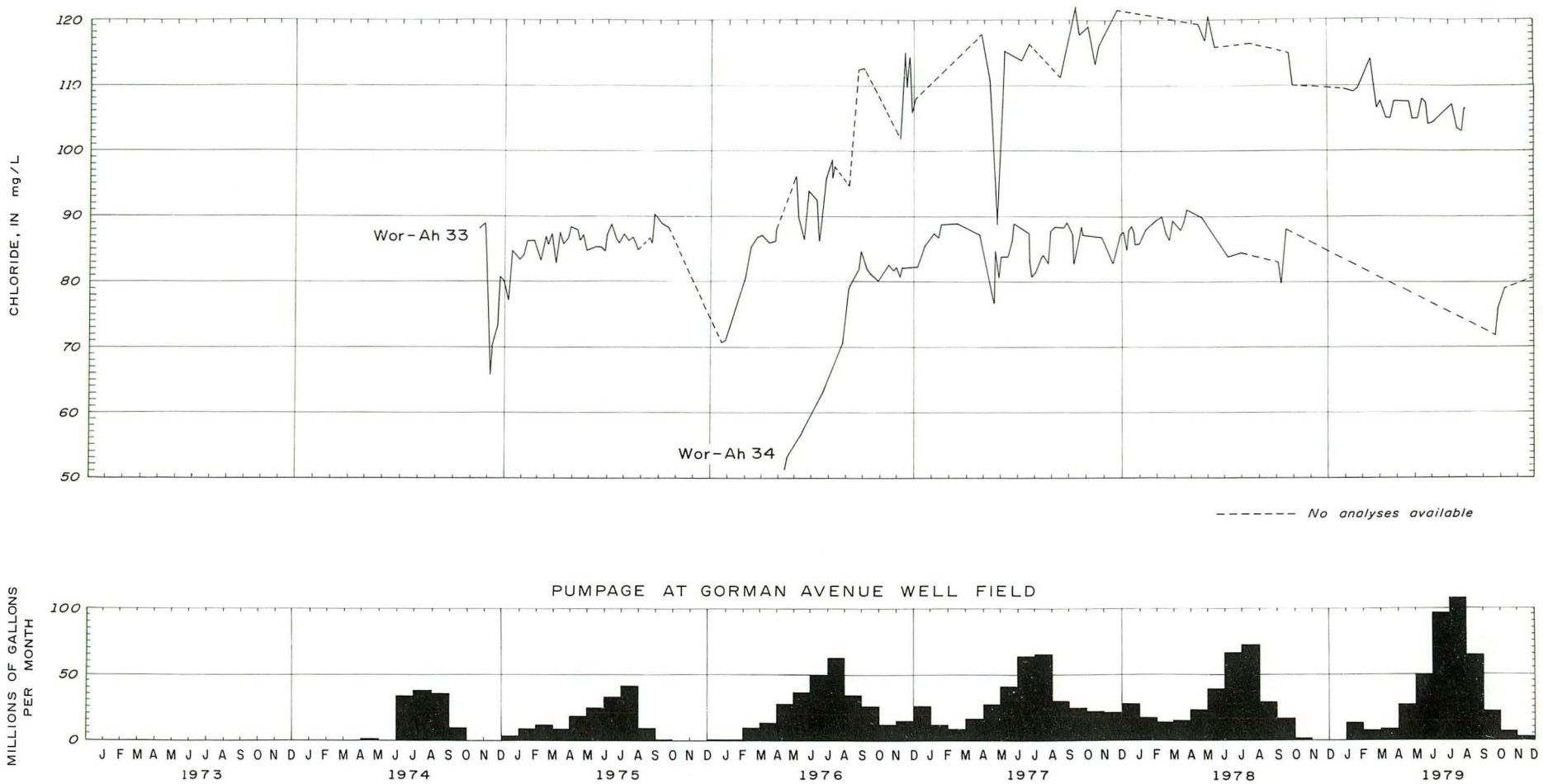


Figure 28.—Comparison of chloride concentration and pumpage of water from the Manokin aquifer at Gorman Avenue well field.

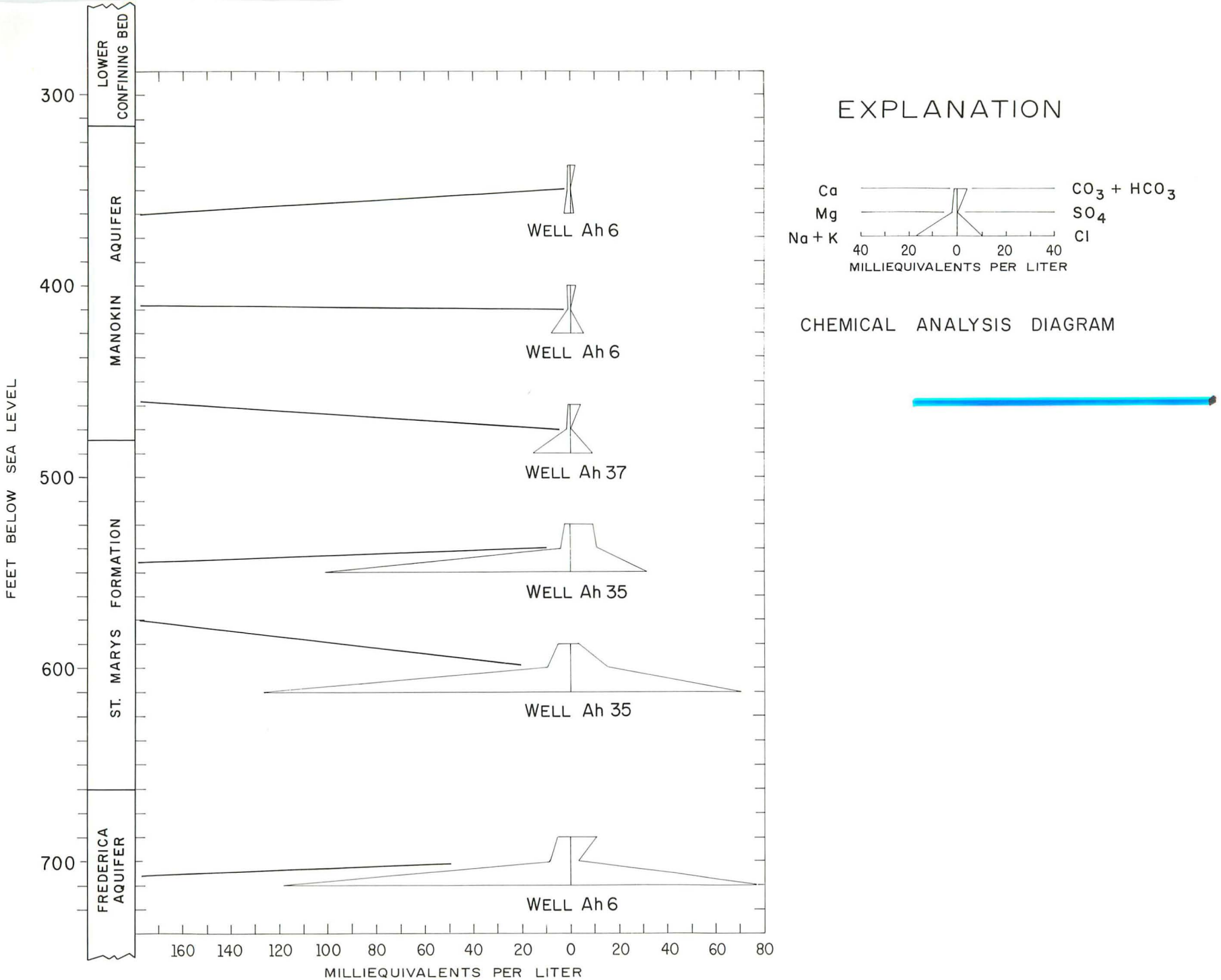


Figure 29.—Comparison of chemical character of water from Frederica and Manokin aquifers and St. Marys Formation. (Analyses in table 6).

CONCLUSIONS

Fresh ground water in northeastern Worcester County is restricted to a block of sediments about 450 ft thick. The top of the block is the land surface, and the base is at or a few feet above the contact between the St. Marys Formation and the overlying Manokin aquifer. Within that block, water occurs under water-table and semiconfined conditions in the Pleistocene aquifer, and under confined conditions in the Pocomoke, Ocean City, and Manokin aquifers. Those four fresh-water aquifers comprise a leaky multiaquifer system.

Interaquifer leakage is extensive in northeastern Worcester County, and is potentially important in some places. In the vicinity of Ocean City, for example, the effectiveness of the several confining layers between the Manokin aquifer and the Pleistocene aquifer is poor. There, long-continued large-scale withdrawals from the Manokin aquifer probably would cause vertical leakage from the overlying units, thereby raising the possibility of salty-water intrusion from above.

Water needs for Ocean City and the nearby mainland are expected to increase substantially and most of this water will probably be withdrawn from the fresh-water aquifers of the area. Simulation of alternate ground-water development plans with a partially calibrated digital model indicates that dispersal of pumping centers may spread the drawdown cones out and thereby reduce the magnitudes of the drawdown. Simulated withdrawal of additional water needs from well fields at Gorman Avenue, the Isle of Wight, 100th Street, and 66th Street appears to produce more moderate drawdowns than the other pumping schemes that were run on the model. This model, however, did not evaluate the movement of salty water in the aquifers.

Excessive hydraulic stress in the aquifer system at Ocean City is of special significance because of the presence of salty water in the nearby ocean and bays, the possible occurrence of salty water offshore in the aquifers, and the presence of salty water in the basal part of the Manokin aquifer. The salty water in the basal part of the Manokin aquifer probably came from the underlying St. Marys Formation, but it remains possible that the salty water may be associated with an offshore salt-water front in the aquifer. No evidence of increase in chloride concentration was found in the Ocean City, Pocomoke or Pleistocene aquifer, but chloride concentrations of water from the Manokin aquifer at Gorman Avenue did increase when pumping began in 1974. This increase was probably from upconing of the salty water at the base of the aquifer, and further increases could occur. The chloride concentration of water from wells constructed in the Ocean City aquifer at 44th Street and southward in Ocean City ranged from approximately 30 mg/L to 80 mg/L in 1975–78, and showed minor fluctuations but no trend. Chloride concentrations at Gorman Avenue wells Ah 33 and Ah 34 (in the Manokin aquifer) tend to vary with pumping rates, and ranged between about 50 mg/L and 120 mg/L during 1973–78. The chloride concentration at the base of the Manokin at Gorman Avenue (well Ah 37) was 360 mg/L in December 1976.

The Ocean City-Manokin aquifer system was traced seaward, tentatively, more than 7 miles east of Ocean City, based on the results of offshore acoustical profiling of sub-bottom sediments in May and offshore test drilling in August 1977.

SUGGESTIONS FOR FURTHER STUDY

Monitoring the effects of pumping requires continued measurement of water levels, pumpage, and chloride concentrations of the water.

Salt-water intrusion probably is a major factor in the development of fresh ground-water supplies in the Ocean City area. Therefore, knowledge of the distribution of salty water in the basal part of the Manokin aquifer is important. Test drilling to the bottom of the Manokin at 66th, 100th, and 44th Streets and on the Isle of Wight probably would help delineate the extent of the salty water. A solute-transport model probably can be used to estimate the possibility of salty water upconing in the basal part of the Manokin aquifer.

Hydrologic study of the Pleistocene deposits will help delineate areas where the upper part of the deposits functions as a confining bed, and intervening areas where recharge can occur more readily. These data would help to evaluate the potential for contamination of the aquifer system from the land surface.

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GROUND-WATER DATA

Table 5—Description of selected wells and test holes.

Well Number	State Permit Number	Owner or name	Driller	Date Completed	Altitude of Land Surface (Feet Above Sea Level)	Method of Construction	Depth of Well (Feet)	Diameter of Well (Inches)	Depth of Bottom of Casing or Top of Screen (Feet Below Land Surface)	Total Screen Length (Feet)	Principal Water Bearing Unit
Ae 19	WO-72-6	U.S. Geological Survey	Ideal Well Drillers	7/21/71	40	Dr	503	6	---	---	---
Ae 23	WO-73-0512	Madison Gray	Delmarva Drilling Company	9/17/75	40	Dr	290	4 - 2	270	10	Mk
Ae 24	WO-73-0513	Madison Gray	Delmarva Drilling Company	9/19/75	40	Dr	210	4 - 2	190	10	O.C.
Ae 25	WO-73-0514	Madison Gray	Delmarva Drilling Company	9/19/75	40	Dr	120	4 - 2	108	10	Poc.
Ah 6	WO-70-9	U.S. Geological Survey	Delmarva Drilling Company	1969	5	Dr	357	6	347	10	Mk
Ah 33	WO-72-0062	Ocean City	Shannahan Artesian Well Company	4/22/72	5	Dr	450	18 - 12	346	104	Mk
Ah 34	WO-72-0059	Ocean City	Shannahan Artesian Well Company	5/1/72	5	Dr	450	18 - 12	350	100	Mk
Ah 35	WO-73-0516	Ocean City	Delmarva Drilling Company	10/23/75	12	Dr	728	4 - 2	716	10	Fr
Ah 36	WO-73-0518	Ocean City	Delmarva Drilling Company	10/31/75	13	Dr	455	4 - 2	420.5	10	Mk
Ah 37	WO-73-0517	Ocean City	Delmarva Drilling Company	12/10/75	10	Dr	478	4 - 2	468	10	Mk
Ah 38	WO-73-0689	Ocean City	C. Z. Enterprises	8/26/76	5	Dr	507	18 - 12	335	100	Mk
Ah 39	WO-73-0690	Ocean City	C. Z. Enterprises	7/28/76	5	Dr	506	18 - 12	330	100	Mk
Bf 63	WO-73-0192	U.S. Geological Survey	Paul White	12/6/73	30	Dr	520	6	---	---	---
Bg 47	WO-73-0521	U.S. Geological Survey	Delmarva Drilling Company	8/27/75	5	Dr	300	4 - 2	258	10	O.C.
Bg 48	WO-73-0522	U.S. Geological Survey	Delmarva Drilling Company	9/4/75	5	Dr	440	4 - 2	410	10	Mk
Bg 49	WO-73-0520	U.S. Geological Survey	Delmarva Drilling Company	10/16/75	10	Dr	255	4 - 2	234	10	O.C.
Bh 84	WO-73-0094	Ocean City	Ideal Well Drillers	4/18/73	5	Dr	89	4	81	5	Pleist.
Bh 85	WO-73-0095	Ocean City	Ideal Well Drillers	4/20/73	5	Dr	203	4	190	5	Poc.
Ce 31		U.S. Geological Survey	Delmarva Drilling Company	6/13/72	25	Dr	1040	9	---	---	---
Cg 68	WO-73-0191	U.S. Geological Survey	Paul White	1/3/74	10	Dr	720	6	---	---	---
Cg 69	WO-73-0064	Mystic Harbour Dev. Company	Delmarva Drilling Company	3/24/73	10	Dr	235	6	215	---	O.C.
De 36	WO-73-0515	Newark Fire Station	Delmarva Drilling Company	9/11/75	30	Dr	340	4 - 2	320	10	Mk
Dg 20	WO-73-0560	Assateague State Park	Delmarva Drilling Company	10/3/75	6	Dr	640	6	---	---	---
Dg 21	WO-73-0519	Assateague State Park	Delmarva Drilling Company	10/9/75	6	Dr	370	4 - 2	300	10	Mk

Method of Construction

Dr - Hydraulic rotary

Principal Water Bearing Unit

Fr - Frederick aquifer
Mk - Manokin aquifer
O.C.- Ocean City aquifer
Pleist. - Pleistocene aquifer
Poc. - Pocomoke aquifer

Table 5.—Description of selected wells and test holes—continued.

Water Level				Yield						
Feet Above or Below Land Surface	Date Measured	Use	Type of Pump	Gallons per Minute (gpm)	Duration of Test (Hrs.)	Drawdown (Feet)	Date	Specific Capacity (gpm/foot of Drawdown)	Remarks	Well Number
---	---	T	N	---	---	---	---	---	D, L, Lg.	Ae 19
13	9/17/75	T	N	35 (est.)	3/4	5	9/17/75	7.0	Lg, O, Q. Cores taken.	Ae 23
11	9/18/75	T	N	35 (est.)	1/2	7.5	9/19/75	4.7	O, Q. Cores taken.	Ae 24
---	---	T	N	---	---	---	---	---	O, Q. Cores taken.	Ae 25
+2	8/-/69	T	N	---	---	---	---	---	L, Lg, O, Q. Logged 1210 ft.	Ah 6
+0.53	4/26/72	PS	T	800	20	18.6	3/30-31/72	43.0	Lg, Q.	Ah 33
+0.44	4/26/72	PS	T	815	20	17.1	4/26-27/72	47.4	L, Lg, Q. T 16° C.	Ah 34
6.35	3/30/75	T	N	---	---	---	---	---	Lg, O. Cores taken.	Ah 35
15.43	3/30/75	T	N	50	1 1/3	---	10/31/75	---	Lg, O, Q.	Ah 36
14.20	3/30/75	T	N	25 (est.)	2	---	10/30/75	---	Lg, O, Q. Cores taken.	Ah 37
13	8/26/76	PS	T	1400	8	35	8/26/76	---	L, Lg, Q.	Ah 38
11	7/28/76	PS	T	1400	8	42	7/28/76	---	L, Lg, Q.	Ah 39
---	---	T	N	---	---	---	---	---	D, L, Lg.	Bf 63
9.02	8/28/75	T	N	---	---	---	---	---	Lg, O, Q.	Bg 47
---	---	T	N	---	---	---	---	---	L, Lg, O, Q. Cores taken.	Bg 48
9.72	10/16/75	T	N	15	---	---	10/16/75	---	L, Lg, O, Q.	Bg 49
4.94	4/18/73	T	N	150-175 (est.)	1/3	---	4/18/73	---	O, Q.	Bh 84
---	---	T	N	---	---	---	---	---	Lg, O, Q.	Bh 85
---	---	T	N	---	---	---	---	---	D, L, Lg.	Ce 31
---	---	T	N	---	---	---	---	---	D, L, Lg.	Cg 68
6.40	4/11/74	PS	N	160	8+	125	---	---	Lg, O.	Cg 69
---	---	T	N	---	---	---	---	---	Lg, O, Q. Cores taken. Low yield of water.	De 36
---	---	T	N	---	---	---	---	---	D, Lg. Cores taken.	Dg 20
3.50	10/9/75	T	N	---	---	---	---	---	O. Cores taken.	Dg 21

Use

T - Test
PS - Public Supply

Type of Pump

T - Turbine
N - None

Remarks

D - Destroyed
L - Descriptive log in Table 7
Lg - Geophysical log available
O - Observation well
Q - Chemical analysis in Table 6

Table 6—Chemical analyses of ground water from northeastern Worcester County and surrounding areas.

USGS WELL NO.	AQUIFER	DATE OF SAMPLE	SAMPLING DEPTH (FT.)	TEMPERATURE (DEG. C)	COLOR (PLATINUM-COBALT UNIT)	SPECIFIC CONDUCTANCE (MICRO-MHO)	PH (UNIT)	BICARBONATE (mg/l AS HCO3)	PHOSPHORUS, TOTAL (mg/l AS P)	HARDNESS (mg/l AS CaCO3)	HARDNESS, NONCARBONATE (mg/l AS CaCO3)	CALCIUM DISSOLVED (mg/l AS Ca)
Ae 23	Manokin	75-09-17	270-280	13.7	85	--	---	68	.13	41	0	12
Ae 24	Ocean City	75-09-17	190-200	13.7	20	--	---	270	.50	200	0	76
Ae 25	Pocomoke	75-09-19	108-118	13.5	230	--	---	290	.45	220	0	86
Ah 2	Pleistocene	53-08-31	8.0	--	--	249	6.5	13	--	34	23	--
Ah 3	Pleistocene	53-08-31	72	--	--	436	7.3	141	--	149	33	--
Ah 6	Manokin	69-07-24	474	22.0	5	1430	8.4	296	--	167	0	42
Ah 6	Manokin	76-12-21	347-357	15.5	50	--	---	112	.46	90	0	26
Ah 6	Frederica	69-07-14	708-718	--	--	8900	8.4	584	--	653	141	100
Ah 33	Manokin	73-09-12	346-450	--	--	420	6.5	111	--	80	0	22
Ah 33	Manokin	74-08-06	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	74-11-18	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	74-11-20	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-06-11	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-06-17	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-07-30	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-08-27	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-08-28	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-09-03	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-09-05	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	75-09-10	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	76-03-08	do.	15.0	360	550	7.1	122	.20	84	0	22
Ah 33	Manokin	76-08-03	do.	19.0	100	--	6.7	116	.25	82	0	23
Ah 33	Manokin	76-09-02	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	76-12-17	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	76-12-21	do.	--	--	--	---	---	--	---	---	---
Ah 33	Manokin	77-05-26	do.	17.5	55	--	---	91	.07	---	---	---
Ah 34	Manokin	72-04-26	350-450	--	--	--	---	---	--	---	---	---
Ah 34	Manokin	72-04-27	do.	16.0	20	341	7.5	109	--	80	0	23
Ah 34	Manokin	76-05-17	do.	--	--	--	---	---	--	---	---	---
Ah 34	Manokin	76-09-02	do.	--	--	--	---	---	--	---	---	---
Ah 34	Manokin	76-09-22	do.	--	--	--	---	---	--	---	---	---
Ah 34	Manokin	76-10-26	do.	16.5	--	480	---	---	--	---	---	---
Ah 34	Manokin	76-12-07	do.	--	--	--	---	---	--	---	---	---
Ah 34	Manokin	77-04-21	do.	17.0	300	--	---	100	.21	---	---	---
Ah 34	Manokin	77-05-26	do.	17.5	150	--	---	110	.16	---	---	---

Table 6—Chemical analysis of ground water from northeastern Worcester County and surrounding areas.—continued.

MAGNESIUM DISSOLVED (mg/l AS Mg)	SODIUM DISSOLVED (mg/l AS Na)	POTASSIUM DISSOLVED (mg/l AS K)	CHLORIDE DISSOLVED (mg/l AS Cl)	SULFATE DISSOLVED (mg/l AS SO4)	FLORIDE DISSOLVED (mg/l AS F)	SILICA DISSOLVED (mg/l AS SiO2)	IRON, TOTAL RECOVERABLE (ug/l AS Fe)	IRON, DISSOLVED (ug/l AS Fe)	MANGANESE, TOTAL RECOVERABLE (ug/l AS Mn)	MANGANESE, DISSOLVED (ug/l AS Mn)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (mg/l)	SOLIDS, SUM OF CONSTI-TUENTS, DISSOLVED (mg/l)	NITROGEN, NITRATE DISSOLVED (mg/l AS NO3)	USGS WELL NO.
2.6	9.4	2.9	7.5	1.7	.1	28	5200	---	110	---	---	98	.18	Ae 23
2.6	7.4	1.3	10	2.3	.2	28	12000	---	90	---	---	261	.04	Ae 24
1.8	8.3	.7	12	3.0	.1	31	13000	---	120	---	---	286	.09	Ae 25
---	---	---	55	14	--	--	20	---	---	---	---	---	1.	Ah 2
---	---	---	66	1.2	--	--	230	---	---	---	---	---	.9	Ah 3
15.0	228	13	296	7.2	.3	58	910	---	50	---	801	812	---	Ah 6
6.0	21	3.6	30	1.7	.1	35	83000	82000	270	260	286	261	.0	Ah 6
98	1690	65	2710	149	.8	51	---	2100	---	40	5240	---	3.3	Ah 6
6.2	52	4.7	68	.0	.2	32	7000	---	210	---	---	243	3.1	Ah 33
---	---	---	81	---	--	--	12000	---	---	---	---	---	---	Ah 33
---	---	---	88	---	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	79	---	--	--	13000	---	---	---	---	---	---	Ah 33
---	---	---	88	2.1	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	88	2.1	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	89	1.2	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	90	1.6	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	90	1.5	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	90	1.6	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	91	1.7	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	89	1.0	--	--	---	---	---	---	---	---	---	Ah 33
7.0	60	4.7	91	5.9	.0	32	14000	---	170	---	---	283	.18	Ah 33
6.0	65	4.9	99	.1	.1	33	13000	14000	150	160	327	302	.58	Ah 33
---	---	---	94	---	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	120	---	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	120	---	--	--	---	---	---	---	---	---	---	Ah 33
---	---	---	87	.3	.1	33	5200	---	150	---	272	---	3.8	Ah 33
---	---	---	55	---	--	--	---	---	---	---	---	---	---	Ah 34
5.6	38	4.7	53	.0	.1	33	12400	---	180	---	216	---	.30	Ah 34
---	---	---	56	.5	--	--	---	---	---	---	---	---	---	Ah 34
---	---	---	97	---	--	--	---	---	---	---	---	---	---	Ah 34
---	---	---	83	---	--	--	14000	---	---	---	---	---	---	Ah 34
---	---	---	84	---	--	--	---	---	---	---	---	---	---	Ah 34
---	---	---	87	---	--	--	---	---	---	---	---	---	---	Ah 34
---	---	---	88	2.1	.1	33	1900	---	140	---	276	---	3.7	Ah 34
---	---	---	80	.5	.3	34	1900	---	130	---	267	---	4.2	Ah 34

Table 6—Chemical analysis of ground water from northeastern Worcester County and surrounding areas.—continued.

USGS WELL NO.	AQUIFER	DATE OF SAMPLE	SAMPLING DEPTH (FT.)	TEMPERATURE (DEG. C)	COLOR (PLATINUM-COBALT UNIT)	SPECIFIC CONDUCTANCE (MICRO-MHO)	PH (UNIT)	BICARBONATE (mg/l AS HCO3)	PHOSPHORUS, TOTAL (mg/l AS P)	HARDNESS (mg/l AS CaCO3)	HARDNESS, NONCARBONATE (mg/l AS CaCO3)	CALCIUM DISSOLVED (mg/l AS Ca)
Ah 35 1/	St. Mary's	75-03-30	560-561	--	--	5650	---	593	--	---	---	52
Ah 35	St. Mary's	75-03-30	590-591	--	--	9000	---	162	--	---	---	102
Ah 36	Manokin	75-10-03	420½-430½	15.4	140	---	---	130	.28	110	6	34
Ah 36	Manokin	76-10-26	do.	17.0	--	---	---	---	--	---	---	---
Ah 37 1/	Pleistocene	75-03-30	54-55	--	--	9075	---	5	--	---	---	318
Ah 37	Manokin	75-10-30	468-478	15.5	41	---	---	210	.31	110	0	21
Ah 37	Manokin	76-10-27	do.	12.0	--	1430	---	---	--	---	---	---
Ah 37	Manokin	76-12-17	do.	--	--	1490	---	---	--	---	---	---
Ah 38	Manokin	76-08-03	335-435	19.0	120	400	6.7	107	.22	77	0	24
Ah 38	Manokin	76-08-26	do.	--	--	---	---	---	--	---	---	---
Ah 38	Manokin	76-08-26	do.	--	--	---	---	---	--	---	---	---
Ah 39	Manokin	76-08-03	330-430	19.0	45	450	6.8	104	.23	88	3	27
Bg 47	Ocean City	76-10-28	258-268	16.5	35	---	---	116	.27	68	0	15
Bg 48	Manokin	76-10-28	410-420	17.0	60	485	---	130	.29	70	0	15
Bg 49	Ocean City	75-10-16	234-244	14.7	6	---	---	245	.13	120	0	33
Bh 1	Ocean City	51-12-12	272	--	5	434	7.2	226	--	158	---	37
Bh 8	Pocomoke	51-12-17	176	--	10	413	7.8	229	--	130	---	29
Bh 81	Ocean City	71-06-16	297	--	35	407	---	136	--	91	0	15
Bh 84	Pleistocene	73-04-18	81-86	--	--	338	7.9	132	--	88	0	17
Bh 84	Pleistocene	76-10-27	do.	16.0	--	---	---	---	--	---	---	---
Bh 85	Pocomoke	73-04-20	190-195	--	--	412	8.0	166	--	93	0	16
Bh 85	Pocomoke	76-10-27	do.	17.5	--	---	---	---	--	---	---	---
Cg 5	Pocomoke	52-01-04	180	15.6	28	325	7.3	183	--	79	0	18
Cg 6	Ocean City-Manokin	52-01-11	285	--	--	414	7.6	220	--	140	0	---
Cg 35	Manokin	71-12-20	240	14.5	--	353	7.9	200	--	124	0	---
Cg 72 3/	Manokin	78-03-28	377-445	--	3	425	6.8	144	3.2	56	---	8.3
Dd 10	Manokin	52-05-27	346	--	2	612	7.9	303	--	63	0	16
De 36	Manokin	75-09-11	320-330	15.5	14	340	---	210	.25	110	0	36
Dg 5	Ocean City-Manokin	53-09-10	150	15.5	--	614	7.4	290	--	115	0	---
Dg 7	Ocean City-Manokin	67-05-12	270-300	15.3	3	422	8.0	254	.2	151	0	39
Dg 8	Ocean City-Manokin	67-11-03	290-310	17	5	516	8.4	305	--	54	0	12
Dg 10	Manokin	71-12-20	313	15.5	--	472	8.2	258	--	134	0	---

Table 6—Chemical analysis of ground water from northeastern Worcester County and surrounding areas.—continued.

MAGNESIUM DISSOLVED (mg/l AS Mg)	SODIUM DISSOLVED (mg/l AS Na)	POTASSIUM DISSOLVED (mg/l AS K)	CHLORIDE DISSOLVED (mg/l AS Cl)	SULFATE DISSOLVED (mg/l AS SO4)	FLORIDE DISSOLVED (mg/l AS F)	SILICA DISSOLVED (mg/l AS SiO2)	IRON, TOTAL RECOVERABLE (ug/l AS Fe)	IRON, DISSOLVED (ug/l AS Fe)	MANGANESE, TOTAL RECOVERABLE (ug/l AS Mn)	MANGANESE, DISSOLVED (ug/l AS Mn)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (mg/l)	SOLIDS, SUM OF CONSTI-TUENTS, DISSOLVED (mg/l)	NITROGEN, NITRATE DISSOLVED (mg/l AS NO3)	USGS WELL NO.
49	1450	57	1155	1038	--	---	---	256	---	---	---	---	---	Ah 35
109	1725	8.4	2450	760	--	---	---	50	---	---	---	---	---	Ah 35
6.8	110	6.1	170	2.3	.2	31	13000	---	150	---	---	424	4.3	Ah 36
---	---	---	180	---	--	---	15000	---	---	---	---	---	---	Ah 36
198	1250	2.6	2925	348	--	---	---	5100	---	---	---	---	---	Ah 37
15	220	11	320	6.5	.2	29	4900	---	80	---	---	726	3.5	Ah 37
---	---	---	340	---	--	---	4300	---	---	---	---	---	---	Ah 37
---	---	---	360	---	--	---	---	---	---	---	---	---	---	Ah 37
4.1	39	4.0	54	.2	.1	33	17000	17000	170	180	268	228	.31	Ah 38
---	---	---	61	---	--	---	---	---	---	---	---	----	---	Ah 38
---	---	---	61	---	--	---	---	---	---	---	---	---	---	Ah 38
5.0	39	4.0	63	.1	.1	34	15000	15000	180	190	273	239	.04	Ah 39
7.3	56	5.8	68	.7	.1	36	7400	100	120	120	224	246	.00	Bg 47
8.0	65	7.1	87	1.2	.2	37	4300	400	100	100	267	285	.00	Bg 48
10	37	10	17	2.9	.2	23	2200	---	50	---	---	254	1.2	Bg 49
16	27	12	30	2.0	.1	24	2900	---	0	---	260	---	.1	Bh 1
14	36	10	20	.1	.1	28	1300	---	0	---	260	---	.7	Bh 8
13	44	11	59	8.0	.2	30	4800	---	120	---	248	248	.7	Bh 81
11	30	8.1	39	6.0	.3	33	11000	---	120	---	---	211	1.2	Bh 84
---	---	---	39	---	--	---	6300	---	---	---	---	---	---	Bh 84
13	41	14	46	5.0	.5	6.6	19000	---	270	---	---	224	.30	Bh 85
---	---	---	46	---	--	---	4400	---	---	---	---	---	---	Bh 85
8.3	39	9.2	16	.8	.2	32	1300	---	0	---	214	214	.1	Cg 5
---	---	---	26	1.0	.2	---	1400	---	---	---	---	---	.2	Cg 6
---	23	.7	7.5	.0	.2	29	---	---	---	---	215	---	.1	Cg 35
8.6	70	3.	63-102	1.1	.2	24.8	678	---	21	---	265	---	1.5	Cg 72
5.6	113	6.4	52	2.5	.1	17	70	---	16	---	381	---	.6	Dd 10
5.1	29	3.7	9.3	1.8	.3	30	2600	---	110	---	---	219	.27	De 36
---	---	---	60	1.2	--	---	270	---	---	---	---	---	.2	Dg 5
13	35	7.6	13	1.4	.1	32	990	---	---	---	264	266	.2	Dg 7
5.8	102	8.6	20	.6	.2	13	260	---	10	---	323	320	.7	Dg 8
---	49	10	21	.4	.1	16	---	---	---	---	260	---	.7	Dg 10

Table 6—Chemical analysis of ground water from northeastern Worcester County and surrounding areas.—continued.

USGS WELL NO.	AQUIFER	DATE OF SAMPLE	SAMPLING DEPTH (FT.)	TEMPERATURE (DEG. C)	COLOR (PLATINUM-COBALT UNIT)	SPECIFIC CONDUCTANCE (MICRO-MHO)	PH (UNIT)	BICARBONATE (mg/l AS HCO3)	PHOSPHORUS, TOTAL (mg/l AS P)	HARDNESS (mg/l AS CaCO3)	HARDNESS, NONCARBONATE (mg/l AS CaCO3)	CALCIUM DISSOLVED (mg/l AS Ca)
Dg 21	Manokin	75-10-09	300-310	16.0	2	365	---	272	.21	150	0	39
Ef 1	Ocean City-Manokin	53-09-10	172	15.5	---	2090	8.2	440	---	228	0	---
Ef 3	Ocean City-Manokin	53-09-10	167	15.5	21	776	8.1	430	---	51	0	12
Fb 96	Manokin	70-07-12	201	----	5	5580	8.0	328	---	590	330	96
6008 1/ 2/ Off Ocean City	Pleistocene (?)	76-08-09	30	21.5	---	---	7.1	---	---	---	---	639
6008 1/ 2/	Pleistocene (?)	76-08-09	60	22.5	---	---	7.5	---	---	---	---	425
6008 1/ 2/	Pleistocene (?)	76-08-09	90	23.5	---	---	7.5	---	---	---	---	551
6008 1/ 2/	(?)	76-08-09	120	22.5	---	---	7.8	---	---	---	---	439
6008 1/ 2/	(?)	76-08-09	171	24.0	---	---	8.4	---	---	---	---	121
6008 1/ 2/	(?)	76-08-09	236	23.5	---	---	---	---	---	---	---	263
6008 1/ 2/	(?)	76-08-09	267	23.6	---	---	8.0	---	---	---	---	162
6008 1/ 2/	(?)	76-08-09	370	----	---	---	---	---	---	---	---	527
Tom's Cove, Well #1, (Va.)	Ocean City-Manokin	67-05-25	208-213	15.6	3	5810	7.8	281	.0	464	233	44

1/ Analysis of pore water squeezed from core samples of clay and silty clay.

2/ Offshore well drilled 8.75 miles off Ocean City.

3/ Analysis made by Worcester County Sanitary District.

Table 6—Chemical analysis of ground water from northeastern Worcester County and surrounding areas.—continued.

MAGNESIUM DISSOLVED (mg/l AS Mg)	SODIUM DISSOLVED (mg/l AS Na)	POTASSIUM DISSOLVED (mg/l AS K)	CHLORIDE DISSOLVED (mg/l AS Cl)	SULFATE DISSOLVED (mg/l AS SO4)	FLORIDE DISSOLVED (mg/l AS F)	SILICA DISSOLVED (mg/l AS SiO2)	IRON, TOTAL RECOVERABLE (ug/l AS Fe)	IRON, DISSOLVED (ug/l AS Fe)	MANGANESE, TOTAL RECOVERABLE (ug/l AS Mn)	MANGANESE, DISSOLVED (ug/l AS Mn)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (mg/l)	SOLIDS, SUM OF CONSTI-TUENTS, DISSOLVED (mg/l)	NITROGEN, NITRATE DISSOLVED (mg/l AS NO3)	USGS WELL NO.
13	44	8.9	26	2.0	.1	21	1000	---	50	--	---	288	1.2	Dg 21
--	--	--	448	34	--	--	80	---	--	--	---	---	1.0	Ef 1
4.7	162	8.0	47	.1	.4	15	360	---	20	--	491	---	.2	Ef 3
86	945	32	1520	307	.2	11	---	---	--	--	3300	3160	5.2	Fb 96
963	8463	283	15352	1847	--	--	---	---	--	--	---	---	---	6008
977	7793	237	13927	1913	--	--	---	---	--	--	---	---	---	6008
545	4608	175	8871	709	--	--	---	---	--	--	---	---	---	6008
312	2110	205	4625	251	--	--	---	---	--	--	---	---	---	6008
44	164	37	231	230	--	--	---	---	--	--	---	---	---	6008
142	586	40	1594	100	--	--	---	---	--	--	---	---	---	6008
--	--	--	---	---	--	--	---	---	--	--	---	---	---	6008
106	353	60	896	1098	--	--	---	---	--	--	---	---	---	6008
86	1090	46	1710	226	.7	3.7	---	90	--	20	3450	3360	1.2	Tom's Cove

Table 7—Logs of wells and test holes.

Wor-Ae 19 (Altitude: 39 ft)
Geologist's log

	Thickness (ft)	Depth (ft)
Pleistocene deposits:		
Sand, fine, tan-gray	15	15
Sand, fine, dark gray	5	20
Sand, fine to medium, gray, and bits of shell	10	30
Sand, fine to very fine, gray, biotitic	9	39
Clay, greenish-white, and coarse sand; shell fragments	2	41
Sand, light gray, and white shell fragments	9	50
Sand, fine, gray	10	60
Sand, coarse to very coarse, tan-gray (greenish or straw hue). Scattered fine pebbles of chert	20	80
Sand, coarse, tan-gray	10	90
Sand, coarse, tan-gray and shell fragments	10	100
Pocomoke aquifer:		
Sand, very coarse, clean, olive-gray	1	101
Sand, very coarse, clean, olive-gray, and shell fragments	19	120
Sand, very coarse, clean, brown-gray	10	130
Lower confining bed:		
Sand, very coarse, and dark-blue clay; interbedded	10	140
Sand, very coarse, interbedded with dark blue-gray clay; pieces of black wood	20	160
Sand, fine, dark brown-gray, and "solid" clay; large pieces of black wood	15	175
"Quicksand", very fine, tight, and a 5-inch-thick layer of finely divided dark-brown wood	5	180
Sand, interbedded fine and coarse, medium-dark; pieces of black wood	10	190
Ocean City aquifer:		
Sand, coarse, medium-dark gray, and pieces of black wood	20	210
Sand, coarse, and small pieces of black wood	10	220
Sand, fine, medium-dark, interbedded with very fine gravel	10	230
Sand, coarse, medium-dark gray, and shell fragments	10	240
Sand, coarse to very coarse, clean, medium-dark gray; some ivory-colored chert	7	247

(Wor-Ae 19, cont.)

	Thickness (ft)	Depth (ft)
Lower confining bed (lower part):		
Clay; black wood pieces 1/2 inch by 1 inch long, some pieces of obsidian(?)	13	260
Manokin aquifer:		
Sand, coarse, and fine gravel; medium-dark gray	35	295
Sand, fine, medium-dark gray; fragments of black lignite	20	315
Sand, coarse to very coarse, clean, dark gray; and some fine gravel	45	360
Sand, very fine, silty, olive-gray; shell fragments	20	380
St. Marys Formation:		
Clay, dark gray, and fine, gray sand	20	400
Clay, dark gray ("gun metal" with green-blue tint); some gray sand	24	424
Silt, fine to very fine sand, gray; many white shell fragments	9	433
Same, but Turritella noted	7	440
Silt, fine-sandy, gray; many shell fragments	20	460
Sand, fine, silty, gray, salt-and-pepper appearance; abundant shell fragments including Turritella; brittle, black wood particles	30	490
Sand, fine, gray, and shell fragments	13	503

Table 7—Logs of wells and test holes—continued.

Wor-Ah6 (Altitude: 5 ft)
Log of drill cuttings (Kantrowitz, 1969)

	Thickness (ft)	Depth (ft)
Sand, very fine, silty, gray	20	20
Sand, very fine to fine, gray; some clay, medium sand, and gravel	20	40
Sand, very coarse, with gravel, gray to white; some gray clay	20	60
Sand, very coarse, with gravel; streaks of clay	20	80
Sand, very coarse, with gravel; streaks of gray clay	20	100
Sand, very coarse, gray-white, and fine gravel	20	120
Clay, greenish gray, and gravel	20	140
Clay, greenish gray, shell fragments; some streaks of gray medium sand	40	180
Sand, medium, gray, and gray clay; abundant shell fragments	20	200
Sand, fine to medium, and gray clay with shells	20	220
Sand, fine to medium, gray; some clay with shells	20	240
Sand, fine to medium, and clay with shells	20	260
Clay, gray, with abundant shell fragments, and sand and gravel	20	280
Clay, gray, with abundant shell fragments; some sand and gravel	20	300
Clay, gray, with abundant shell fragments	40	340
Sand, very coarse to fine gravel, gray; streaks of greenish-gray clay with shells	20	360
Sand, very coarse to fine gravel; some shells and gray clay	20	380
Sand, very coarse to fine gravel; some woody material	20	400
Sand, very coarse; some fine gravel	40	440
Sand, very coarse to fine gravel	20	460
Sand, very fine; some clay	20	480
Sand, very fine, silty; some clay	20	500
Silt and very fine sand, some clay	20	520
Silt and clay; some very fine sand and shell fragments	20	540
Silt and clay; shell fragments; some very fine sand and coarse sand	20	560
Clay, white-gray with shell fragments	40	600
Clay, white-gray, some shell fragments	20	620
Clay, white-gray; some shell fragments and fine sand	40	660
Clay and fine to medium sand; some shell fragments and coarse sand	20	680
Clay and medium to coarse sand	20	700
Sand, coarse to very coarse; abundant shell fragments; some fine to medium sand, fine gravel, and clay	20	720

(Wor-Ah6, cont.)

	Thickness (ft)	Depth (ft)
Sand, coarse; abundant shell fragments; some fine to medium sand, very coarse sand, and clay	20	740
Clay with abundant shell fragments; some fine sand	20	780
Clay with shells, and medium to coarse sand	20	800
Sand, medium to very coarse; some clay and shells	20	820
Clay, shell fragments, and medium sand	20	840
Clay, gray; some fine sand and shell fragments	20	860
Clay, gray, with shell fragments	20	880
Clay, gray, very abundant shell fragments	20	900
Clay, silty, with fine sand, some shell fragments	20	920
Sand, very fine, silty and clayey; shell fragments and some fine to coarse sand	20	940
Clay and very fine to fine sand; shell fragments	20	960
Clay; shell fragments and some very fine to fine sand	20	980
Clay; some very fine to fine sand and shell fragments	20	1,000
Clay; some very fine to fine sand	20	1,020
Clay; some very fine to fine sand and shell fragments	20	1,040
Clay and very fine to fine sand; some medium sand and shell fragments	20	1,060
Clay and shell fragments	30	1,090
Silt and very fine sand	30	1,120
Clay, sandy	20	1,140
Silt and very fine sand	40	1,180
Clay; some sand	30	1210

Table 7—Logs of wells and test holes—continued.

Wor-Ah34 (altitude: 5 ft)
Driller's log

	Thickness (ft)	Depth (ft)
Stones, wood, and sand	5	5
Sand, Gray	5	10
Sand, white and brown, and clay	9	19
Clay, gray	5	24
Clay, sandy, green; sand streaks	26	50
Sand, white and gray	43	93
Clay, gray	8	101
Sand, white and brown	20	121
Clay, "tough", white	19	140
Clay, soft, green	27	167
Clay, sandy, green, and shells	8	175
Clay, green	30	205
Sand, white and gray; and shells, clay, and wood	55	260
Clay, shell, and wood	20	280
Sand, clay, and wood	20	300
Clay, shell, and wood	33	333
Sand, clay,and wood	10	343
Sand, medium-white and gray and some brown	115	458
Sand and clay	10	468
Clay, sandy	9	477
Clay and sand	11	488

Wor-Ah38 (Altitude: 5 ft)
Driller's log

	Thickness (ft)	Depth (ft)
Sand, white	1	1
Clay, black	2	3
Sand, brown; clay layer	15	18
Clay, gray	6	24
Clay, gray; and sand	5	29
Sand, fine, white	12	41
Sand, coarse, white	33	74
Sand, coarse, white, and gravel; and thin layers of clay	49	123
Clay, gray, wood, and layers of sand	56	179
Clay, gray, wood, and layers of shell	33	212
Sand, gray, wood, and shell; "hard spots"	46	258
Clay, wood, shell, and layers of sand	22	280
Sand and wood; a few "hard spots"	26	306
Sand, coarse, gray; wood, and shell. A few "hard spots"	45	351
Sand, coarse, gray, and shell	39	390
Wood	6	396
Sand, wood, and shell; "hard spots"	42	438
Sand, medium-coarse, clean	42	480
Clay, gray	27	507

Table 7—Logs of wells and test holes—continued.

Wor-Ah39 (Altitude: 5 ft)
Driller's log

	Thickness (ft)	Depth (ft)
Fill	5	5
Wood, including logs	3	8
Sand, white	5	13
Clay, gray	4	17
Sand, and layers of gray clay	21	38
Sand, coarse, white; and shell	51	89
Sand, wood, shell, and "small" gravel	35	124
Clay, gray	5	129
Gravel, coarse; shell; and layers of clay	38	167
Clay, gray; wood; and layers of clay	41	208
Sand, hard-packed, gray; and layers of wood	29	237
Sand, coarse, hard-packed, gray	64	301
Sand, coarse and fine and wood, "mixed"; "hard spots"	111	412
"Hard spot"	5	417
Sand, medium-coarse, gray	14	431
Sand, hard-packed, gray; "hard spots"	48	479
Clay, gray	27 1/2	506 1/2

Wor-Bf63 (Altitude: 30 ft)
Geologist's log

	Thickness (ft)	Depth (ft)
Pleistocene deposits:		
Sand, yellow to yellow-brown	8	8
Clay, light gray	6	14
Clay and sand	11	25
Sand, coarse to very coarse and fine gravel, tan-gray. Pebbles mostly clear, gray, or milky quartz; and subangular, polished, black, aphanitic pieces of volcanic (?) rock	41	66
Sand, coarse to very coarse, and fine gravel; thin beds of tough, light-gray clay	22	88
Sand, coarse to very coarse, and fine to medium gravel; clean; tan-gray	32	120
Sand, fine to very coarse and fine to medium gravel, tan-gray; mostly fine to medium sand	38	158
Pocomoke aquifer:		
Sand, medium to coarse, and fine gravel; tan-gray	37	195
Lower confining bed:		
Clay, sticky, plastic, medium-dark greenish gray	35	230
Sand, fine to coarse, and fine pebbles; gray. Fragments of brittle "black"wood or lignite	6	236
Sand, fine to medium, gray, and shells and scattered fine pebbles; thin beds of medium-dark blue-gray sandy, clayey silt	27	263
Ocean City aquifer:		
Sand, fine and medium, and some shells (pelecypods); clay (gray) layer 301-305 ft	67	330
Lower confining bed (lower part):		
Sand, very fine to fine, and some medium to coarse, light-gray; and sticky gray clay in alternate very thin layers	20	350
Sand, medium to coarse, gray, and fine to medium pebbles	27	377
Sand, fine to very fine, some medium; gray; and thin layers of gray clay	13	390
Manokin aquifer:		
Sand, fine to medium, "gritty", gray and some soft, gray clay	30	420
Clay, gray; and gritty, fine to medium, gray sand; some shells	18	438
Sand, fine to coarse, light gray, and a little gray clay; some shell fragments	19	457

Table 7—Logs of wells and test holes—continued.

(Wor-Bf63, cont.)

	Thickness (ft)	Depth (ft)
St. Marys Formation:		
Sand, very fine to fine, light gray, and fine-sandy gray clay in thin layers; some small pieces of shell	39	496
"Sand, hard-cemented"	1	497
Sand, fine to very fine, silty, gray. Fine fragments of shell	23	520

Wor-Bg 48 (Altitude: 6 ft)
Geologist's log

	Thickness (ft)	Depth (ft)
Holocene deposits:		
Sand, fine, and silt	5	5
Pleistocene deposits:		
Clay, silty (sandy toward base); multicolored	17	22
Silt, clayey, stiff, medium-dark gray; micaceous	21	43
Sand, coarse, and very fine gravel; clay stringers; gray	34	77
Sand, coarse to very coarse, and very fine gravel; gray. Worn shell fragments	43	120
Pocomoke aquifer:		
Sand, coarse, clean, tan-gray	24	144
Lower confining bed:		
"Quicksand," fine to medium, well-sorted, clean, tan-gray	18	162
Sand, coarse, and fine gravel	12	174
Silt, sandy, dark green, and gray	20	194
Ocean City aquifer:		
Gravel, medium, and very coarse sand; gray	23	217
Sand, coarse, and fine gravel, tan-gray	23	240
Sand, fine to coarse, tan-gray	20	260
Sand, fine to medium, pebbly, tan-gray	10	270
Lower confining bed (lower part):		
Clay or silt, blue-gray, and fine sand	25	295
Clay, blue-gray, and fine sand	20	315
Manokin aquifer:		
Sand, fine, white; traces of wood	15	330
Sand, medium,white; small pebbles	10	340
Sand, medium, white	10	350
Sand, coarse, white	20	370
Sand, medium to fine, white	10	380
Sand, fine, white	5	385
Clay, olive-green	21	406
Sand, medium, white	4	410
Sand, coarse, white	10	420
Sand, medium, white; clay, olive-green	10	430
Sand, medium,white; clay, olive-green	4	434
St. Marys Formation:		
Clay, olive-green, and fine white sand	6	440

Table 7—Logs of wells and test holes—continued.

Wor-Bg 49 (Altitude: 15 ft)
Geologist's log

	Thickness (ft)	Depth (ft)
Fill	10	10
Pleistocene deposits:		
Sand, fine, and clay	12	22
Sand, coarse; shells	6	28
Sand, very fine	17	45
Sand, coarse; shells	9	54
Clay, soft; very fine sand	16	70
Sand, coarse to very coarse; shell fragments and fine gravel	28	98
Sand, very fine	12	110
Gravel, fine	15	125
Upper Confining bed:		
Sand, fine	21	146
Pocomoke aquifer:		
Sand, coarse	10	156
Sand, fine	6	162
Sand, coarse, pebbly	17	179
Lower confining bed:		
Clay, gray	4	183
Sand, very coarse, pebbly; shell fragments	11	194
Clay, silty, gray; shell fragments	8	202
Clay, tough, brown	23	225
Silt and sand	3	228
Ocean City aquifer:		
Sand, coarse; gravel, fine; coarse shell fragments	9	237
Sand, fine to medium	18	255

Wor-Ce 31 (Altitude: 25 ft)
Geologist's log

	Thickness (ft)	Depth (ft)
Holocene and Pleistocene deposits:		
Sand, fine, tan, and gray clay	5	5
Sand, fine to medium, light brown	5	10
Sand, brown	5	15
Sand, medium to coarse, dark gray, and white shell fragments	5	20
Sand, fine, blue-gray, and copious white, fine, thin shell fragments	20	40
Sand, silty, blue-gray	10	50
Sand, medium to coarse, gray, "clean"	25	75
Upper confining bed:		
Sand, medium to coarse, gray, scattered shell fragments	15	90
Sand, coarse; green clay fragments; and a few pieces of thin, white shell, sand mostly clear and gray quartz, but also shiny black chert, reddish jasper, and some muscovite	20	110
Pocomoke aquifer:		
Sand, gray, very coarse; very fine gravel, and some coarse shell fragments. Sand and gravel mostly quartz (clear, gray, or milky) and black chert	17	127
Sand, medium to fine	18	145
Sand, coarse to very coarse, uniform	6	151
Sand, very coarse, uniform	19	170
Lower confining bed (upper part):		
Sand, fine to medium	17	187
Ocean City aquifer:		
Sand, coarse	17	204

Table 7—Logs of wells and test holes—continued.

(Wor-Ce 31 - cont.)

	Thickness (ft)	Depth (ft)
Lower confining bed (lower part):		
Sand, fine to very fine, gray, biotitic shell fragments common	50	254
Manokin aquifer:		
Sand, coarse to very coarse, and very fine gravel; gray with light green-tan tint; about one-third of grains iron-stained	90	344
Sand, coarse, grading downward to fine to medium; gray shell fragments	53	397
St. Marys Formation:		
Sand, very fine, dark gray	7	404
Sand, very fine and silt, dark gray	21	425
Sand, fine to very fine, dark gray; shell fragments	22	447
Sand, fine to very fine, silty, dark gray; shells, including **Turritella**	23	470
Sand, fine to very fine, biotitic, dark gray; shell fragments	48	518
Silt and clay, gray; and stringers of fine sand	41	559
Choptank and Calvert Formations (undivided)		
Shells and fragments, and recrystallized calcite cemented into a hard "shell bed"	4	563
Sand, fine, and brown-black wood or lignite	29	592
Shell bed, calcite-cemented, hard	3	595
Sand, fine to very fine, silty, some clay with pockets of soft, white, sandy clay, dispersable in water	10	605
Shell bed, calcite cemented, hard	2	607
Sand, fine; shell layers, some calcite-cemented and hard; black "lignite"	37	640
Sand, fine to very fine, becoming finer toward base; shell layers, some calcite-cemented and hard; brown, massive calcite, and some black	50	690

(Wor-Ce 31 - cont.)

	Thickness (ft)	Depth (ft)
Clay, silty, greenish-brownish gray	30	720
Sand, fine; a little silt	20	740
Sand, fine, and thin beds of cemented shell; very hard	12	752
Sand, fine to very fine, gray; thin beds of hard cemented shell	28	780
Sand, very fine, silty, gray, and some greenish clay; grading to sandy silt and greenish clay toward base; very thin, hard layers of shell	42	822
Sand, very fine, silty, and green clay	43	865
Shell layer, calcite-cemented, hard	2	867
Sand, fine, glauconitic, and calcite-cemented shell layers	21	888
Shell layer, calcite-cemented, hard	2	890
Sand, fine to very fine, gray ("salt-and pepper"); thin hard beds of calcite-cemented shell; and some ash-white soft clay, readily dispersed in water (diatomite?). Sand includes fine, shiny black pellets of glauconite or phosphate. Recrystallized calcite is tan, some fragments coated jet black one or more sides	110	1,002
Sand, gray, very fine to fine, silty; soft, white clay (diatomite?)	38	1,040

Table 7—Logs of wells and test holes—continued.

Wor-Cg 68 (Altitude: 10 ft)
Geologist's log

	Thickness (ft)	Depth (ft)
Holocene deposits:		
Sand, brownish-white	1	1
Clay, fine-sandy, yellow-brown	7	8
Pleistocene deposits:		
Peat, chocolate-brown	3	11
Clay, sandy, yellow	22	33
Clay, slick, stiff, sandy, dark gray, and sand layers	29	62
Sand, coarse to very coarse, and very fine gravel; light brown-gray ("white")	28	90
Sand, fine to very fine, greenish gray; thin layers of gray clay	15	105
Sand, coarse to very coarse, brownish gray ("white"); wood fragments at 125-135 ft	35	140
Upper confining bed:		
Sand, coarse, "dirty" or with thin beds of gray clay	24	164
Pocomoke aquifer:		
Sand, coarse, white; some gray clay	24	188
Clay, gray, and interbedded coarse "white" sand	19	207
Clay, sandy, gray, and silt	25	232
Ocean City aquifer:		
Sand, very fine; silt; and sandy gray clay	28	260
Silt and clay, sandy	8	268
Sand, fine to coarse, medium to dark gray; many shell fragments	30	298
Silt or fine sand	12	310
Lower confining bed (lower part):		
Sand, medium to coarse, gray; coarse shell fragments, mostly pelecypods	10	320
Sand, fine-to-medium, silty or clayey, gray. Shell fragments	20	340
Clay or silt, medium-dark gray	12	352
Manokin aquifer:		
Sand, fine to medium, silty or clayey, gray; shell fragments fewer	28	380
Sand, fine and silt or clay; gray	25	405
Sand, medium-to-coarse, gray; coarse shell fragments	30	435
Sand, coarse to fine (finest toward base), gray; coarse shell fragments	10	445
Sand, poorly sorted, fine to very coarse, gray. Many coarse shell fragments (pelecypods). Drilled through shell beds	35	480
Sand, fine to medium, some coarse; slightly silty; gray	26	506

(Wor-Cg 68 cont.)

	Thickness (ft)	Depth (ft)
St.Marys Formation:		
Silt and fine to medium sand, interbedded. Sand finest toward base	34	540
Silt and fine to medium sand, thin-bedded. Some fine shell fragments	60	600
Sand, fine to medium, and some very fine pebbles; gray. Sand "quick". Some fine shell fragments	20	620
Sand, fine, silty (?) Hard shell bed 2-3 feet thick in upper part. Coarser shell fragments including black fragment of an oyster shell	20	640
Beds of fine sand and scattered pebbles, and partially-cemented shells. Pebbles of clear and white quartz and brown and black angular fragments of chert	10	650
Clay, soft, gray, and very fine sand	30	680
Frederica aquifer:		
Interbedded sand and layers of shell (probably shell fragments more or less cemented)	40	720

MARYLAND GEOLOGICAL SURVEY
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Selected Reports of Investigations:

1. Chemical quality of water and trace elements in the Patuxent River Basin, by S.G. Heidel and W.W. Frenier, 1965., 40 p. $3.50*
3. Water resources of the Salisbury area, Maryland, by D.H. Boggess and S.G. Heidel, 1968, 69 p. 3.00
5. Chemical quality reconnaissance of water of Maryland streams, by J.D. Thomas, 1966, 61 p. 2.00
9. Chemical and physical character of municipal water supplies in Maryland, by J.D. Thomas and S.G. Heidel, 1969, 52 p. 1.00
10. Ground-water occurrence in the Maryland Piedmont, by L.J. Nutter and E.G. Otton, 1969, 56 p. 2.50
13. Extent of brackish water in the tidal rivers of Maryland, by W.E. Webb and S.G. Heidel, 1970, 46 p. 1.50
14. Geologic and hydrologic factors bearing on subsurface storage of liquid wastes in Maryland, by E.G. Otton, 1970, 39 p. 2.75
16. Flow characteristics of Maryland streams, by P.N. Walker, 1971, 160 p. 3.50*
17. Water resources of Dorchester and Talbot Counties, Maryland with special emphasis on the ground-water potential of the Cambridge and Easton areas, by F.K. Mack, W.E. Webb, and R.A. Gardner, 1971, 107 p. 5.25
18. Solid-waste disposal in the geohydrologic environment of Maryland, by E.G. Otton, 1972, 59 p. 3.00
19. Hydrogeology of the carbonate rocks, Frederick and Hagerstown Valleys, Maryland, by L.J. Nutter, 1973, 70 p. 3.50
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22. An evaluation of the Magothy Aquifer in the Annapolis Area, Maryland, by F.K. Mack, 1974, 75 p. 3.00
24. Availability of fresh ground water in northeastern Worcester County, Maryland: With special emphasis on the Ocean City Area, by J.M. Weigle, 1974, 64 p. 4.00
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33. A quasi three-dimensional finite-difference ground-water flow model with a field application, by G. Achmad and J.M. Weigle, 1979, 22 p. with appendix..... 6.50
34. The availability of ground water in western Montgomery County, Maryland, by E.G. Otton, 1981, 76 p. 5.75
37. Geohydrology of the fresh-water aquifer system in the vicinity of Ocean City, Maryland, with a section on simulated water-level changes, by J.M. Weigle and G. Achmad, 1982, 56 p. 10.00

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*microfiche

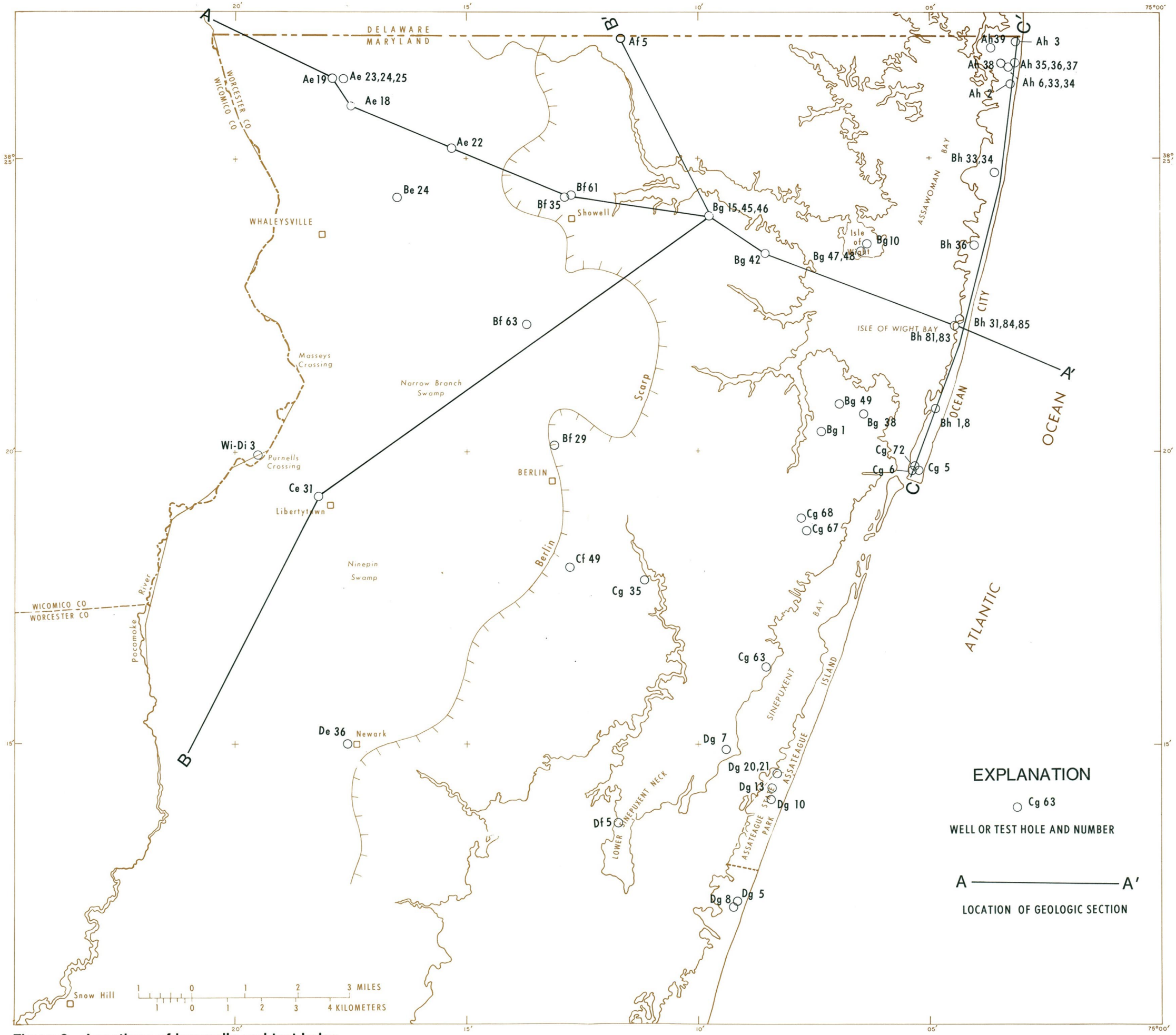


Figure 3.—Locations of key wells and test holes.

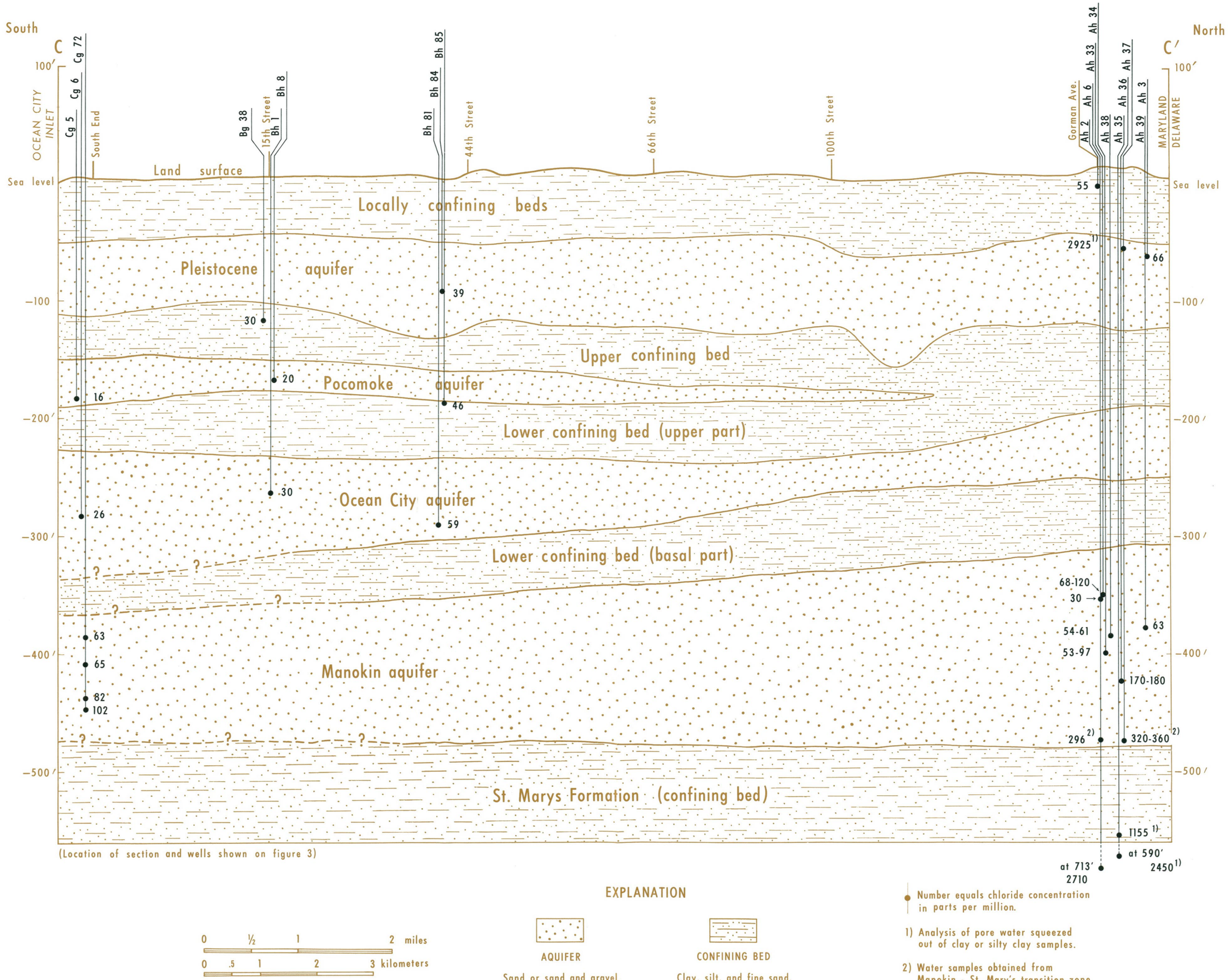
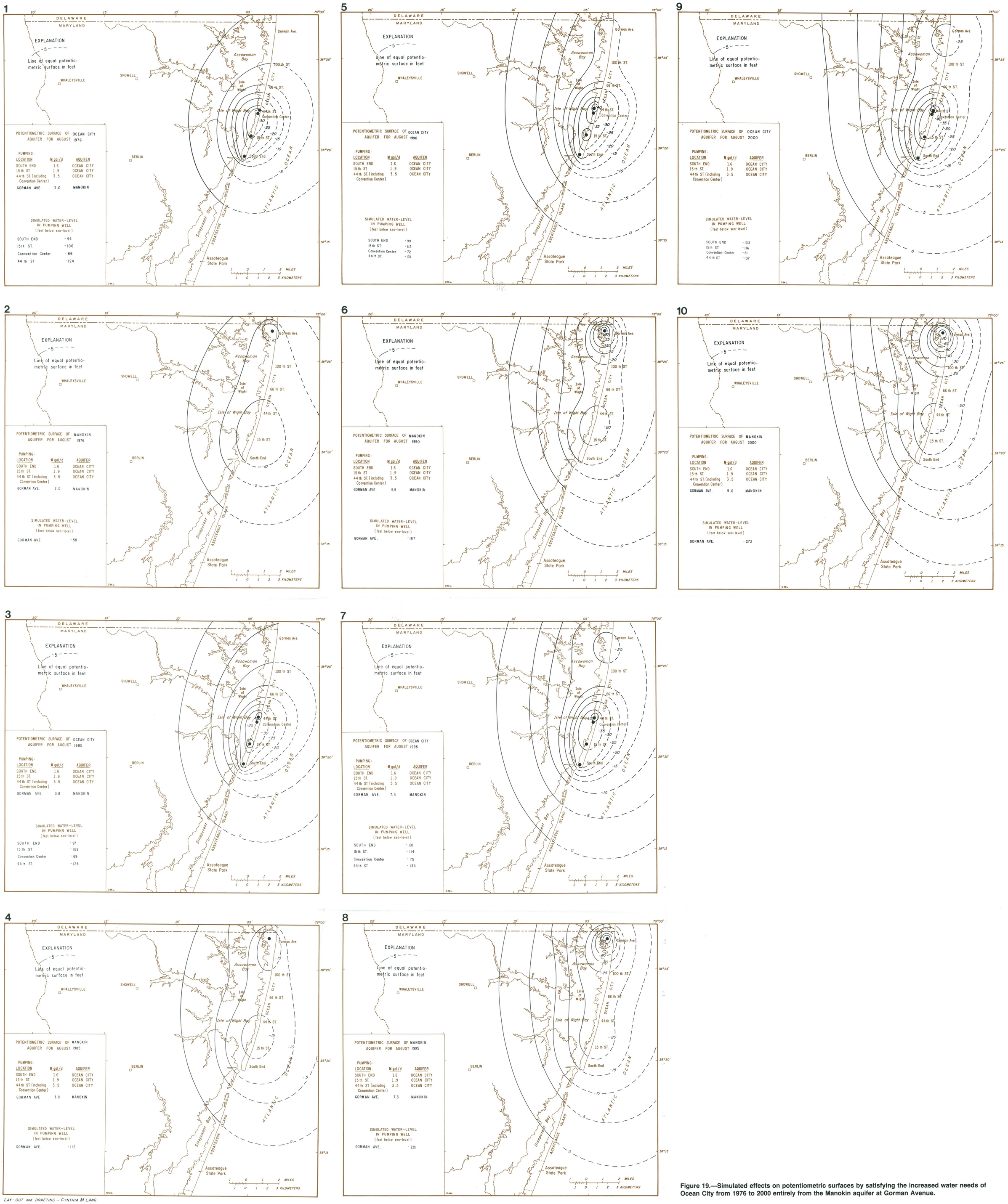
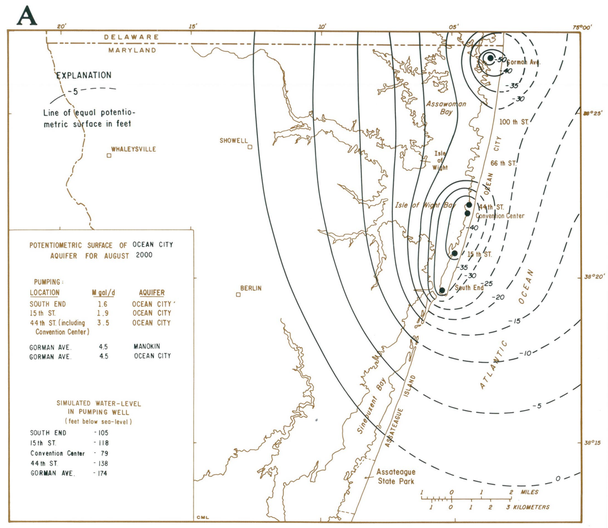


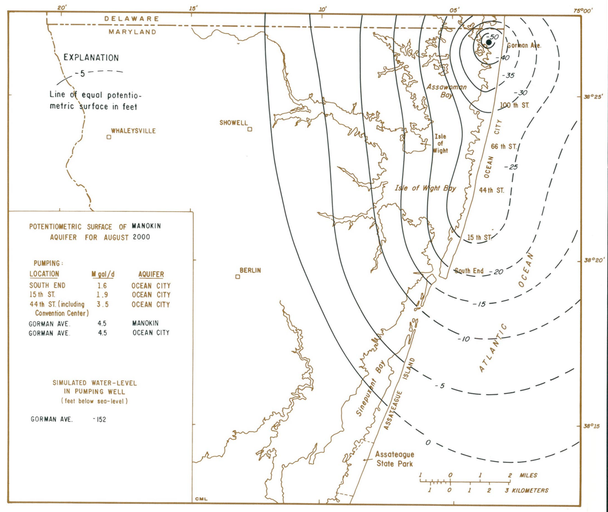
Figure 5.—Generalized section showing aquifers and confining beds, and vertical distribution of chloride in ground water beneath Ocean City. (Refer to Table 5 for well screen intervals).

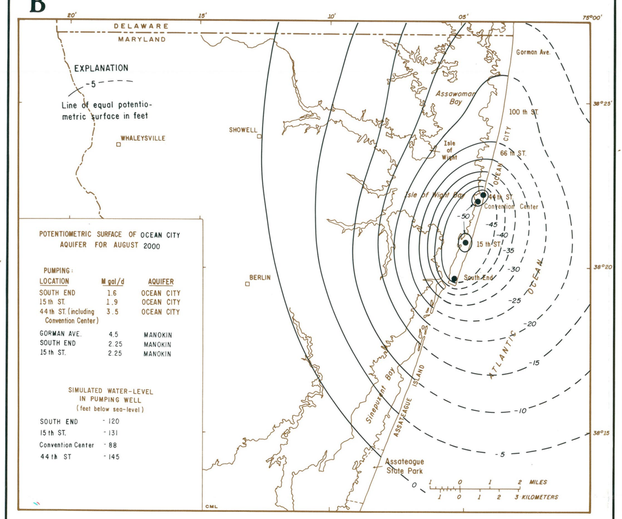


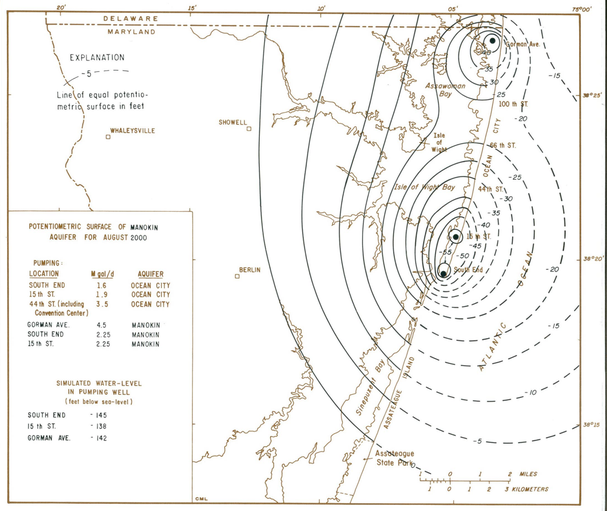
LAY-OUT and DRAFTING – CYNTHIA M. LANG

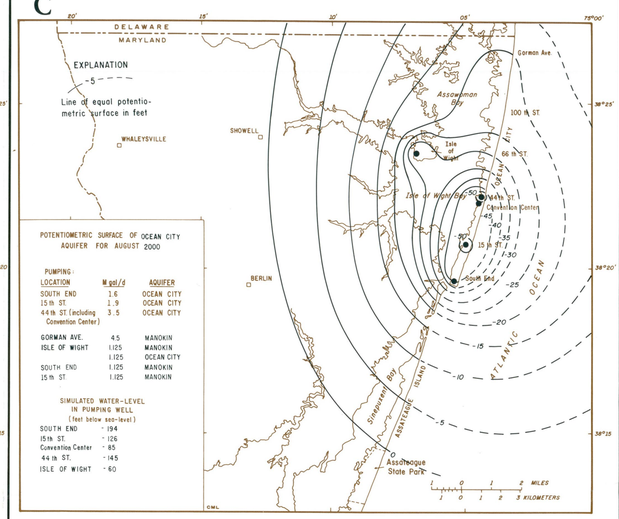
Figure 19.—Simulated effects on potentiometric surfaces by satisfying the increased water needs of Ocean City from 1976 to 2000 entirely from the Manokin aquifer at Gorman Avenue.

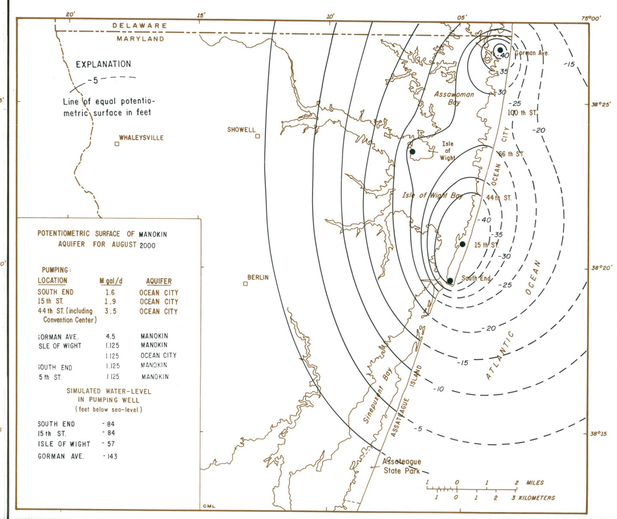


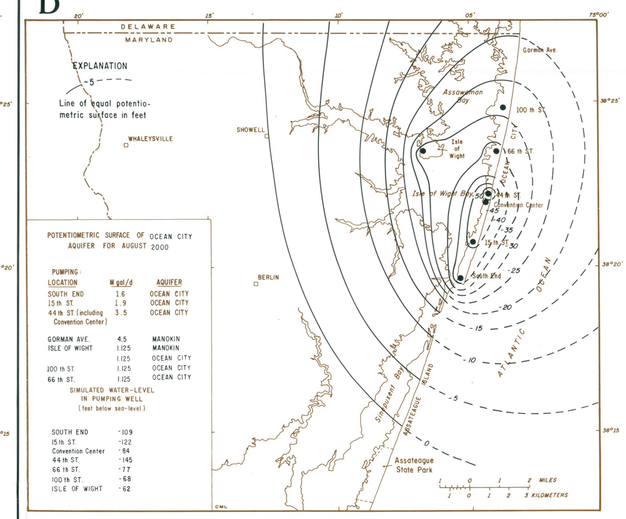


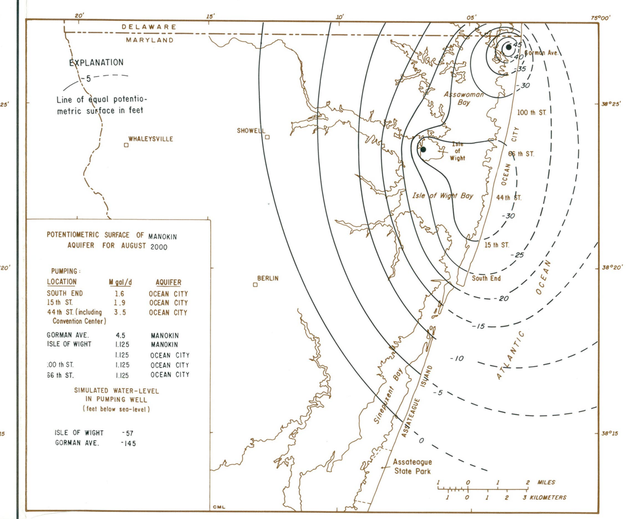


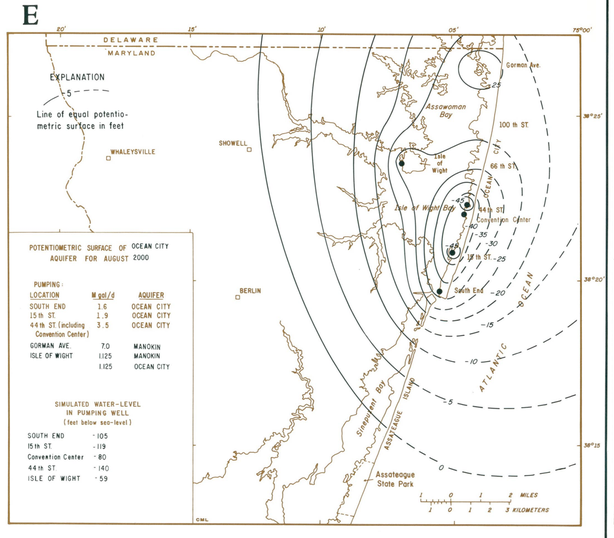


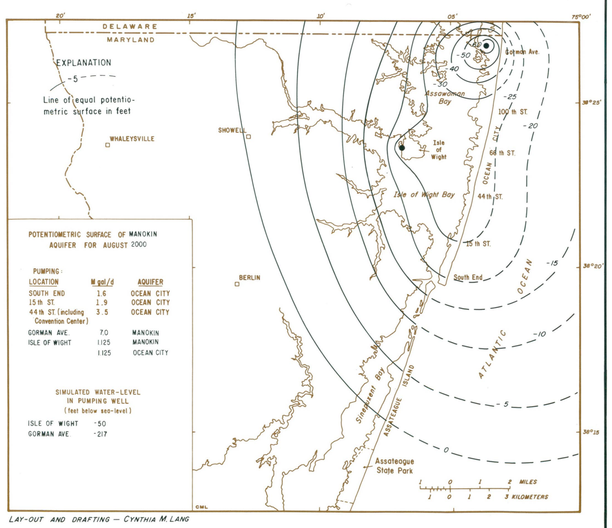


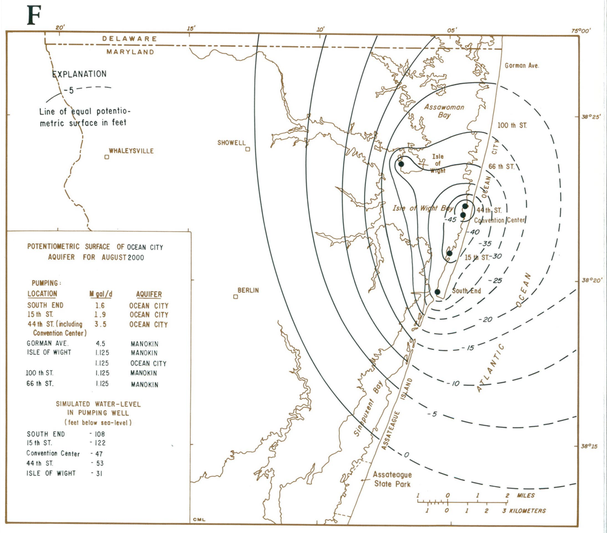


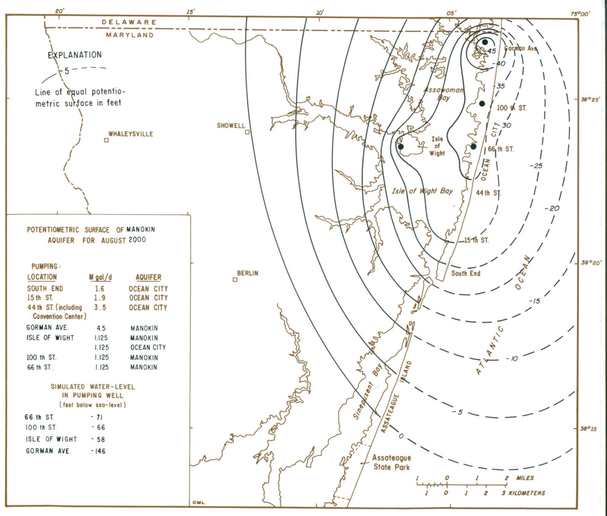












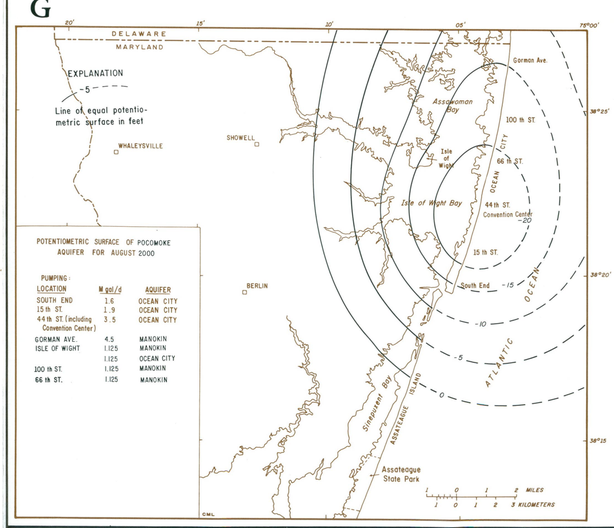


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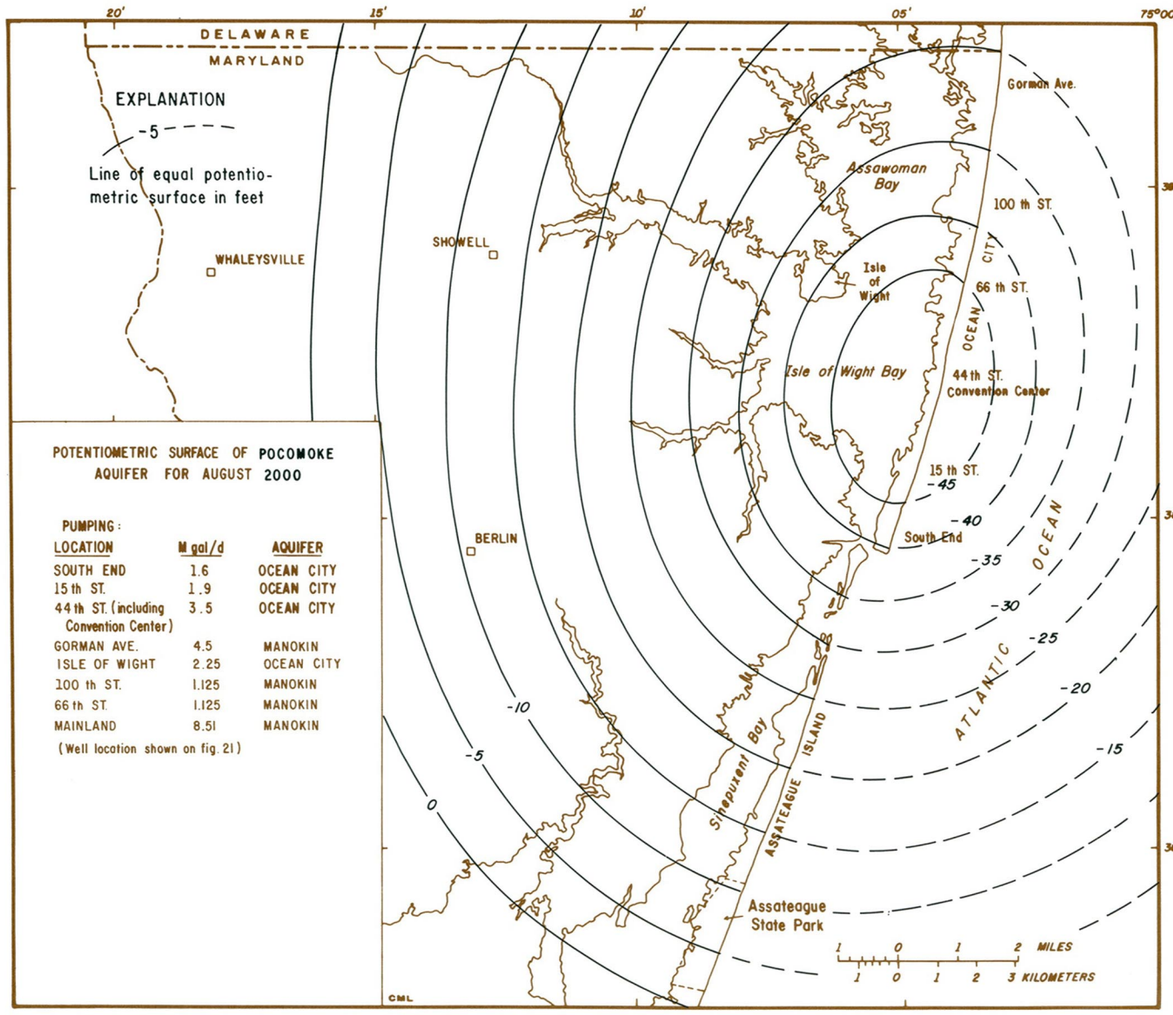
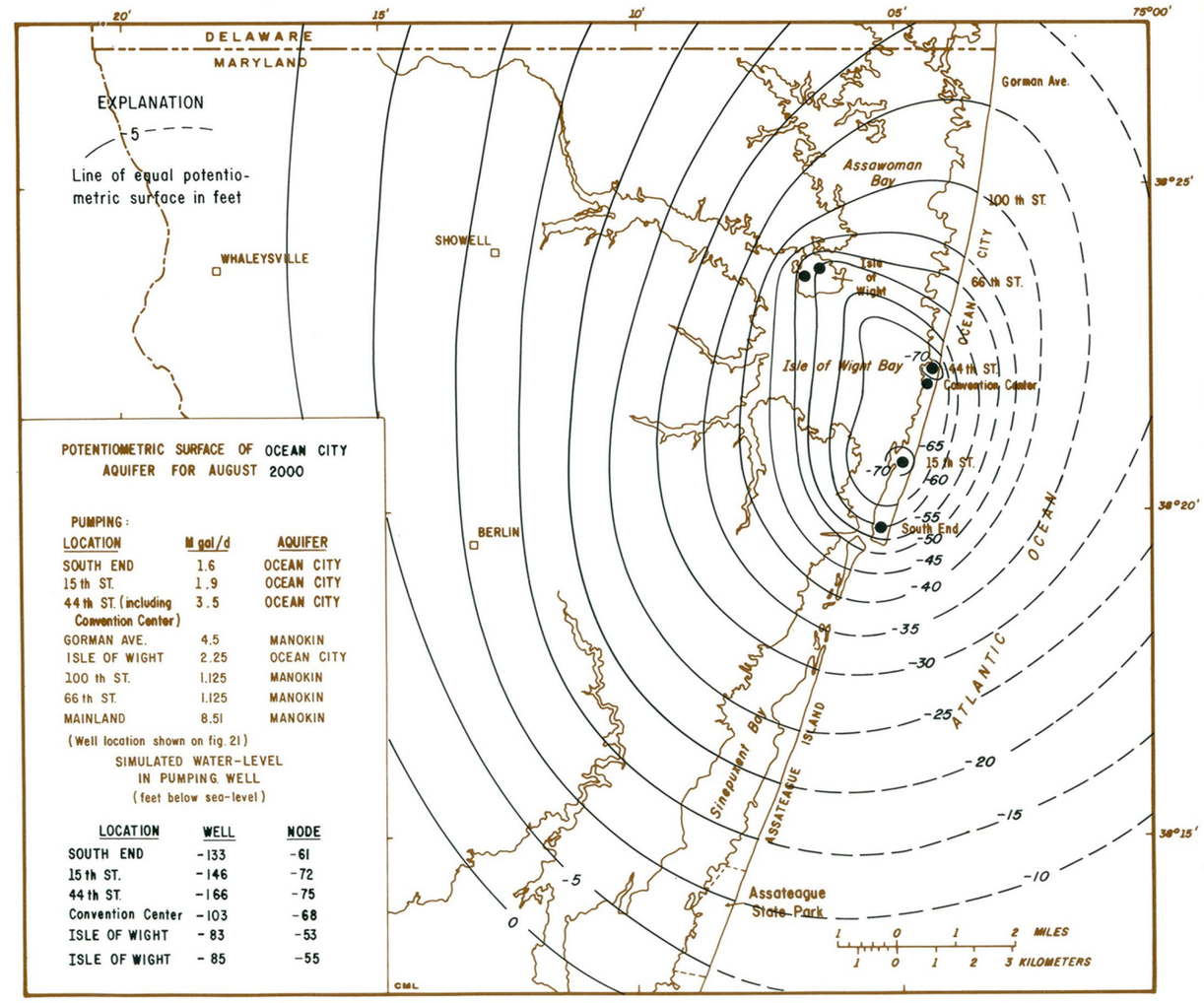
Figure 20.—Simulated potentiometric surfaces of the Ocean City and Manokin aquifers for August 2000, modified by changing withdrawal centers and aquifer sources.





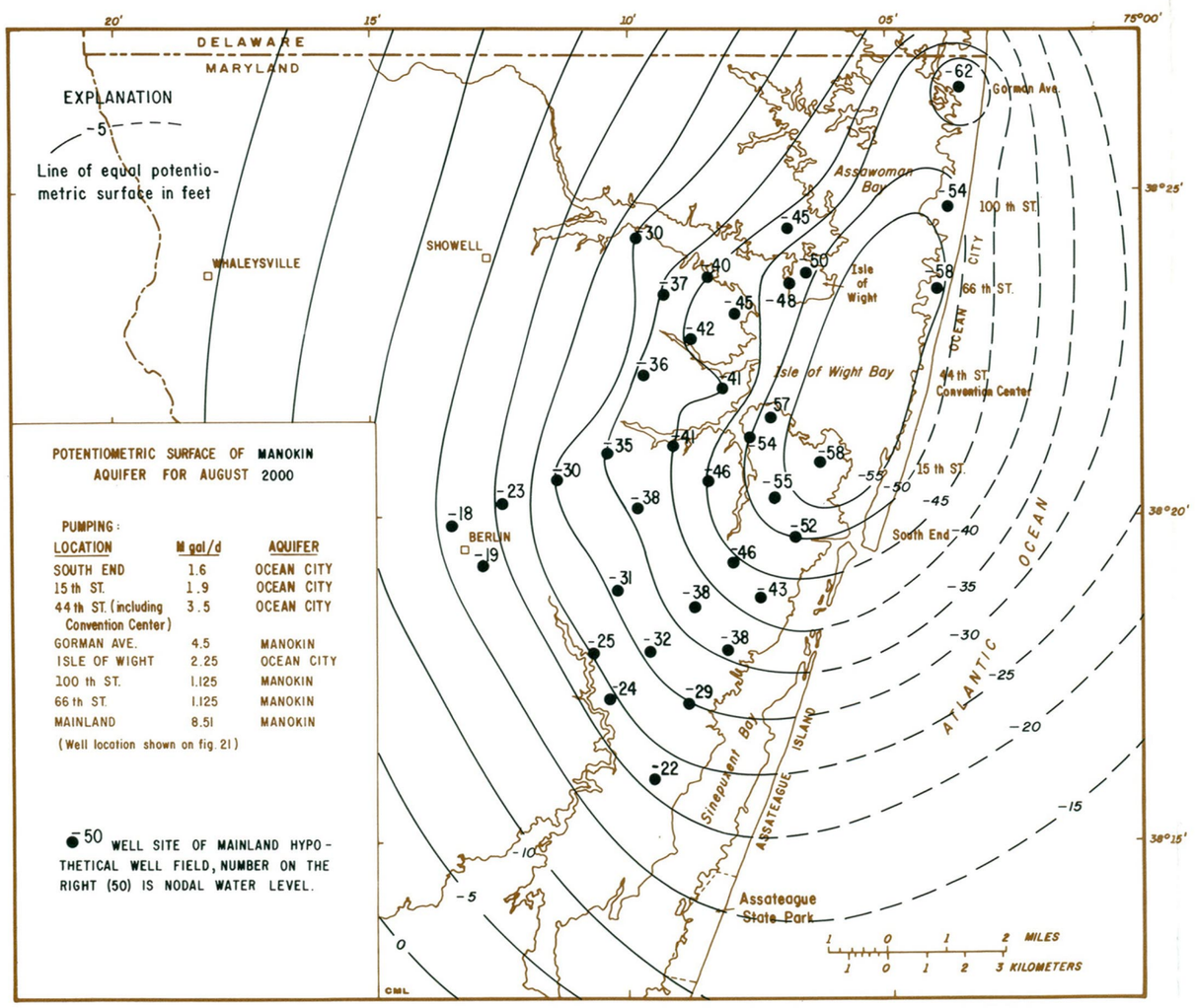
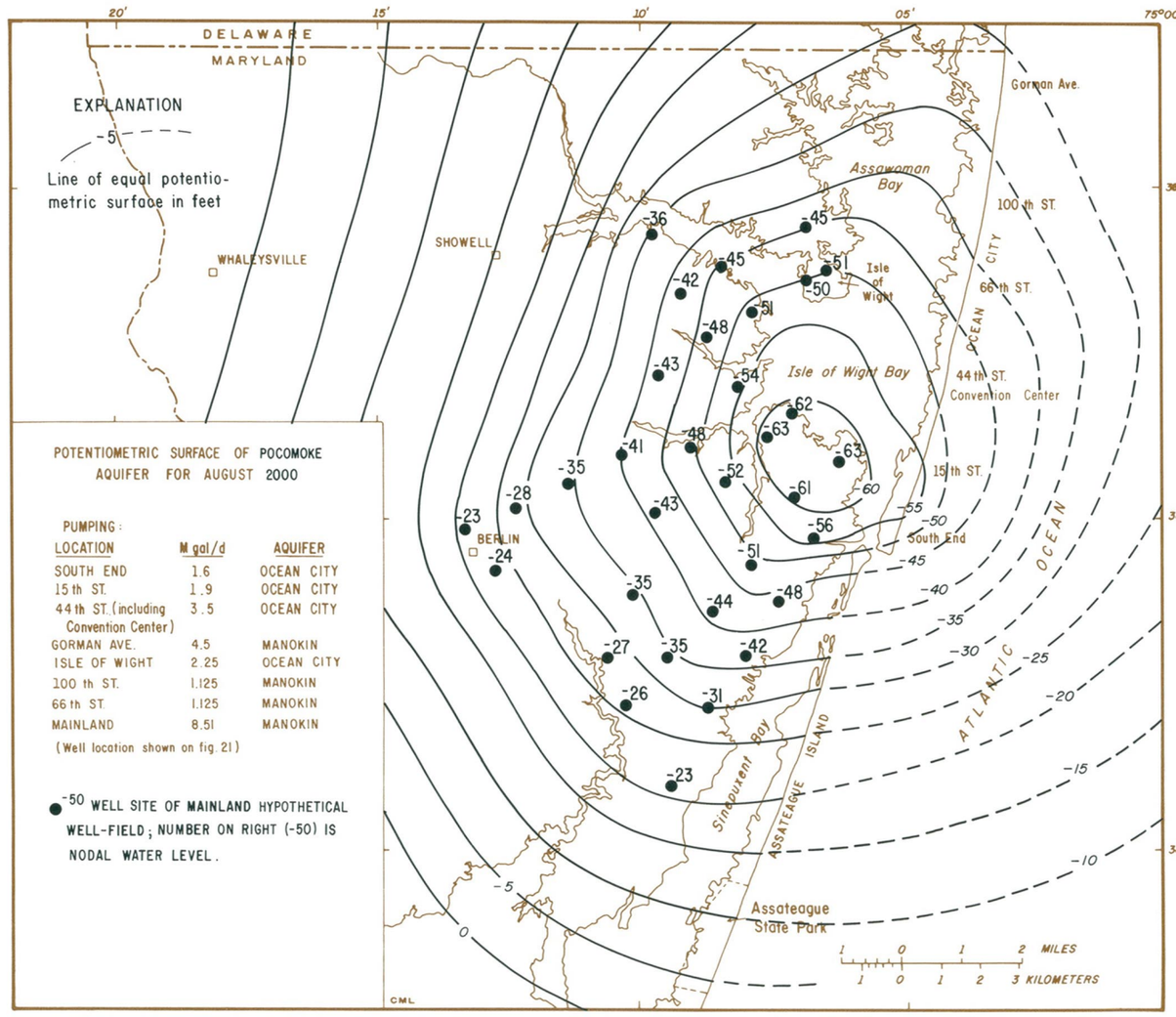
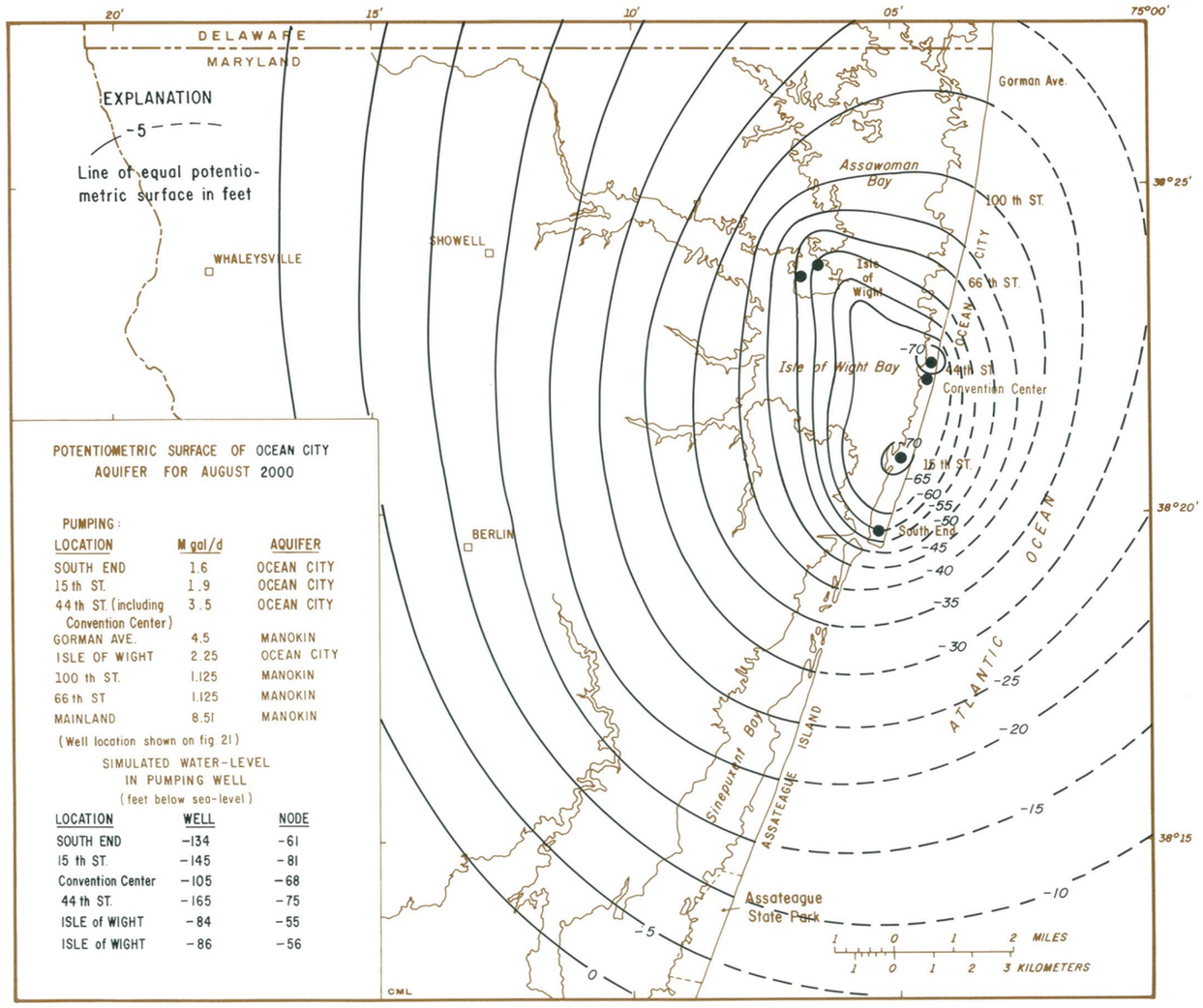


Figure 23.—Simulated potentiometric surfaces for August 2000, assuming nearby mainland water needs satisfied by Manokin aquifer.





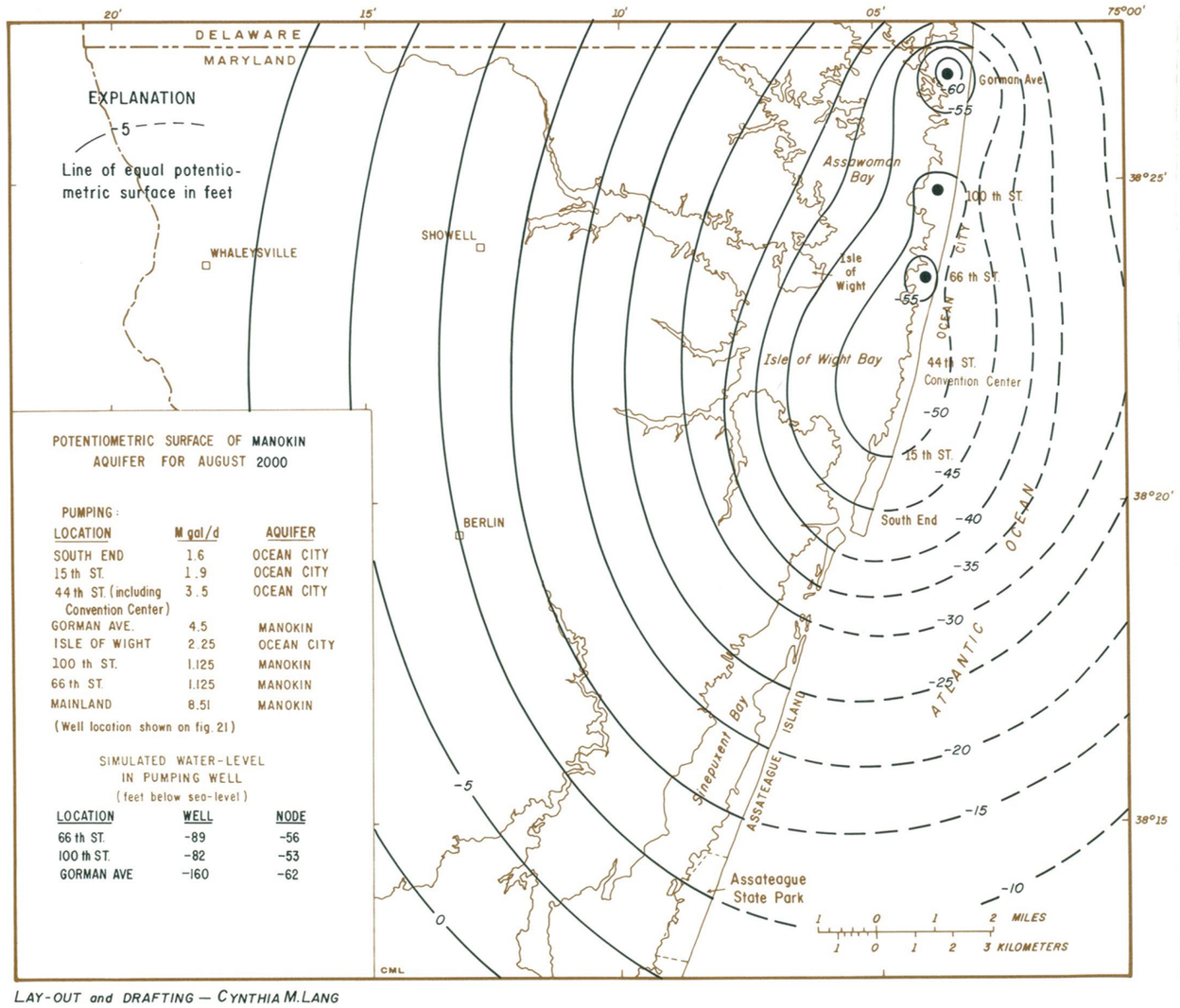


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Figure 24.—Simulated potentiometric surfaces for August 2000, assuming nearby mainland water needs satisfied by Pocomoke aquifer.

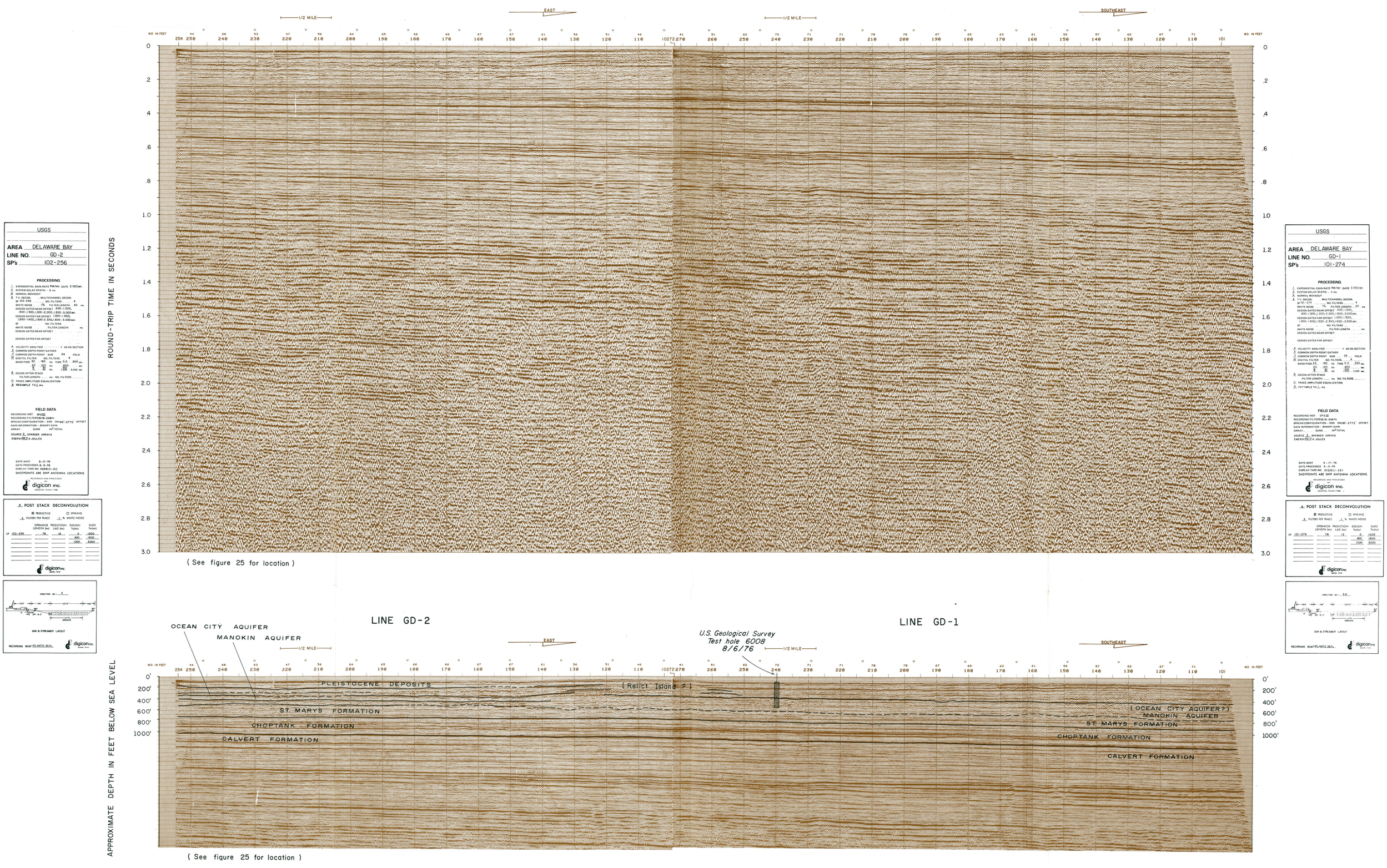

Figure 26.—Interpretation of upper part of east-west marine acoustical profiles.

Table 1—Geologic units in northeastern Worcester County and their geohydrologic characteristics.[1] (adapted from Weigle, 1974)

System	Series	Group	Geologic unit	Thickness (Feet)	Hydrologic unit(s)	Lithologic character	Water-bearing characteristics and hydrology 2/
	Holocene	---	Holocene deposits	0 - 40 average 5	---	Soil, alluvial sand and silt, dune sand, and peat. Disconformable base.	Commonly unsaturated, but permits water to percolate downward to underlying units. Possibly provides water locally for a few wells near the coast.
Quaternary	Pleistocene		Upper Pleistocene deposits	90 - 160	---	Lenticular deposits of sand, silt, clay, and peat. Some beds of coarse sand and fine gravel. Tan; some gray, and blue.	Functions as a partial confining bed. Generally capable of yielding supplies of water sufficient for household needs, but water "irony" locally. Susceptible to local salt-water contamination near coast.
			Beaverdam Sand		Pleistocene aquifer	In lower half of Pleistocene deposits. Lensoidal or rudely stratified deposits of medium-to-very-coarse sand and gravel. Color generally tan, green brown, white, or gray. Near coast, the bottom 10 or 20 feet is stratified blue clay and gray sand. Aquifer is 25 - 90 feet thick.	Important aquifer having a potential for large short-term yields. Water "irony" locally. Susceptible locally to salt-water contamination near coast. Water occurs under water-table conditions generally, but is semi-confined or confined in much of the area.
Quaternary (?)	Pleistocene (?)		Pleistocene (?) deposits	0 - 20			
Tertiary	Miocene	Chesapeake		0 - 50	Upper confining bed	Lenticular silts, clays, and fine sands. Green-blue silt and fine gray sand most common, but occasionally includes blue-green pebbly clay.	Confining bed, providing partial hydraulic separation of the Pleistocene and Pocomoke aquifers. Pinches out in extreme northwestern part of area, and absent locally elsewhere. Effectiveness as a confining bed is good to poor.
				0 - 80	Pocomoke aquifer	Sand, gray or tan-gray; coarse and pebbly generally, but locally fine.	Important aquifer generally 30 to 60 feet thick, but absent under northern Ocean City. Where present, generally has a potential for large short-term yields. Potential yields and transmissivity greatest from Newark to Isle-of-Wight Bay; less to northwest, southeast, and northeast. Water confined except in extreme northwestern part of area.
				15 - 85	Lower	Blue and gray clayey silt and sand; some peat. Some beds of shell and calcite and/or limestone in top and bottom parts. Middle generally sandy; bottom part sandy in much of area; material in upper part (15 - 20 feet thick) fine.	Leaky confining layer. In much of the area only the upper part (15 - 20 feet thick) persists as a confining layer and the middle and lower parts are an aquifer (the Ocean City aquifer).
					Ocean City aquifer	Coarse gray sand, fine gravel.	Important aquifer at Ocean City; provided the entire public supply in 1972. Hydraulically connected with Manokin.
					confining bed		
				< 100 - 240	Manokin aquifer	Fine to very coarse gray sand, and some lignite or peat. Some silty sand and clay, especially in middle part of aquifer, toward southeast. Occasional beds of shell and/or "rock".	Very important artesian aquifer. The Ocean City-Manokin aquifer system has a potential for large to very large short-term yields except in the southeastern part of the area, where the potential is for moderate to large yields. Transmissivities of the Ocean City-Manokin aquifer system increase north-northwestward, and range from about 1,000 to more than 10,000 feet squared per day. At the coast, the Manokin may be susceptible to salt-water invasion in response to large-scale ground-water withdrawals there.
			St. Marys Formation	160 - 190	Confining layer	Compact, gray, fossiliferous clay, silt, silty clay, and sandy clay. Possibly some very fine sand.	Confines the base of the Manokin aquifer, preventing or retarding movement of salt water from the Choptank Formation to the Manokin. In this area, saturated with brackish or salty water and generally unproductive of water.
			Choptank Formation	130 - 240	Frederica aquifer	Gray fine sand. Thin beds of shell and calcite or limestone.	The aquifer could yield supplies of water at least sufficient for domestic needs, but the water is salty.
					Confining layer	Green or brown clay and fine sand. Thin beds of shell and calcite or limestone.	
			Calvert Formation	430 - 680	Aquifers and confining layers	Gray sand and diatomaceous silt and clay. Shell beds.	The aquifers could probably yield individual supplies of water measurable in hundreds of gallons per minute, but the water is salty.

1/ The nomenclature is that of the Maryland Geological Survey and does not necessarily agree with that of the U. S. Geological Survey.

2/ "Moderate" indicates yields of 100 - 300 gpm; "large", 300 - 1,000 gpm; "very large", more than 1,000 gpm. Short-term yields are maintainable for several hours at a time with longer intervening periods of no pumping, and assume optimum conditions of well construction and spacing.

Tertiary

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Geohydrology Of The Fresh-Water Aquifer System In The Vicinity Of Ocean City, Maryland, With A Section On Simulated Water-Level Changes

R.I. No. 37, 1982