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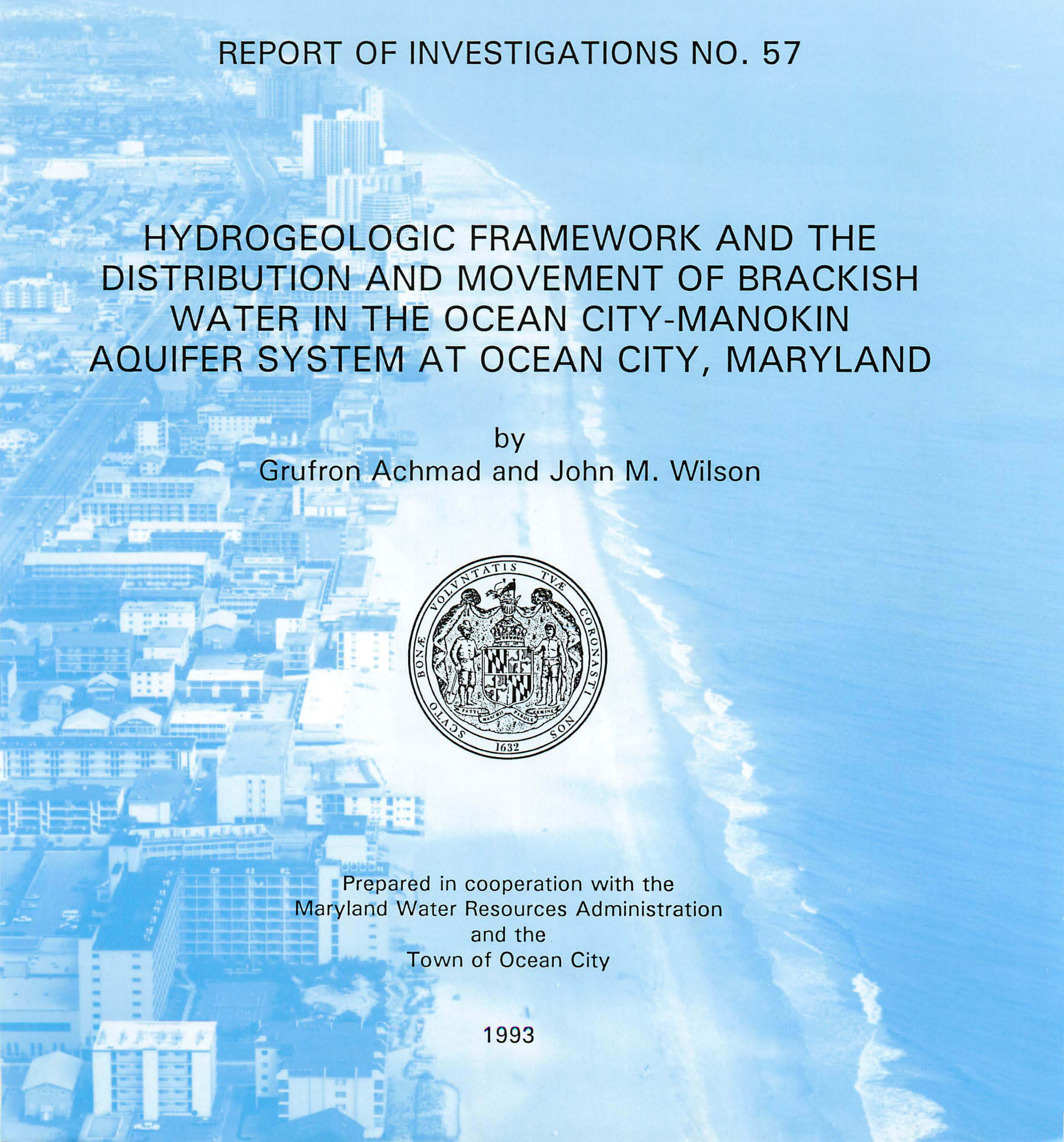

REPORT OF INVESTIGATIONS NO. 57

HYDROGEOLOGIC FRAMEWORK AND THE DISTRIBUTION AND MOVEMENT OF BRACKISH WATER IN THE OCEAN CITY-MANOKIN AQUIFER SYSTEM AT OCEAN CITY, MARYLAND

by
Grufron Achmad and John M. Wilson

Prepared in cooperation with the
Maryland Water Resources Administration
and the
Town of Ocean City

1993

CONVERSION FACTORS AND ABBREVIATIONS

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

Multiply inch-pound unit	by	To obtain metric units
inch (in.)	25.40	millimeter (mm)
inch per year (in./yr)	0.254	meter per year (m/yr)
foot (ft)	30.48	millimeter (mm)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.589	square kilometer (km^2)
million gallons (Mgal)	3,785	cubic meter (m^2)
million gallons per day (Mgal/d)	0.0438	cubic meter per second (m^3/s)

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

Aquifer and fluid properties used in the transport model are expressed in metric units. Thickness of cross sections is expressed in meters. Fluid and matrix compressibilities are expressed in meters. Longitudinal and transverse dispersivities are expressed in $(\text{kiloPascals})^{-1}$. Diffusivity is expressed in square meters per second. Fluid viscosity is expressed in kilograms per meter per second. Chloride concentration is expressed in milligrams per liter. Water density is expressed in kilograms per cubic meter. Water temperature is expressed in degrees Celsius.

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ABSTRACT

Ocean City, Maryland, is a coastal resort on the Atlantic Ocean. The town's public-water supply is provided by the Ocean City-Manokin aquifer system, which in 1990 supplied about 2,000 million gallons of water to the town. The uppermost aquifer at Ocean City is the unconfined to semiconfined Columbia aquifer. The Columbia aquifer is comprised of the Beaverdam Sand and overlying surficial units. Underlying the Columbia aquifer in order of increasing depth are the Pocomoke, Ocean City, Manokin, and Choptank aquifers. In the northern part of Ocean City, the Pocomoke aquifer is absent.

The Ocean City and Pocomoke aquifers contain only freshwater. At the Town of Ocean City's 44th Street well field, however, chlorides in the Ocean City aquifer rose from about 70 mg/L in 1975 to about 215 mg/L in 1988 due to upconing of brackish water from the underlying Manokin aquifer. Brackish water occurs in parts of the Columbia and Manokin aquifers at Ocean City although both these aquifers are predominantly fresh. The Choptank aquifer contains only brackish water. The confining unit between the Choptank and overlying Manokin aquifer, the St. Marys Formation, is brackish.

At Ocean City the upper Miocene Manokin formation (an informal unit) consists of a series of stacked coarsening upward sand sequences that comprise the Manokin aquifer. The Manokin formation is the product of a fluvial dominated, high-constructive delta system that was subject to some marine reworking along the delta front. Truncation and channelling within the Manokin formation have resulted in breached and discontinuous confining beds that influence the distribution of chlorides within the Manokin aquifer.

The upper Miocene "Ocean City beds" (an informal unit) overlie the Manokin formation at Ocean City and contain the Ocean City aquifer. The Ocean City beds are comprised predominantly of fine to coarse sand in the central and southern parts of Ocean City. In the northern section of Ocean City, the Ocean City beds are predominantly glauconite- and shell-bearing, clayey silts and fine clayey sands that contain discontinuous 10 to 25 foot thick beds of fine to medium sand. The lithofacies of the Ocean City beds have several hydrologic implications. The Ocean City aquifer has a higher transmissivity in the central and southern parts of the island than further north because of its coarser texture and greater thickness. Additionally, in the central part of Ocean City, infilled distributary channels have almost completely breached the confining unit between the Manokin and Ocean City aquifers and formed pathways for the upconing of brackish water from the Manokin aquifer.

Aspects of the hydrogeologic framework that influence the distribution of chlorides in the Manokin aquifer are: 1) the altitude of the contact between the basal sand facies of the Manokin aquifer and the underlying St. Marys Formation and 2) the effectiveness of the confining units within the Manokin aquifer. Chloride distribution in the Ocean City aquifer is controlled by 1) the effectiveness of the confining unit between the Manokin aquifer and the Ocean City aquifer, 2) the chloride distribution in the sands of the Manokin aquifer that underlie the Ocean City aquifer, and 3) head differences between the Ocean City aquifer and the Manokin aquifer caused by pumpage from the Ocean City aquifer.

A ground-water-flow model was constructed to determine the effects of increased pumpage on the ground-water-flow system at Ocean City. An annual average pumping rate of 9.1 Mgal/d was assigned to the model to simulate the expected amount of pumpage required from the Ocean City well fields in 2010. The increased pumpage, approximately 1.6 times the 1990 pumpage, expanded and deepened the cones of depression in the Manokin, Ocean City, and Pocomoke aquifers.

A particle-tracking program applied to the results of the flow model indicated that most of the recharge particles backtracked from the 44th Street and Gorman Avenue well fields originated inland of Ocean City in freshwater recharge areas of the Ocean City-Manokin aquifer system. However, some particles followed flowlines that went through the offshore part of the freshwater-saltwater mixing zone before arriving at the well fields. Mass balance calculations for the pumping cells indicate that lateral encroachment from the offshore part of the freshwater-saltwater mixing zone is the major source of brackish water in the Manokin aquifer at the Gorman Avenue well

field. At the 44th Street well field, mass balance calculations for the pumping cell indicate that annual average pumping rates greater than 1.6 Mgal/d result in increasing chloride concentrations in the Ocean City aquifer because of greater upward leakage from the brackish Manokin aquifer.

A cross-sectional solute-transport model was developed for the 44th Street and Gorman Avenue well fields in order to simulate chloride distributions in the coastal aquifers. The simulation produced an offshore plume of fresh to brackish water in the Ocean City-Manokin aquifer system that extended over 13 miles offshore. Using that result as an initial condition, the model simulated annual average pumping rates at the 44th Street well field of 2.6, 3.3, and 4.4 Mgal/d; chloride concentrations in the pumping cell in 2010 were about 230, 235, and 243 mg/L respectively. Simulated annual average pumping rates of 4.5 and 9 Mgal/d at the Gorman Avenue well field resulted in chloride concentrations in the pumping cells of about 170 and 185 mg/L respectively in 2010.

INTRODUCTION

PURPOSE AND SCOPE

Ocean City, Maryland, is a popular coastal resort (fig. 1) that obtains its water supply from two hydraulically connected, confined aquifers, the Ocean City aquifer and the Manokin aquifer, which comprise the Ocean City-Manokin aquifer system. Chloride levels in one of the town's primary production wells screened in the Ocean City aquifer rose from about 70 mg/L in 1975 to about 215 mg/L in 1988. In addition, observation wells drilled by the Town of Ocean City in 1987 and 1988 indicated that chloride concentrations in parts of the Manokin aquifer ranged from 250 to over 1,000 mg/L, and that the occurrence of brackish water in the Manokin aquifer was more widespread than previously recognized.

The Maryland Geological Survey began a study of saltwater intrusion in the Ocean City and Manokin aquifers in 1988. The purpose of the study was to evaluate the extent of saltwater intrusion in the aquifers, determine the geologic and hydrologic factors that control the chloride distribution within the Ocean City-Manokin aquifer system, estimate the rate of saltwater movement using ground-water-flow, particle-tracking, and solute-transport modeling techniques, and determine the potential of the Ocean City-Manokin aquifer system to supply the projected freshwater demands of Ocean City.

This report describes the hydrogeologic framework and distribution of chlorides within the aquifers at Ocean City, the geologic and hydrologic factors that control the chloride distribution within the Ocean City-Manokin aquifer system and the freshwater-saltwater mixing zone. This report also describes a ground-water-flow model that was used to determine water level changes due to pumpage, a steady-state particle-tracking program that was used to compute pathlines toward well field locations, and a cross-sectional solute-transport model that was used to simulate the chloride distribution in the freshwater-saltwater mixing zone.

LOCATION OF STUDY AREA

Ocean City is located on the Atlantic coast in Worcester County, Maryland. The town is about 100 miles east-southeast of Baltimore, Maryland, and 110 miles east of Washington, D.C. (fig. 1). Ocean City occupies the southern 8 miles of Fenwick Island, a barrier island that is about 10 miles long and averages 0.7 miles wide (fig. 2). Although the Ocean City area is the focus of this report, the study area encompassed about 3,500 square miles (fig. 3) so that a regional framework for the ground-water-flow and solute-transport models could be developed.

PRODUCTION WELL FIELDS

Ocean City is supplied by four "well fields": the South Division Street, 15th Street, 44th Street, and Gorman Avenue well fields (fig. 2). All the wells for a given well field are not located exactly at the street for which the well field is named. For example, the 44th Street well field includes production wells located between 39th and 45th Streets, and the Gorman Avenue well field includes wells located between 125th and 141st Streets. Figure 2 is a street map of Ocean City that shows the sites of the production or observation wells.

In 1990, about 2,000 million gallons of water were pumped from the Ocean City and Manokin aquifers. Eighty-seven percent of the pumpage was supplied by the Gorman Avenue and 44th Street well fields. Production at the Gorman Avenue well field is solely from the Manokin aquifer and production at the 44th Street well field is solely from the Ocean City aquifer. The 15th Street and South Division Street well fields have production wells screened in both the Manokin and Ocean City aquifers, but these two well fields usually only pump from the Ocean City aquifer. A generalized hydrogeologic section through Ocean City showing the location of the well fields and the aquifers that each well field taps is shown in figure 4. A generalized stratigraphic column for Ocean City describing the lithostratigraphic units and the aquifers that they contain is shown in table 1.

CLASSIFICATION OF WATER

For the purposes of this report the definition of fresh water, brackish water and saltwater is based on the concentration of chloride in mg/L (tab. 2). The reason for using a classification based on chloride concentration is that chloride concentration data are routinely collected for the monitoring well network at Ocean City. Also, chloride is a conservative ion that can be simulated using a variable density transport model. The limit of freshwater is set at a chloride concentration of 250 mg/L. This limit is based on the U.S. Environmental Protection Agency's (U.S. EPA) secondary maximum contaminant level (SMCL) of 250 mg/L for chloride concentration in public drinking-water supplies. Water with chlorides exceeding 250 mg/L tastes salty to most people. Also, the 1958 Venice System of saltwater classification puts the upper limit of freshwater at 0.5 ppt (parts per thousand) salinity. Reid and Wood (1976) provide an empirical equation (salinity $= 0.03 + 1.805 \times$ chlorinity) relating salinity and chlorinity for water in which all the ions occur in the same ratio found in average seawater. A salinity of 0.5 ppt is equivalent to a chloride concentration of 260 mg/L, which is reasonably close to the 250 mg/L limit used in this report.

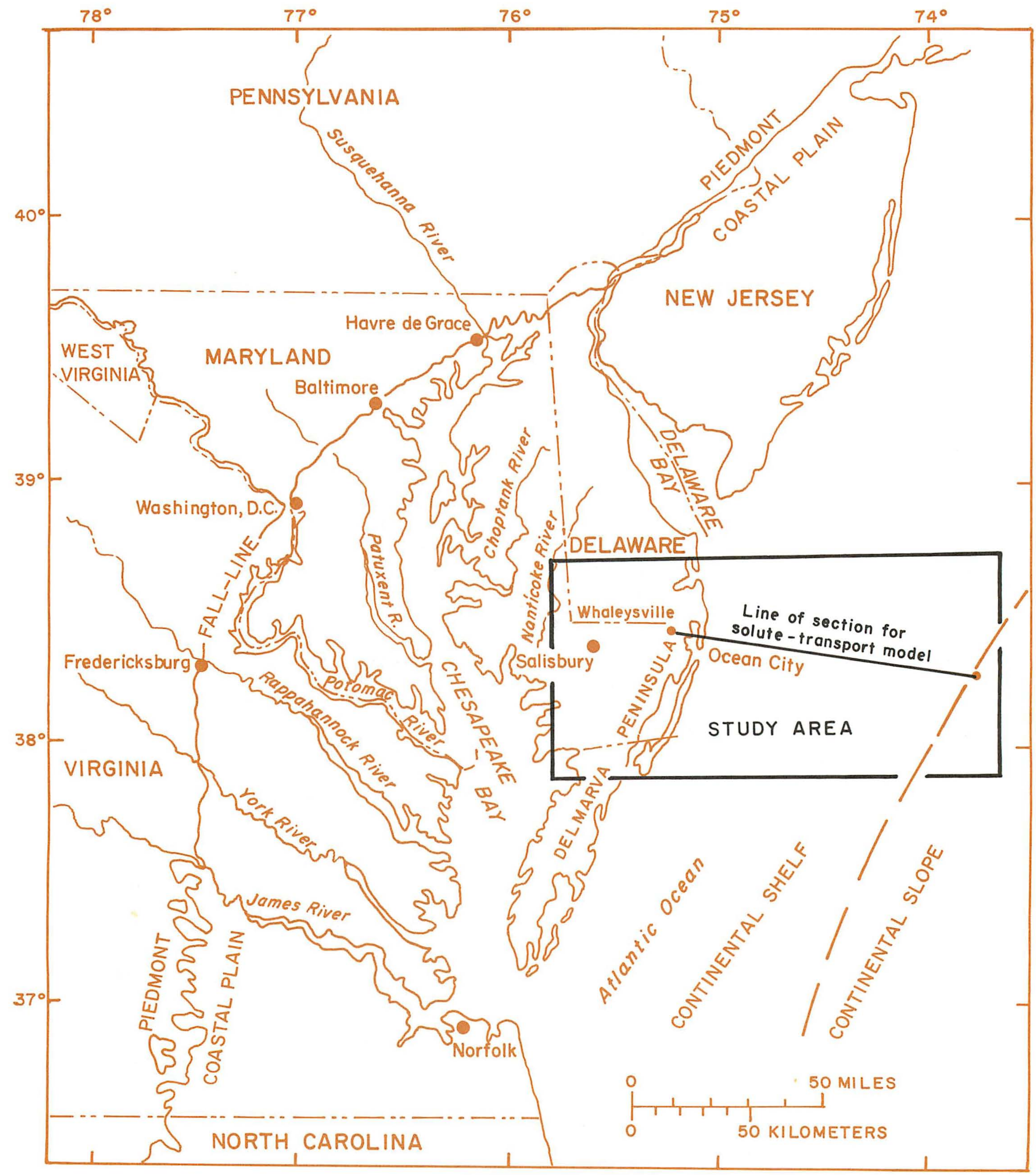


Figure 1.—Location of study area in the mid-Atlantic Coastal Plain and line of section for the solute-transport model through Ocean City, Maryland.

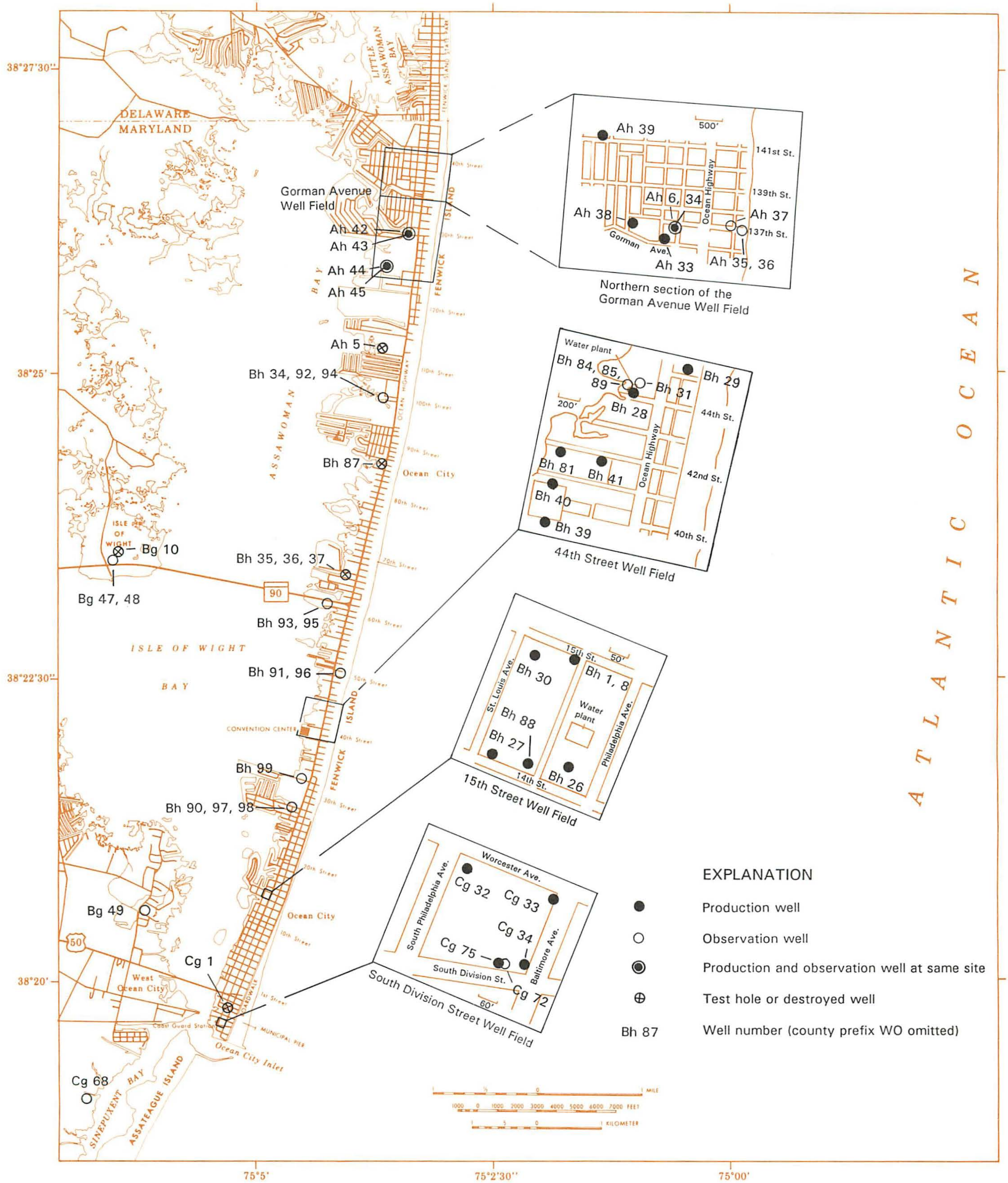


Figure 2.—Locations of test holes, production and observation wells, and well fields in Ocean City, Maryland.

EXPLANATION

● Cg 72 — Site location and well number (County prefix WO omitted from well number).

Figure 3.—Locations of key wells and test holes used for hydrogeologic control.

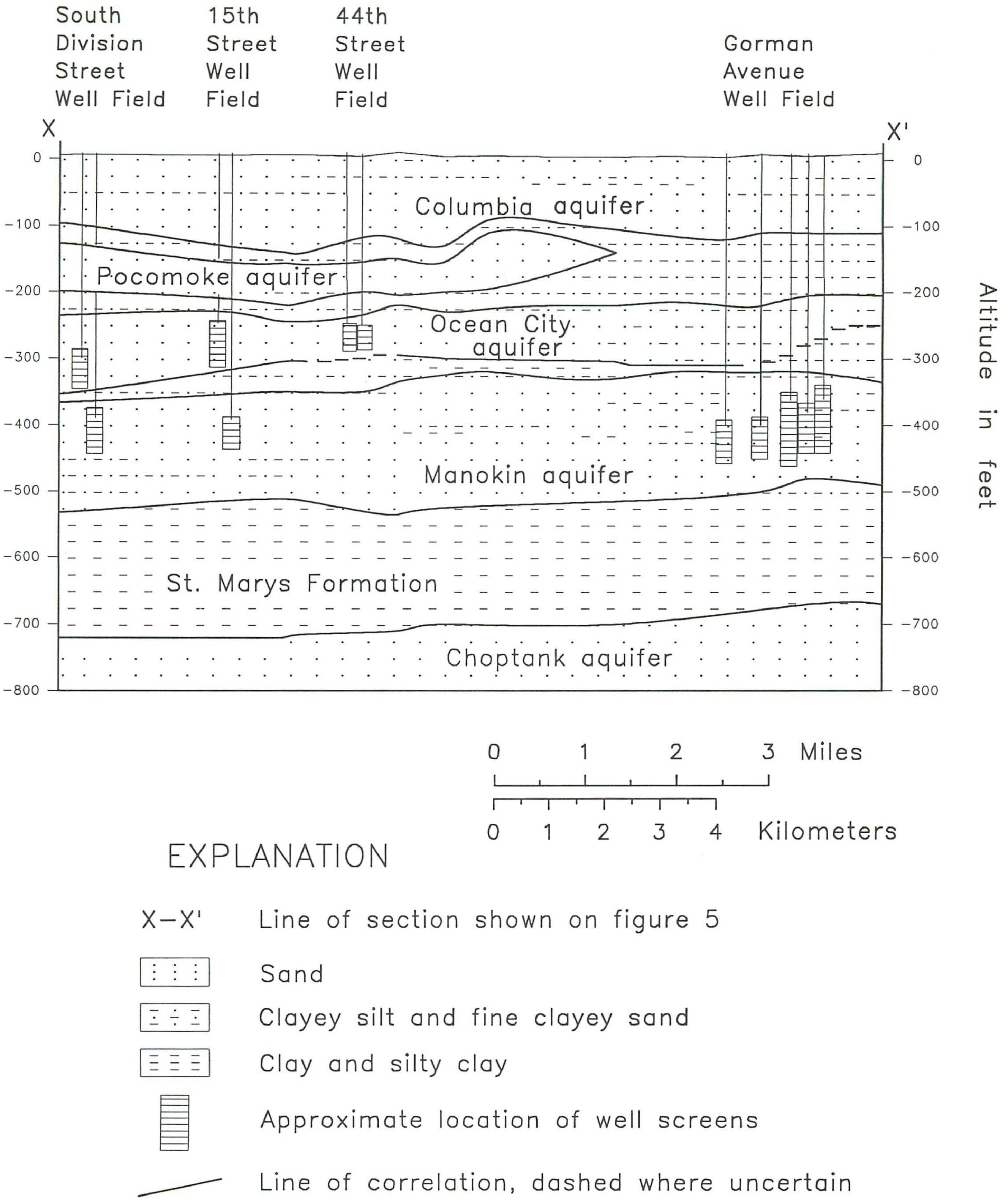


Figure 4.—Generalized hydrogeologic section along south-north direction showing the production well fields and aquifers in Ocean City, Maryland.

Table 1.—Generalized stratigraphic column for Ocean City, Maryland

ERA	SYSTEM	SUBSYSTEM	SERIES/STAGE	GROUP	FORMATION/ INFORMAL UNIT	LITHOLOGY	HYDROLOGIC PROPERTIES	APPROXIMATE THICKNESS OF UNIT (FEET)	APPROXIMATE DEPTH TO BASE (FEET)
CENOZOIC	QUATERNARY		Holocene		Recent deposits	Gray to white, fine to medium, shelly sands and dark gray, silty muds.	Generally unsaturated. Permits leakage to underlying units.	20	20
			Pleistocene	COLUMBIA	Sinepuxent	Dark gray, poorly sorted fine to medium sand; more clayey near base.	Unconfined to semi-confined water-table aquifer and leaky confining unit. Water is mostly fresh; some brackish water intrusion from surface.	30	50
	TERTIARY	NEOGENE	? Pliocene		Beaverdam Sand	Light blue-gray to white, and pale orange, fine to coarse and gravelly feldspathic sand.	Semi-confined water-table aquifer; part of the Columbia aquifer. Water is generally fresh; susceptible to brackish water intrusion from surface.	70	120
			?	CHESAPEAKE	Pocomoke beds	Grayish-green to orange brown; fine to coarse sand; some gravels and clayey silts. Lignite, glauconite, and shell bearing in places.	Pocomoke aquifer and associated confining units. Water is fresh.	80	200
			Upper Miocene		Ocean City beds	Fine to coarse, orange tan sands; and greenish gray, glauconite bearing clayey silts and fine sands; lignite and shell bearing in places.	Ocean City aquifer and underlying confining unit. Water is fresh, but subject to upconing of brackish water in places.	125	325
					Manokin	Light gray to orange brown, fine to coarse and gravelly sand and clayey silts and fine sands; shell, lignite, and glauconite bearing in places.	The Manokin aquifer and associated confining units. Contains brackish water in some areas; chlorides range from less than 50 to 1,000 mg/L.	175	500
			?		St. Marys	Light gray to olive gray, fine sand, and silty clay; mica, glauconite, and shell bearing, minor lignite.	Confining unit. Pore water is brackish. Chlorides range from 1,000 to 2,000 mg/L	200	700
			Middle Miocene		Choptank	Light olive gray, fine to coarse sands; shelly, lignite bearing.	Choptank aquifer. Water is brackish. Chlorides range over 2,700 mg/L.	330	1,030
			? Lower Miocene		Calvert	Pale olive gray to pale brown, silty, clays; sands are fine to medium where present; shell fairly common.	Predominantly a confining unit. Water is brackish at Ocean City.	630	1,660
		PALEO-GENE	Oligocene Eocene Paleocene	PAMUNKEY	Undivided at Ocean City	Light olive gray and brown clays; subordinate fine to medium glauconitic sands.	Predominantly a confining unit at the coast.	440	2,100
MESOZOIC	CRETACEOUS		Upper and Lower undifferentiated	INCLUDES POTOMAC	Cretaceous not divided in this report; see Anderson (1948), Hansen and Doyle (1982) for detailed stratigraphy.	Marine clays and glauconitic sands in upper part of section; nonmarine brown, red and gray clays, and sands in lower part of section.	Confining units and aquifers. Water is salty.	5,150	7,250
	Jurassic (?) and/or Triassic (?)				--	Sandstones and shales.	Confining unit	>460	>7,700
Precambrian (?) and Paleozoic					--	Igneous and metamorphic rocks.	Confining unit	?	?

The break between brackish and saltwater is set at 9,400 mg/L chlorides. This value is based on applying the empirical chlorinity relationship noted above to water with a salinity of 17 ppt. Brackish is a term usually used to describe seawater with a salinity of less than 17 ppt (Davis, 1977).

Table 2.—Classification of water used in the report

Name	Chloride concentration, milligrams per liter (mg/L)
Freshwater	0 – 250
Brackish water	250 – 9,400
Saltwater	More than 9,400

PREVIOUS STUDIES

Rasmussen and Slaughter (1955) and Slaughter (1962) described the hydrogeology of the predominantly freshwater aquifers at Ocean City. Kantrowitz (1969) discussed the hydrogeologic data from test well Ah 6 and found that the Manokin aquifer contained a lower, previously undescribed freshwater sand. Weigle (1974) subdivided Rasmussen and Slaughter's Manokin aquifer into the Ocean City and Manokin aquifers and described the extent of freshwater in northeastern Worcester County. Weigle (1974) found freshwater in most of the section, from land surface to near the base of the Manokin aquifer. Weigle (1974), however, found brackish water (water with a chloride concentration of more than 250 mg/L) in the basal 10 to 20 feet of the Manokin aquifer at Gorman Avenue and also in the upper sands of the surficial aquifer at two locations in the northern half of Ocean City. Weigle and Achmad (1982) used a digital model to simulate ground-water flow in the aquifer systems at Ocean City. The input parameters of Weigle and Achmad's (1982) flow model were based on the hydrogeologic framework described in Weigle (1974). Data from wells drilled by Weigle and Achmad (1982) showed that brackish water occurred in the lower part of the Manokin aquifer in the northern part of Ocean City.

Phelan (1987) included data showing chloride concentrations and municipal pumpage data from 1969 to 1986 for the Ocean City-Manokin aquifer system and other coastal aquifers in Delaware and Maryland. Phelan (1987) documented a trend of rising chloride levels in the Ocean City aquifer at the 44th Street well field. He attributed the rise in chloride concentrations to upconing of brackish water from the Manokin aquifer to the Ocean City aquifer in response to pumpage from the Ocean City aquifer at the 44th Street well field. Whitman, Requardt and Associates (1985, 1989) discussed the threat of saltwater intrusion and described plans for the future development of the Ocean City well fields; the later report includes hydrogeologic data from test and production wells drilled in Ocean City between 1985 and 1990. Other hydrogeologic studies concerning the Ocean City area include a compilation of basic ground-water data for Worcester County (Lucas, 1972). Hydrologic studies in Delaware that are relevant to the Ocean City area include a description of the hydrology and ground-water flow in the Manokin, Ocean City, and Pocomoke aquifers in southeastern Delaware (Hodges, 1984) and a compilation of basic hydrologic data for the coastal part of Sussex County, Delaware (Talley and Andres, 1987).

Studies concerned primarily with the stratigraphy of the region include Owens and Denny's (1978) geologic map of Worcester County and Owens and Denny's (1979) report on the upper Cenozoic deposits of the central Delmarva Peninsula, Delaware, and Maryland. Hansen (1981) discusses a major unconformity separating the Columbia Group from the underlying upper Miocene aquifer complex on the Eastern Shore of Maryland. Gibson (1983) discusses the depositional environments and stratigraphy of the Neogene section in the Salisbury and Albemarle Embayments of the mid-Atlantic Coastal Plain. Andres (1986) describes the offshore and onshore stratigraphy and depositional history of the post-Choptank Chesapeake Group in Delaware and Maryland and he introduced two informal formation names for the section included in the "Yorktown and Cohansey Formations(?) undifferentiated" of Rasmussen and Slaughter (1955). Benson and others (1986) describe the seismic stratigraphy off the coast of southern Delaware and the northern part of Ocean City, Maryland. Mixon (1985) discusses the stratigraphy and geomorphic framework of the uppermost Cenozoic deposits in the Eastern Shore of Virginia and Maryland. Toscano and others (1989) describes the seismic stratigraphy of the Quaternary and uppermost Tertiary units off the Maryland coast. Groot, Ramsey, and Wehmiller (1990) discuss the age relations of the Miocene, Pliocene and Quaternary units on the Delmarva Peninsula. Benson (1990) describes the litho- and biostratigraphy, paleoenvironments, and hydrogeology of the Oligocene to Pleistocene section near Lewes, Delaware, and Ramsey and Schenck (1990) show the distribution of the surficial geologic units, major faults, and the updip limit of the subsurface units in southern Delaware.

NOMENCLATURE

This report focuses on the part of the hydrogeologic section that includes the Manokin, Ocean City, and Pocomoke aquifers in Ocean City and adjacent areas of northeastern Worcester County. This part of the section was previously included in one lithostratigraphic unit, the "Yorktown and Cohansey Formations(?) undifferentiated" (Rasmussen and Slaughter, 1955; Weigle, 1974). Hydrostratigraphic units were erected by Rasmussen and Slaughter (1955) to describe the predominantly freshwater aquifers at Ocean City. From stratigraphically highest to lowest, Rasmussen and Slaughter's (1955) units are: a semiconfined to unconfined water-table aquifer that included the Beaverdam Sand and the Red Gravelly Sand; the "upper aquiclude"; the Pocomoke aquifer; the lower "aquiclude"; the Manokin aquifer; and the St. Marys Formation aquiclude (a confining unit) (tab. 3). Rasmussen and Slaughter (1955) included the sands now assigned to the Ocean City aquifer in the Manokin aquifer. Weigle (1974) subdivided Rasmussen and Slaughter's (1955) Manokin aquifer into upper and lower units (tab. 3). Weigle called the upper unit the Ocean City aquifer and retained the name Manokin aquifer for the lower unit. In Weigle's (1974) aquifer framework, the basal part of the "lower confining" unit separates the Ocean City aquifer from the underlying Manokin aquifer, and the upper part of the "lower confining" unit separates the Ocean City aquifer from the overlying Pocomoke aquifer. Weigle (1974) recognized, however, that the Ocean City and Manokin aquifers form an interconnected aquifer system. Hansen (1981) discusses some of the problems associated with this nomenclature.

Both Owens and Denny (1979) and Hansen (1981) recognized the sands that comprise the Manokin aquifer as a mappable lithostratigraphic unit, and Owens and Denny (1979) used the informal name "Manokin beds" for this sandy interval. Owens and Denny (1979) also used the informal term "Pocomoke beds" to describe the sandy interval corresponding to the Pocomoke aquifer of Rasmussen and Slaughter (1955).

In southern Worcester County, Mixon (1985) and Mixon and Powars (oral communication, 1990) have recognized different lithostratigraphic units within the "Yorktown and Cohansey Formations(?) undifferentiated" and correlated these units with formations established in Virginia. In Delaware, Andres (1986) proposed two informal lithostratigraphic units—the Manokin formation and the Bethany formation—to replace the "Yorktown and Cohansey Formations(?) undifferentiated." Andres' (1986) Manokin formation corresponds to the predominantly sandy interval occupied by the Manokin aquifer. Andres' (1986) Bethany formation overlies the Manokin formation and corresponds to the part of the geologic section that lies between the Manokin formation and the Columbia Group.

In this report the Manokin formation of Andres' (1986) as modified by Groot, Ramsey, and Wehmiller (1990) is used to refer to the sands and associated subordinate clayey beds that overlie the St. Marys Formation and which include the Manokin aquifer at Ocean City. Correlation of the Bethany formation through the Ocean City area and the relation of the Bethany to the units mapped by Mixon (1985) and Mixon and Powars (oral communication, 1990) in southeastern Worcester County is at present uncertain. Therefore, two informal lithostratigraphic units are used in this report to denote sediments in the Ocean City area that lie between the Manokin formation and the overlying Columbia Group. One, the "Ocean City beds" refers to the part of the section that includes the economically important sands of the Ocean City aquifer and the associated clayey silts. The other, the "Pocomoke beds" (Owens and Denny, 1979) refers to the sands of the Pocomoke aquifer and associated clayey silts.

STRATIGRAPHIC AND HYDROGEOLOGIC DATA

The stratigraphy and hydrogeologic framework of the upper Neogene section on the lower Eastern Shore of Maryland are described using hydrogeologic cross-sections and maps showing the depth below sea level and thickness of formations and aquifers. Sources of stratigraphic and hydrogeologic data include previously published reports, data on file at the Maryland Geological Survey, and field investigations conducted as part of this study. The thickness and structure contour maps in this report extend into southern Delaware to provide a regional context for the Ocean City area. The primary source of data, including formation and aquifer contacts, used to construct the parts of these maps that lie in Delaware were the cross-sections and maps published in Andres (1986) and Talley (1987).

WATER CHEMISTRY DATA

Water chemistry data were obtained from the U.S. Geological Survey National Water Quality Data Base, records on file at the Maryland Geological Survey, Phelan (1987), and Whitman, Requardt and Associates (1989). Weekly water samples from the pumping wells have been collected by the Ocean City Water Department and analyzed for chlorides by the Worcester County Health Department since 1974. The weekly chloride data, compiled as part of an ongoing water quality monitoring project of the coastal aquifers in Maryland, were significant to this study. Additional water chemistry data were obtained from sampling done as part of this study. The water quality data were used to map chloride distribution and calibrate the solute-transport model.

ACKNOWLEDGMENTS

The authors thank Daniel Phelan and Debra Bringman (U.S. Geological Survey) for providing us with the water-level and water-quality data they collected at Ocean City; Perry Linz and Ronald Ellis (Ocean City Water Department) for providing access to the town's production wells; Louis Vlangas (Whitman, Requardt and Associates) who shared the hydrogeologic data he collected and also provided a helpful review. We also thank our other reviewers, Barry Smith (U.S. Geological Survey); John Talley, A. Scott Andres, and Kelvin Ramsey (Delaware Geological Survey); and David Drummond and Harry Hansen for providing constructive comments that improved earlier drafts of the manuscript. We also thank Donajean Appel who typed the report and Barbara Cooper, Frances Baldwin and Cynthia Lang-Bachur for drafting assistance. The cover photograph was provided by the Shore Erosion Control Program of the Maryland Department of Natural Resources. It is an oblique, aerial view of Ocean City looking north and was taken on September 22, 1988.

Table 3.—Lithostratigraphic and hydrostratigraphic nomenclature used in Wicomico, Worcester, and Somerset Counties, Maryland, and adjacent parts of Delaware

System	Series	Stage	Lithostratigraphic units: Owens and Denny (1979) Worcester, Wicomico and Somerset counties	Lithostratigraphic units: Andres (1986) Southern Delaware, northern Worcester County, Maryland	Lithostratigraphic units: Groot, Ramsey and Wehmiller (1990) Southern Delaware	Lithostratigraphic units: This Report Ocean City and northeastern Worcester County	Hydrostratigraphic units: Rasmussen and Slaughter (1955) Worcester, Wicomico and Somerset counties	Hydrostratigraphic units: Weigle (1974) Weigle and Achmad (1982) Ocean City and northeastern Worcester County	Hydrostratigraphic units: This Report Ocean City and northeastern Worcester County
Quaternary	Holocene		Barrier beach and lagoonal deposits	Unnamed beds	not studied	Recent deposits	Unnamed units	Unconfined aquifer	Leaky confining unit
Quaternary	Pleistocene		Sinepuxent, Ironshire and Omar Formations	Omar Formation Beaverdam Formation	Omar Formation	Sinepuxent, Ironshire and Omar Formations ?	Pleistocene sands and aquicludes Beaverdam Sand ?	partial confining bed Pleistocene aquifer (Beaverdam Sand)	Columbia aquifer
Tertiary	Pliocene		Walston Silt Beaverdam Sand	No units assigned to the Pliocene	Beaverdam Formation ?	Beaverdam Sand ?	Red gravelly sand	No units assigned to the Pliocene	?
Tertiary	Miocene	Upper	Pensauken Yorktown and Cohansey (?) Formations	Stages not assigned Bethany formation	Bethany formation	Pocomoke beds	upper aquiclude Pocomoke aquifer lower aquiclude	upper confining bed Pocomoke aquifer	confining unit Pocomoke aquifer confining unit
Tertiary	Miocene	Upper				Ocean City beds	Manokin aquifer	upper part of lower confining bed Ocean City aquifer basal part of lower confining bed	Ocean City aquifer and confining unit
Tertiary	Miocene	Upper		Manokin formation	not studied in southern Delaware	Manokin formation		Manokin aquifer	Manokin aquifer
Tertiary	Miocene	Upper	St. Marys (?) Formation	St. Marys (?) Formation ?		St. Marys Formation ?	aquiclude (St. Marys Fm.)	aquiclude (St. Marys (?) Fm.)	confining unit (St. Marys Fm.) ?
Tertiary	Miocene	Middle	not studied	Choptank Formation		Choptank Formation ?	Choptank aquifer	Choptank aquifer and confining beds	Choptank aquifer ?
Tertiary	Miocene	Lower		Calvert Formation		Calvert Formation	Nanticoke aquifer	aquifers and confining beds of the Calvert Fm.	confining unit (Calvert Fm.)

GEOLOGY

REGIONAL SETTING

Ocean City lies on a barrier island that marks the present eastward edge of the emerged Atlantic Coastal Plain in Maryland (fig. 1). The Coastal Plain sediments of Maryland form a thick clastic wedge of generally unconsolidated, eastward dipping sediments that thicken from a few feet at the Fall Line to over 7,700 feet at Ocean City (Anderson, 1948; Olsson and others, 1988) (tab. 1). Offshore, the wedge of Coastal Plain sediments continues to thicken eastward to the continental slope (fig. 1). The Coastal Plain sediments in Maryland were deposited in the Salisbury Embayment, a depositional basin located between two structural highs—the South New Jersey Arch to the north and the Norfolk Arch to the south.

STRATIGRAPHY AT OCEAN CITY

Calvert Formation

The lower(?) to middle Miocene Calvert Formation is the basal unit of the Chesapeake Group in Maryland. Rasmussen and Slaughter (1955) tentatively picked the base of the Calvert Formation at 1,642 feet and the top of the Calvert at 962 feet below sea level in Bh 11 (Maryland Esso No. 1) (fig. 3). The contact of the Calvert with the overlying Choptank Formation at Ocean City is not, however, established biostratigraphically. Subsurface correlations by Benson (1990) suggest that the contact of the Calvert and Choptank Formations is deeper than where Rasmussen and Slaughter (1955) picked the contact. Eight miles west of Ocean City, near Berlin (fig. 3), the Calvert section in Ce 12 (Mobil Bethards No. 1) is a "pale-gray to grayish-white silty clay with occasional streaks of fine to medium sand. Traces of glauconite, shell, lignite were noted" (Anderson, 1948). The lithology of the Calvert section at Ocean City is probably similar to that in Ce 12.

Choptank Formation

The Choptank Formation is a middle Miocene, marginal marine to middle shelf marine unit that overlies the Calvert Formation (Gibson, 1962, 1983; Gernant, 1970). At Ocean City, the upper part of the Choptank is predominantly a light olive-gray, fine to coarse, shelly sand with subordinate beds of light olive-gray, glauconite-bearing, silty fine sand and light gray, clayey silt. The top of the Choptank ranges from 660 to 730 feet below sea level at Ocean City (fig. 6).

St. Marys Formation

The St. Marys Formation unconformably overlies the Choptank Formation on the lower Eastern Shore of Maryland (Hansen, 1981). The St. Marys at Ocean City is predominantly a light olive gray, shell-, lignite-, glauconite- and mica-bearing, clayey silt and silty clay; subordinate beds of clayey, fine silty sand are present in the formation. The St. Marys in the subsurface of the Eastern Shore is considered middle(?) (Owens and Denny, 1979) to upper Miocene (Gibson, 1983; Benson, 1990). At Ocean City, the depth to the top of the St. Marys ranges from 480 to 530 feet below sea level and the thickness ranges from 180 to 220 feet (figs. 7 and 8).

Manokin Formation

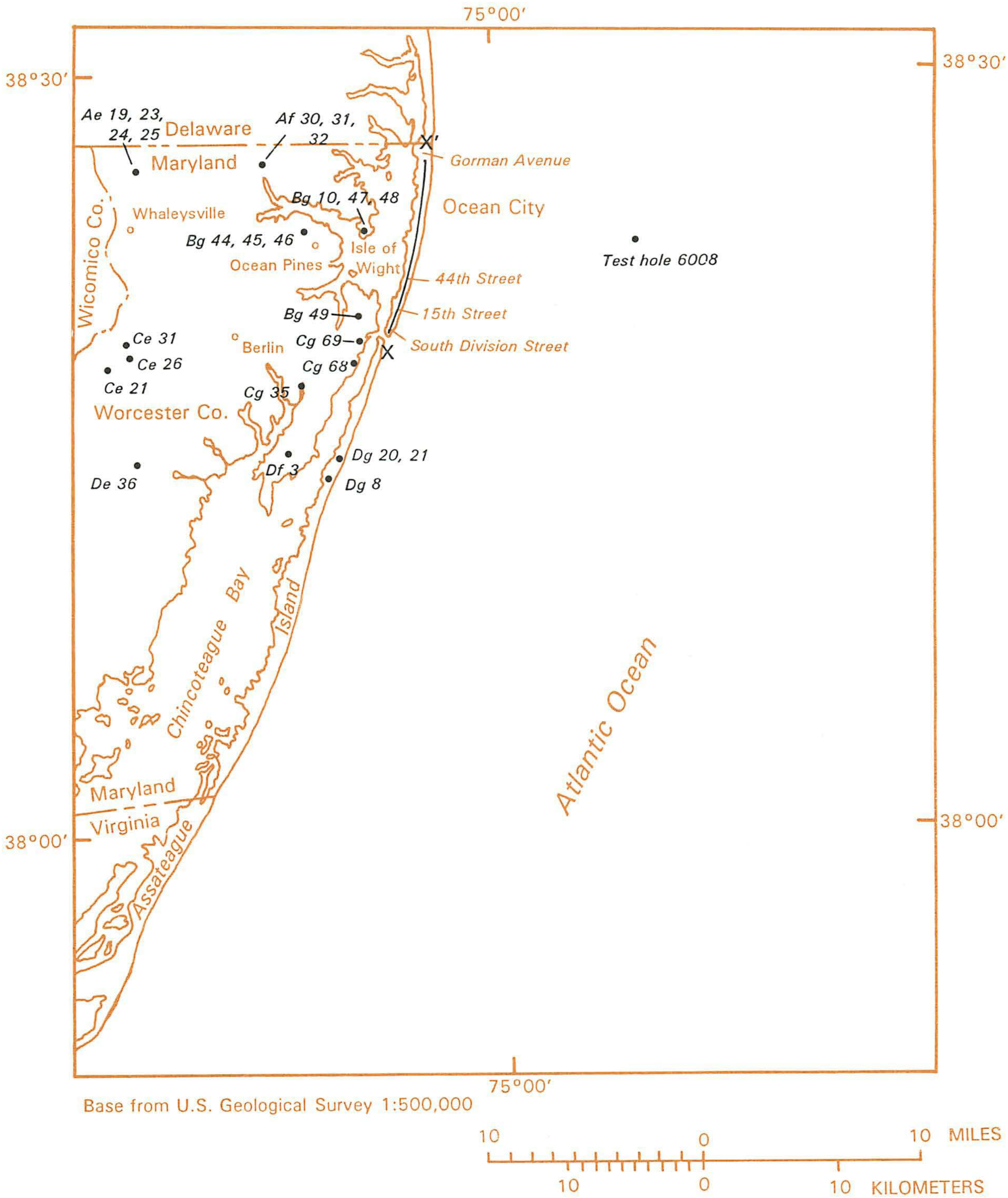
The upper Miocene Manokin formation (Andres, 1986) conformably overlies the St. Marys Formation at Ocean City and throughout Worcester County. At Ocean City, the base of the Manokin ranges from about 480 to 530 feet below sea level and the top of the Manokin varies between about 300 to 360 feet below sea level (figs. 7 and 9, pls. 1–3). The Manokin at Ocean City ranges from 145 to 195 feet thick (fig. 10).

The contact of the St. Marys Formation with the Manokin is generally gradational and characterized by an overall coarsening-upward cycle that is recognizable in well logs. The nature of the contact suggests 1) the St. Marys-Manokin section is part of a single depositional sequence and 2) the transition from the middle to inner shelf sediments of the St. Marys to the marginal-marine lithofacies of the Manokin represents a major regressive cycle (Hansen, 1981). The base of the Manokin formation is defined as the first inflection point (50 percent clay–50 percent sand) above the typical St. Marys gamma-log trace (Groot, Ramsey, and Wehmiller, 1990). The contact of the St. Marys Formation and overlying Manokin ranges from gradational to locally sharp and unconformable in Maryland and Delaware (Hansen, 1981; Groot, Ramsey, and Wehmiller, 1990). At Ocean City the uppermost sand of the Manokin formation has a characteristic blocky shape on gamma logs. The top of this sand is picked as the contact between the Manokin formation and the overlying Ocean City beds.

Owens and Denny (1979) and Hansen (1981) recognized that the sediments assigned to the Manokin formation and overlying Ocean City and Pocomoke beds represent deltaic and shallow shelf facies. Andres (1986) reports that the sediments of the Manokin are probably wave reworked distributary channel sands and channel mouth bars deposited in a delta front to lower delta plain setting. Groot, Ramsey, and Wehmiller (1990) believe that it is unclear whether the Manokin delta system was a fluvial or wave dominated system.

At Ocean City, the Manokin was deposited in a fluvial-dominated, high constructive, delta system. A strong fluvial component in the construction of the Manokin delta system is suggested by the persistence updip of the upper Manokin sand

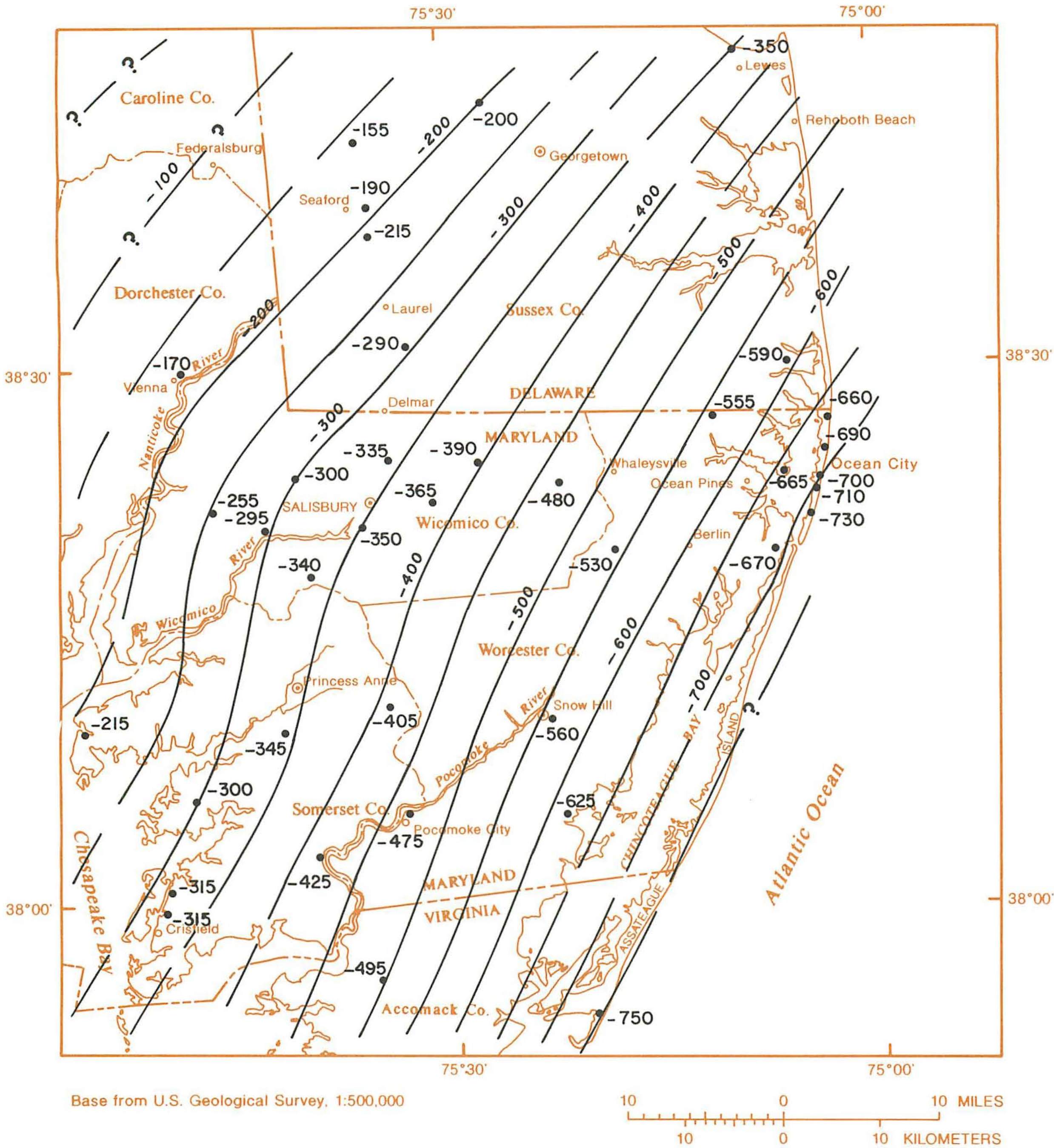
(Text continued on p. 19.)



EXPLANATION

● Cg 69	Site location and well number (County prefix WO omitted from well number).
X——X'	Location of hydrogeologic section, shown in figures 4, 24 and 25.

Figure 5.—Locations of wells and test holes in northeastern Worcester County, excluding Ocean City.



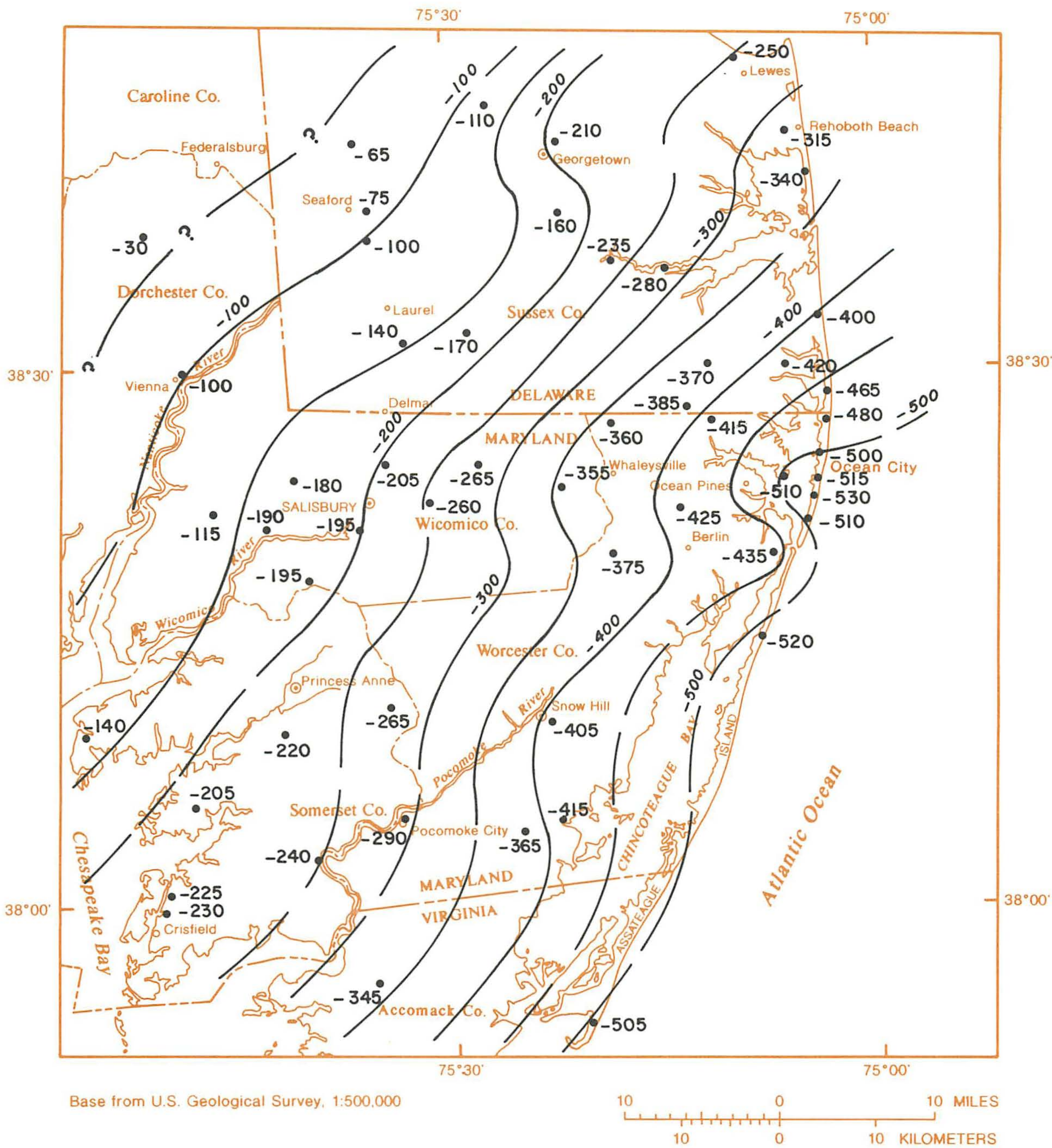
EXPLANATION

● -700 Data point and altitude in feet below sea level.

-750 ? Line of equal altitude; queried where uncertain.

Contour interval 50 feet. Datum is sea level.

Figure 6.—Altitude of the top of the Choptank Formation (base of the St. Marys Formation).



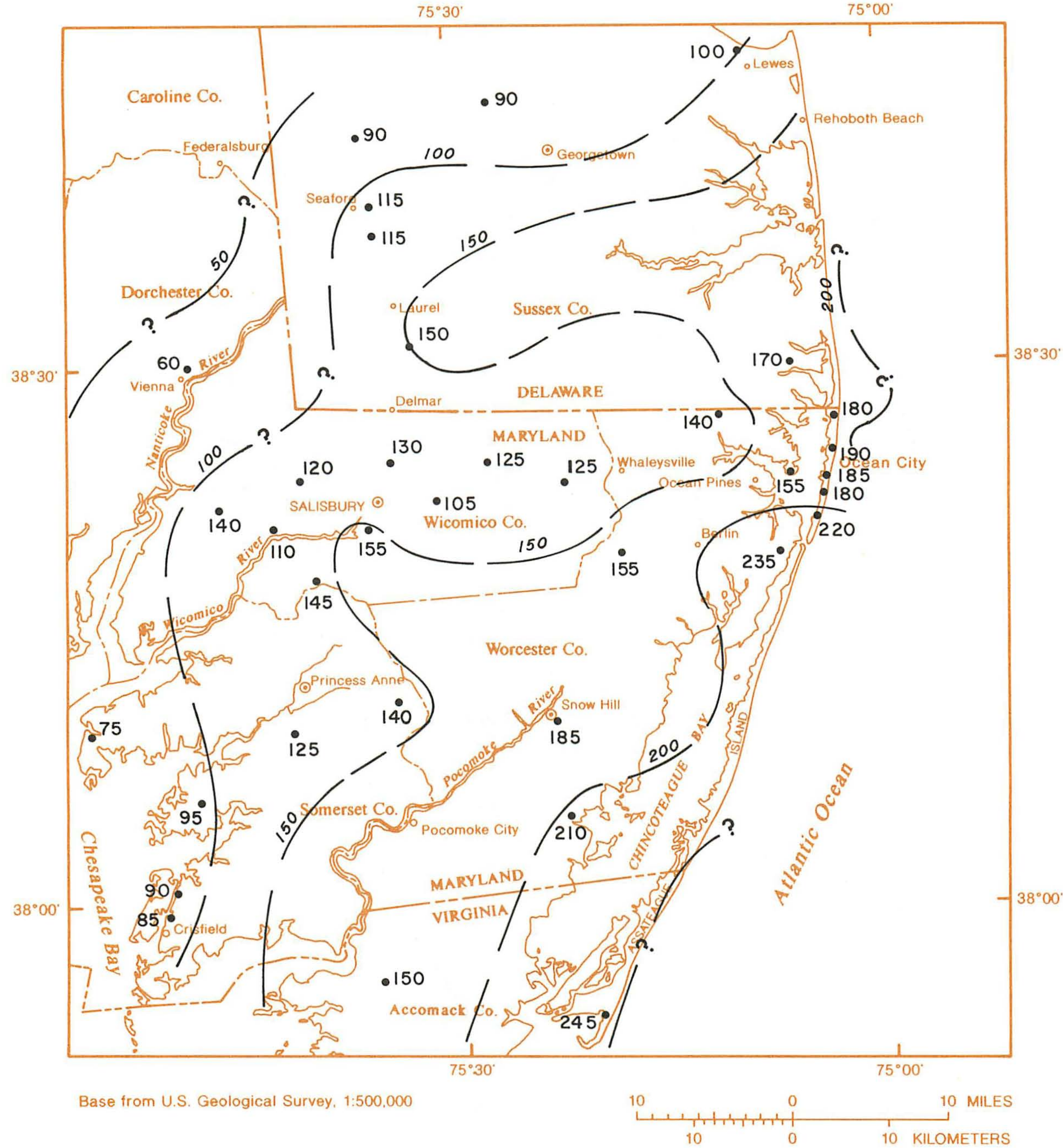
EXPLANATION

● -500 Data point and altitude in feet below sea level.

-500 ——— ? — Line of equal altitude; queried where uncertain.

Contour interval 50 feet. Datum is sea level.

Figure 7.—Altitude of the top of the St. Marys Formation.



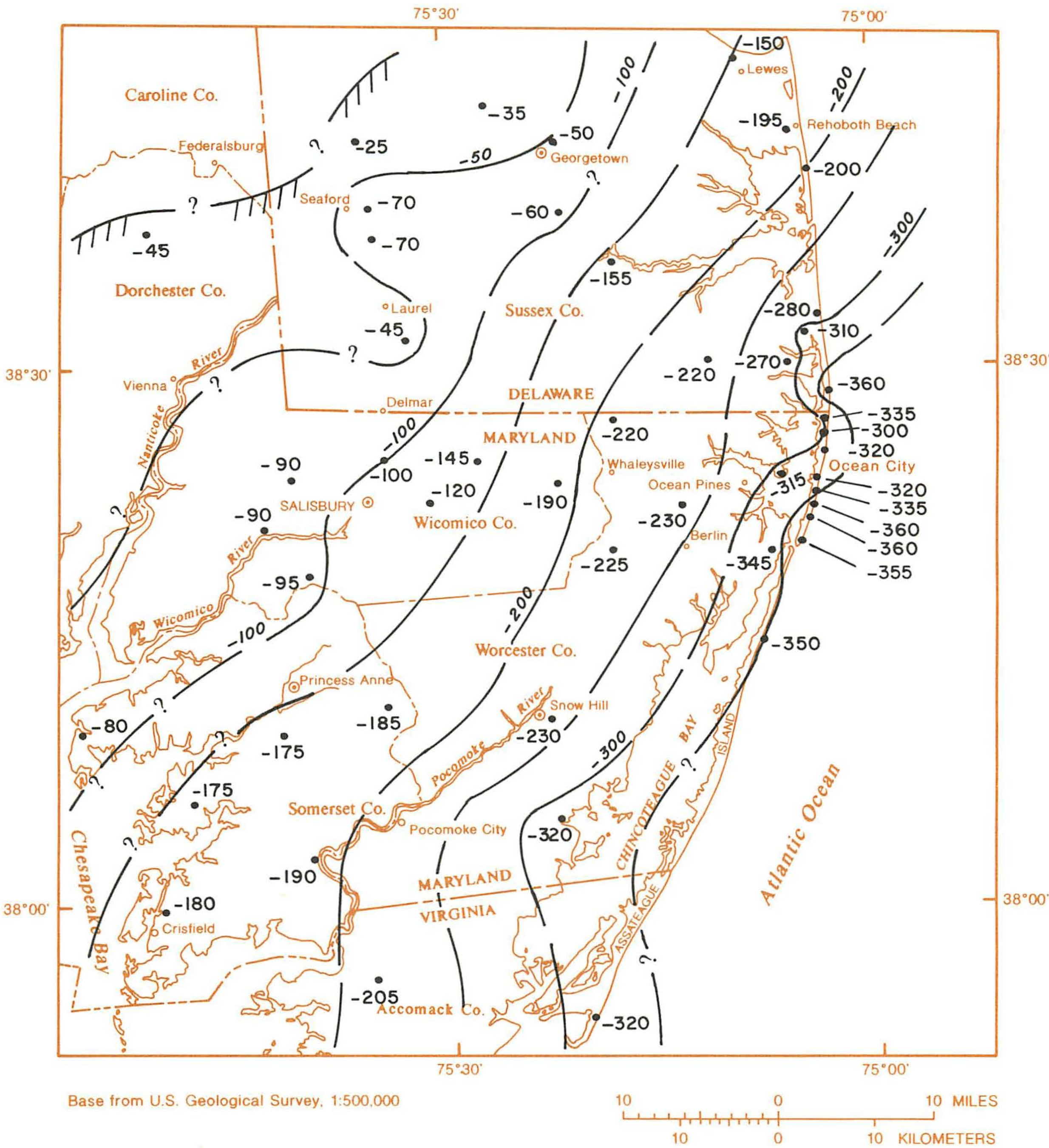
EXPLANATION

● 185 Data point and thickness in feet of the St. Marys Formation.

200 ——— ? — Line of equal thickness; queried where uncertain.

Contour interval is 50 feet.

Figure 8.—Thickness of the St. Marys Formation.



EXPLANATION

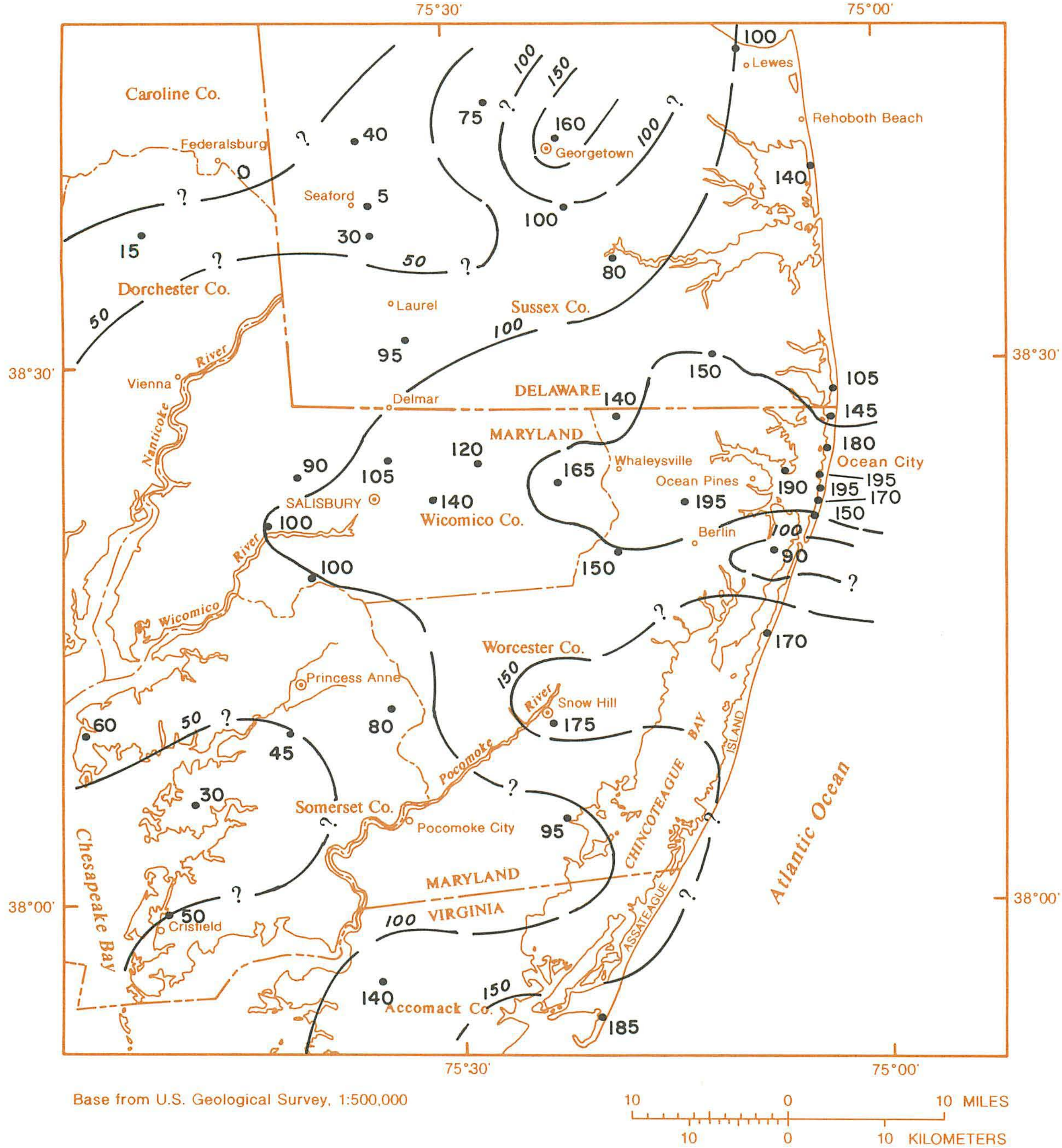
• -190 Data point and altitude in feet below sea level.

-200 ? Line of equal altitude; queried where uncertain.

Updip limit of formation; queried where uncertain.

Contour interval 50 feet. Datum is sea level.

Figure 9.—Altitude of the top of the Manokin formation.



EXPLANATION

● 185 — Data point and thickness in feet.

200 ———?— Line of equal thickness; queried where uncertain.

Contour interval is 50 feet.

Figure 10.—Thickness of the Manokin formation.

facies (probably coalesced distributary channel-sands) from Ocean City west to at least Salisbury (pl. 2). Marine reworking of the Manokin sediments at Ocean City appears restricted to the lower parts of the formation. Figure 11 (after Fisher and others, 1969) illustrates schematically the principal facies of this type of delta. Deposition in a fluvial-dominated, high-constructive delta system is indicated by the following:

a) Progradational coarsening-upward gamma-log facies[1] and aggradational gamma-log facies with erosive bases comprise the bulk of the Manokin section at Ocean City (pls. 1–3). For example on plate 1 in well Bh 91, the gamma log shows a series of coarsening-upward sequences. Each sequence is overlain, probably by truncation, by a coarsening-upward sequence that is coarser than the underlying sequence. A series of gamma-log sequences like those in the lower part of the Manokin are characteristic of prograding delta systems. Sands in the upper part of the Manokin in wells Bh 90, 91 and 93 have gamma-log curves with sharp basal contacts that are characteristic of channel-fill sequences. In a delta environment these gamma-log traces most likely represent distributary channels or channel-mouth bars.

b) The lithology of the Manokin drill cuttings (app. D), is characteristic of deltaic deposits. Three sandy facies of the Manokin formation, each related to the overall coarsening-upward trend, are characteristic of the section at Ocean City. A basal silty-sand facies of the Manokin section represents the transition from the silty clays and clayey silts of the St. Marys Formation to the sands of the lower part of the Manokin. Environmentally, the basal coarsening-upward sequences represent the transition from inner-shelf deposition in the upper part of the St. Marys to delta-front deposition in the Manokin. This transition facies is illustrated on plate 1 by the initial coarsening-upward sequences shown on the gamma-log traces above the St. Marys Formation contact. At some sites in Ocean City (for example Bh 91 at 51st Street), the transition from the clayey silts of the St. Marys to the Manokin sands is both lower in the section and more abrupt than elsewhere on the island.

A second sandy facies is present in the lower part of the Manokin section at Ocean City. This facies is a gray to grayish orange, fine to medium (ranging up to coarse), silty sand; shell is relatively common and minor amounts of lignite and glauconite occur in this section. This lithology is characteristic of delta front sands. The gamma-log trace of this facies represents stacked, 15 to 25 foot thick, coarsening-upward sequences. This gamma-log facies is best represented in well Bh 91 (pl. 1) between 530 and 400 feet below sea level. Each coarsening-upward sequence is generally coarser than and appears to truncate the underlying sequence. The stacked coarsening-upward sequences indicate prograding delta-front sands, shallowing water, and the transition from distal delta-front to proximal delta-front deposition at Ocean City. The St. Marys-Manokin transition facies and the lower sandy unit of the Manokin described above correspond to the Manokin A lithostratigraphic unit of Groot and others (1990) and Ramsey and Schenck (1990).

A third sand facies of the Manokin formation forms the upper part of the Manokin at Ocean City. This facies is a grayish-orange to orange-tan, fine to coarse, sometimes gravelly sand in which lignite is a common but minor accessory. There is generally little shell in this lithofacies. (Glauconite is a rare occurrence in the drill cuttings from this section, but it may be recirculated from higher in the hole). This lithology is characteristic of distributary channels (on the delta plain or proximal part of the delta front) and channel-mouth bars, and it suggests a strong fluvial influence during construction of this part of the delta sequence. On gamma logs, the upper Manokin facies is characterized by blocky gamma-traces with erosive bases that appear to truncate underlying coarsening-upward sequences (pl. 1). This upper sand facies corresponds to the Manokin B lithostratigraphic unit of Groot, Ramsey, and Wehmiller (1990) and Ramsey and Schenck (1990). Sands of this facies occur deeper in the Manokin section at the northern end of Ocean City than in the central and southern parts of the town (pl. 1).

c) The structure contour map of the top of the St. Marys Formation (fig. 7) illustrates the lobate shape of the base of the Manokin formation in Worcester County, and in eastern Somerset and eastern Wicomico County. (In western Somerset and western Wicomico County, the top of the St. Marys may not always coincide with the base of the Manokin due to truncation of the Manokin by younger units.) Comparison of the thickness maps of the St. Marys and overlying Manokin formation (figs. 8 and 10) shows that the thicker Manokin section is obtained at the expense of the underlying St. Marys Formation and that the Manokin formation has a lenticular cross-section parallel to strike. The Manokin section thickens markedly from well Cg 68 located southwest of Ocean City north to Bh 91 at 51st Street (pl. 3). The section then thins from Bh 91 north to Ah 6. The deepest and thickest part of the entire Manokin section encountered to date occurs at Ocean City in well Bh 91 (51st Street) (pl. 1, figs. 7 and 10). In Bh 91 the base of the Manokin occurs at 530 feet below sea level and the Manokin section is 195 feet thick. Andres (1986) mapped several principal lobes of Manokin deposition including one that trends through Ocean City. The greater thickness and depth of the Manokin at Ocean City supports Andres (1986) conclusion that the Ocean City area coincides with the axis of a principal lobe of the Manokin delta system.

Ocean City Beds

The upper Miocene "Ocean City beds" overlie the Manokin formation at Ocean City. The "Ocean City beds" include the Ocean City aquifer and the associated clayey silts that form the confining beds within the aquifer and the underlying confining unit. Two lithofacies are present in the Ocean City beds at Ocean City (pl. 1). In the central and southern part of Ocean City (south of about 61st Street), the Ocean City beds are predomi-

[1] Gamma-log facies—distinctive shapes of the gamma-log curve can correspond to specific depositional facies. Although there may be more than one depositional facies that corresponds to a distinctive gamma-log trace, other environmental indicators such as texture and mineralogy can often eliminate an alternative interpretation. Interpretation of depositional facies using gamma-log facies is described in Selley (1978), and Fisher and others (1969).

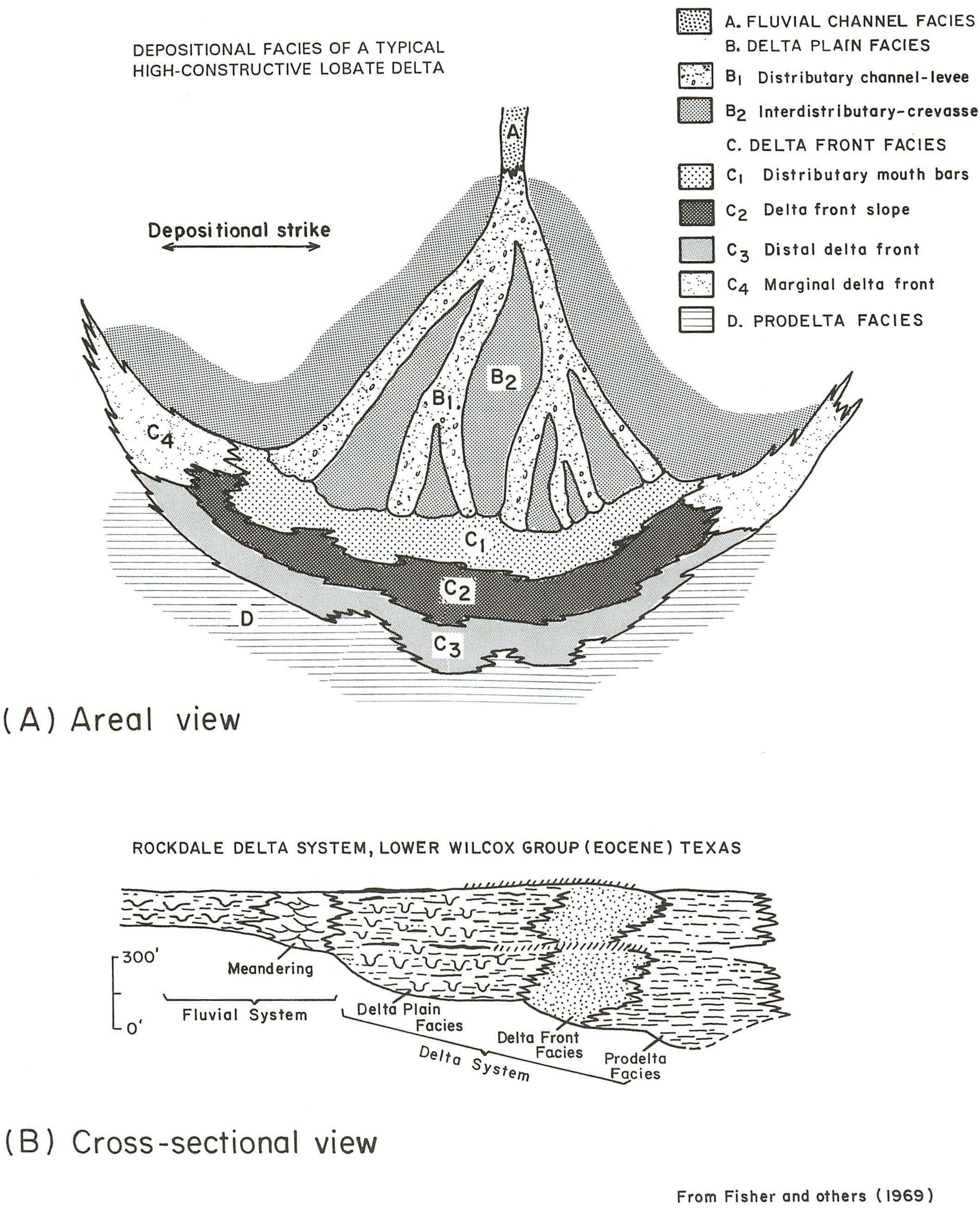


Figure 11.—Principal facies of a high-constructive lobate delta: (A). Areal view and (B). Cross-sectional view.

nantly a fine to coarse, grayish-tan and orange-tan sand. Shell is generally absent in this sand between 44th and 61st Streets, but shell becomes more common in the section to the south (at South Division Street and on Assateague Island). The gamma log trace and lithology of this facies are suggestive of distributary channel-sands or channel-mouth bars (pl. 1, app. D).

Between 61st and 100th Streets, the Ocean City beds become a gray, shell-bearing, glauconite-bearing, fine clayey sand and clayey silt with discontinuous, fine to medium, 10 to 25 foot thick sands occurring in the section. This lithology is suggestive of distal delta-front sediments that have been reworked by marine processes with the sand bodies in the section representing offshore bars. The lithology of the Ocean City beds in the northern part of Ocean City is more similar to the lithology of the Bethany formation in southeastern Delaware (Andres, 1986) than the lithology of the Ocean City beds south of 61st Street. Andres (1986) and Groot, Ramsey, and Wehmiller (1990) interpret the Bethany formation as a deltaic deposit and note that the Bethany becomes muddier down dip.

The relationship of the Ocean City beds south of 61st Street to the Ocean City beds north of 61st Street is uncertain. The relatively abrupt change in lithology south of 61st Street suggests that the Ocean City beds south of 61st Street may represent a younger prograding delta sequence that has truncated the more muddy unit north of 61st Street.

The Ocean City beds at Ocean City are on strike with the Eastover Formation in Fd 33, but these units may not be stratigraphically correlative (fig. 3; pl. 3). R. B. Mixon and D. S. Powars (oral communication, 1990) tentatively pick the base of the Eastover Formation in Fd 33 at the base of a glauconite-bearing sand at 298 feet below sea level.

Pocomoke Beds

In the Ocean City area, the Pocomoke beds are gray to grayish-orange, shell- and lignite-bearing sands interbedded with glauconite-bearing, fine sandy silts and clays. The base of the Pocomoke beds at Ocean City is a gray, glauconite-bearing, clayey silt and fine, clayey sand. The "Pocomoke beds" is an informal unit erected by Owens and Denny (1979). The Pocomoke beds include the sands of the Pocomoke aquifer in northeastern Worcester County. The age of the Pocomoke beds is uncertain. Owens and Denny (1979) considered them late Miocene, but Mixon (1985) suggested a Pliocene age for at least the upper part of the unit.

Beaverdam Sand

The Beaverdam Sand at Ocean City is a light gray to light brownish-gray, medium to coarse sand, that in places is gravelly; finer grained, silty sands are common in the upper part of the unit. The Beaverdam Sand unconformably overlies the Pocomoke beds at Ocean City. Paleochannels infilled with sands of the Beaverdam breach the upper clayey silt and sand of the Pocomoke beds (pls. 1–3; fig. 12). Groot, Ramsey, and Wehmiller (1990) note that the Beaverdam is divisible into two parts: a lower, fluvial, channel-fill sequence that fines upward into an upper, estuarine-fill sequence. The Beaverdam Sand is considered Pliocene (Owens and Denny, 1979; Groot, Ramsey, and Wehmiller, 1990). The thickness of the Beaverdam Sand ranges from about 50 to 80 feet at Ocean City.

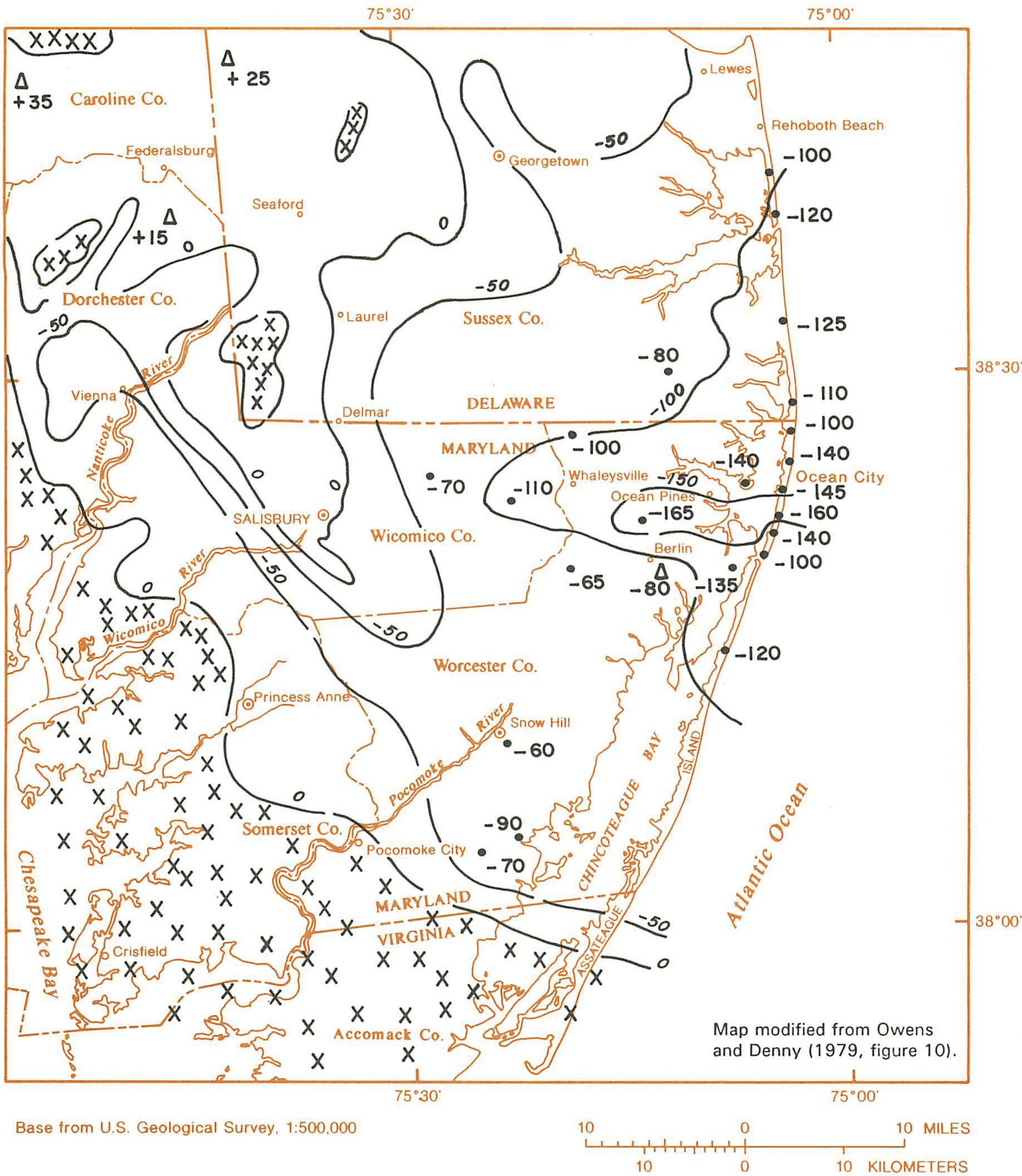
Sinepuxent Formation

At Ocean City, the Pleistocene Sinepuxent Formation (Owens and Denny, 1979) is a fine to medium, silty, light orange tan to gray sand that becomes more clayey towards the base of the formation. The contact of the Sinepuxent and the underlying Beaverdam is unconformable (Owens and Denny, 1979). The gamma log signature of the Sinepuxent generally indicates a fining-upward sequence (pl. 3). Owens and Denny (1979) interpret the Sinepuxent as a marginal marine unit that marks a major mid-Wisconsin transgressive event. The Sinepuxent is about 35 feet thick. At Ocean City, the Sinepuxent is overlain by 5 to 15 feet of modern barrier beach, and lagoonal deposits associated with the current Holocene transgression.

Other Pliocene(?) and Pleistocene Units in Worcester County

The Omar Formation (Jordan, 1962) does not subcrop at Ocean City, but does occur between about 12 and 20 miles west of Ocean City as an 8 to 10 mile wide band of interbedded clay, silt and sand that generally parallels the coast (fig. 16 of Owens and Denny, 1979). Groot, Ramsey, and Wehmiller (1990) place the lower part of the Omar in the Pliocene and the upper part of the Omar in the Quaternary. Owens and Denny (1979) assigned the Omar to the Pleistocene (Sangamon Interglacial). In core hole Fd 33, R. B. Mixon and D. S. Powars (oral communication, 1990) tentatively place the upper 40 feet of section in the Omar Formation (pl. 3).

The Ironshire Formation (Owens and Denny, 1979) is an orange-tan, cross-bedded, medium sand and gravel that is assigned to the Pleistocene (Sangamon Interglacial). The Ironshire outcrops about 7 miles west of Ocean City and forms a low, narrow ridge that parallels the coast from Delaware south to Virginia. The Sinepuxent Formation is younger than the Omar and Ironshire Formations. At Ocean City, the Ironshire was eroded prior to deposition of the Sinepuxent (Owens and Denny, 1979).



EXPLANATION

● -165	Data point and altitude in feet above (+) or below (-) sea level.
Δ +25	Data point and altitude in feet above (+) or below (-) sea level from Owens and Denny (1979).
-100 ——— ?—	Line of equal altitude; queried where uncertain.
X X X	Areas where the Beaverdam Sand is absent.
	Contour interval is 50 feet.

Figure 12.—Altitude of the base of the Beaverdam Sand.

HYDROGEOLOGY

AQUIFER CHARACTERISTICS AT OCEAN CITY

Columbia Aquifer

The Columbia aquifer is a regional water-table aquifer that blankets much of the Delmarva Peninsula. In northeastern Worcester County, sands of the Beaverdam Sand and overlying Pleistocene and Holocene units form the unconfined to semiconfined Columbia aquifer. The Beaverdam aquifer comprises the bulk of the Columbia aquifer at Ocean City. The saturated thickness of the Columbia aquifer ranges from about 80 to 120 feet at Ocean City.

Hydraulic conductivities for the Columbia aquifer range from 25 to 75 ft/d (feet per day). The values were derived from well specific capacities, geophysical and lithologic logs, and a few aquifer tests (Weigle, 1974). The highest conductivities occur in the vicinity of Berlin and west of Newark, Maryland.

Recharge to the Columbia aquifer is from rainfall and snowmelt. The average annual precipitation at the Salisbury weather station is 45 in./yr and of this about 18 in./yr becomes ground-water recharge. Part of the ground-water recharge flows through the Columbia aquifer to the subcropping Pocomoke, Ocean City, and Manokin aquifers. Discharge from the Columbia aquifer occurs as evapotranspiration and discharges to the Pocomoke River, the back bays, and the Atlantic Ocean.

The water level of the Columbia aquifer, the water table, mimics the topography of the region. The water table is about 40 feet above sea level in the Parsonsburg area near Salisbury and slopes gradually to less than 5 feet above sea level near the coast at Ocean City. The regional ground-water-flow direction is from northwest to southeast with an average gradient of 1 to 2 feet per mile.

Pocomoke Aquifer

The Pocomoke aquifer as used in this report refers only to the sands included in the Pocomoke beds shown in figures 13 and 14 and plates 1–3. Mixon (1985) states that the sands of the "Pocomoke aquifer" in southwestern Somerset County, and the lower sands of the Pocomoke aquifer at Pocomoke City in Worcester County, the site of Rasmussen and Slaughters' (1955) "type aquifer" section for the Pocomoke, are not contiguous with the Pocomoke aquifer in eastern Worcester County, but are older, stratigraphically lower sands that Mixon assigns to the Eastover Formation. Hansen (1981) points out that the Pocomoke aquifer has been considered the first sand encountered below the Columbia Group unconformity throughout the lower eastern shore of Maryland and that this practice has caused confusion regarding the regional extent of the Pocomoke aquifer.

The Pocomoke aquifer in northeastern Worcester County is usually a confined aquifer consisting of individual sands 10 to 20 feet thick (figs. 13 and 14). At locations where the sands are stacked, the cumulative sand thickness of the Pocomoke ranges from 20 to 65 feet (pls. 1–3). The Pocomoke aquifer provides water for the community of Newark, Maryland and formerly supplied most of the water for Ocean City, Maryland (Weigle, 1974).

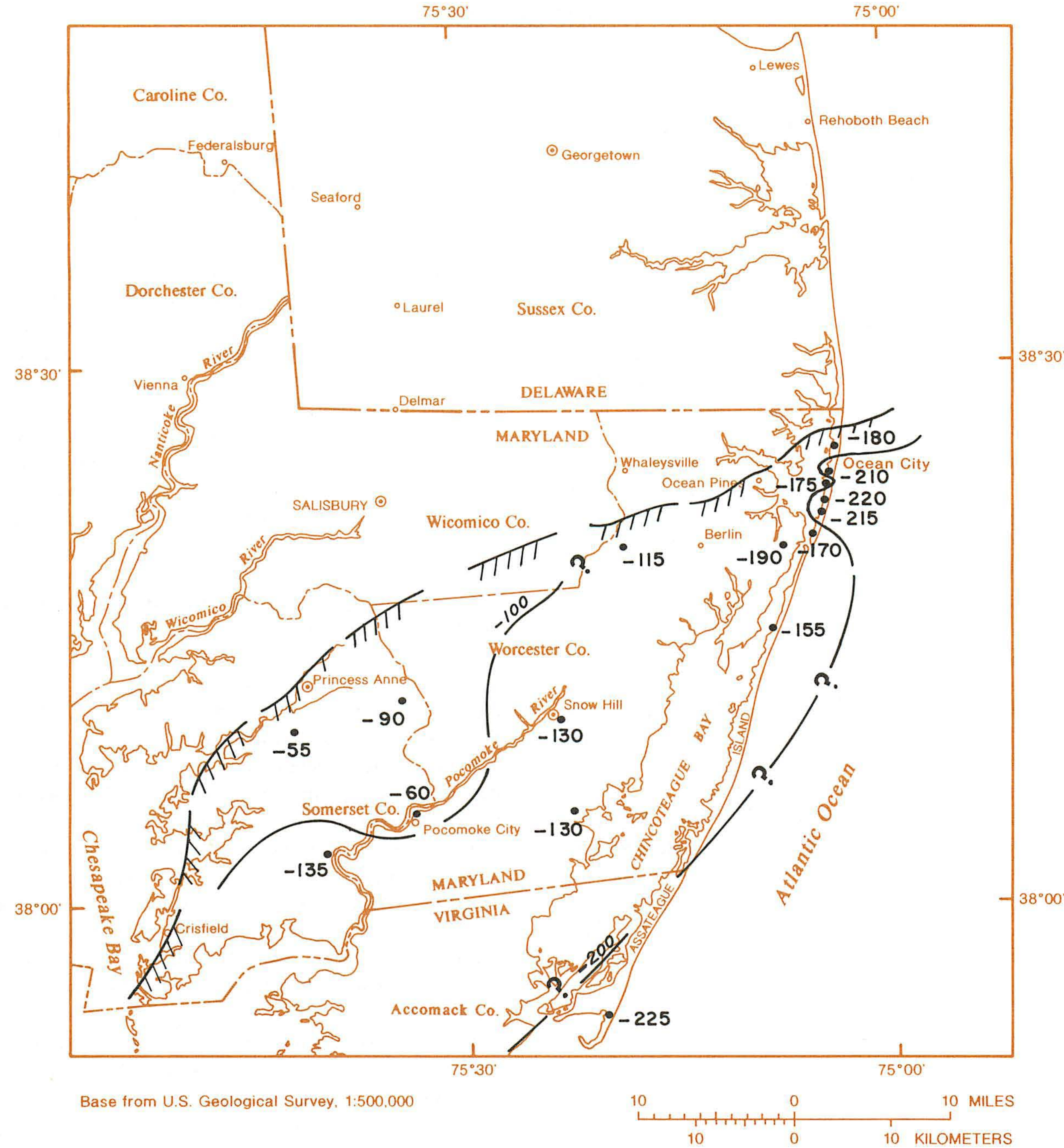
Sand to clay facies changes are common within the section that includes the Pocomoke aquifer. For example, at 28th Street (Bh 90), the Pocomoke aquifer becomes very clayey while in the northern part of Ocean City (Ah 6), the Pocomoke sands pinch out (pls. 1–2, fig. 13). Elsewhere, in northeastern Worcester County, the Pocomoke aquifer is absent because the Pocomoke beds have been eroded by the Beaverdam Sand. In places where the Beaverdam Sand has breached the confining unit overlying the Pocomoke aquifer, the Pocomoke aquifer and Beaverdam Sand are in contact and the Pocomoke aquifer is under semiconfined conditions (pls. 1–3). In southeastern Delaware, sands that have been considered part of the Pocomoke aquifer (Hodges, 1984; Phelan, 1987) do not appear to have a direct hydraulic connection to the Pocomoke aquifer in northeastern Worcester County (fig. 13).

The transmissivity of the Pocomoke aquifer ranges from 8,000 ft^2/d southwest of Newark, Maryland to 2,000 ft^2/d at Whaleysville and the northern part of Ocean City, Maryland. The transmissivity values were derived from specific capacity data corrected for partial penetration effects. The upper range of the transmissivity values coincide with the region where the Pocomoke aquifer is thick. The potentiometric surface of the Pocomoke aquifer ranges from about 25 feet above sea level in the vicinity of Whaleysville, to 5 feet above sea level and less at Ocean City. The general ground-water-flow direction is from northwest to southeast with a gradient of about 1 to 2 ft/mi.

The confining unit that underlies the Pocomoke aquifer at Ocean City is a fine, silty sand to clayey silt assigned to the Pocomoke beds. The confining unit is equivalent to the lower confining unit of Rasmussen and Slaughter (1955) and the upper part of the lower confining unit of Weigle (1974). The confining unit that underlies the Pocomoke aquifer is widespread and correlative over most of the study area (pls. 1–3).

Ocean City Aquifer

The Ocean City aquifer and the basal part of the lower confining unit of Weigle (1974) are included in the Ocean City beds. The Ocean City aquifer is restricted to northeastern Worcester County (figs. 15 and 16). At Ocean City, the Ocean City aquifer ranges from about 20 to 110 feet thick (fig. 16). Updip near Willards in Wicomico County, the Ocean City aquifer appears to pinch out (pl. 2). Southwest of Ocean City in core-hole Fd 33, sands that are probably hydrologically continuous with the Ocean City aquifer occur between 125 feet and 215 feet below sea level. Sands in Delaware that may have hydrologic continuity with the Ocean City aquifer are shown in figures 15 and 16 as



EXPLANATION

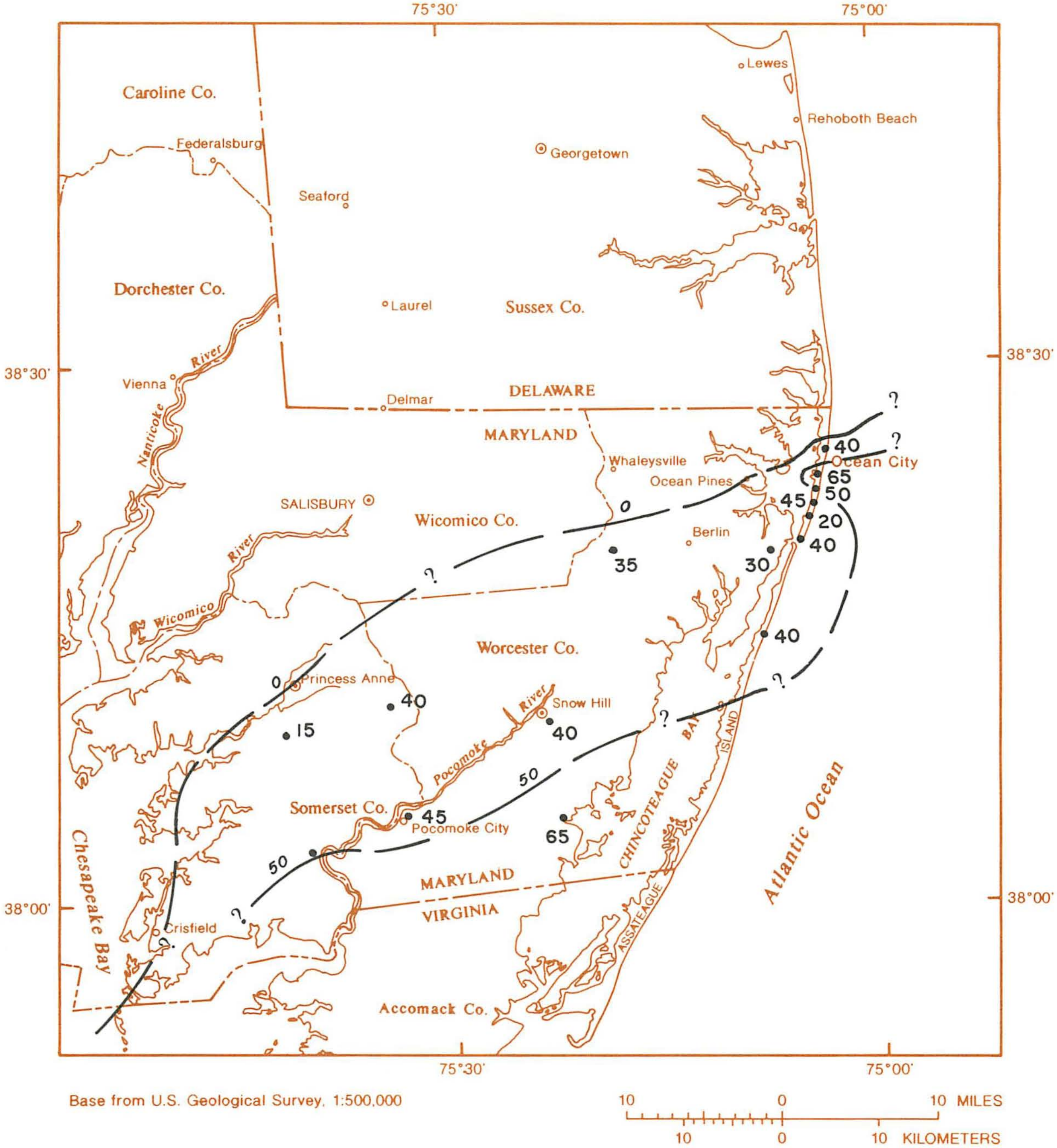
● -130 — Data point and altitude in feet below sea level.

-200 ——? — — Line of equal altitude; queried where uncertain.

Approximate updip limit of Pocomoke aquifer.

Contour interval 50 feet. Datum is sea level.

Figure 13.—Altitude of the base of the Pocomoke aquifer.



EXPLANATION

● 60	Data point and thickness in feet.
50 ——— ? —	Line of equal thickness; queried where uncertain.
	Contour interval is 50 feet.

Figure 14.—Cumulative sand thickness of the Pocomoke aquifer.

sands hydraulically equivalent to the Ocean City aquifer. These sands in Delaware are difficult to correlate with the Ocean City aquifer in Maryland because in Delaware, the sands break up into discontinuous channel-mouth and offshore bars distributed within a dominantly clayey section (Andres, 1986; Groot, Ramsey, and Wehmiller, 1990).

Transmissivities for the Ocean City aquifer range from 2,500 to 7,500 ft^2/d in the model area. The most transmissive sands in the Ocean City aquifer are the fine to coarse sands that are dominant in the section south of 100th Street (pl. 1). Transmissivities of the Ocean City aquifer range from a high of 5,300 ft^2/d at 44th Street to less than 2,700 ft^2/d in the area from 61st to 100th Streets (Weigle, 1974; Weigle and Achmad, 1982; Whitman, Requardt and Associates, 1989).

At Ocean City, the Ocean City aquifer and the Manokin aquifer are hydraulically connected. In much of the study area the potentiometric surfaces of the Ocean City aquifer and Manokin aquifer are similar. The potentiometric surface of the Ocean City-Manokin aquifer system ranges from about 25 feet above sea level in northwestern Worcester County to less than 5 feet above sea level in Ocean City. The general direction of ground-water flow is from northwest to southeast with a gradient of about 1 ft/mi.

Both thickness and vertical hydraulic conductivity of the confining unit that underlies the Ocean City aquifer vary throughout the study area. At 44th Street, this "confining unit" is absent. The gamma logs at 44th Street (Bh 89; pl. 3) show that the Manokin and Ocean City aquifers are in sand-on-sand contact; the stratum that forms the "confining unit" in Bh 89 is about 70 percent sand. Strata with sand percentages greater than 50 percent have approximately equal vertical and horizontal permeabilities that do not impede vertical flow (Fogg, 1986). To the north and south of 44th Street, this confining unit thickens and becomes more clayey and provides greater hydraulic separation between the Ocean City and Manokin aquifers (pl. 3). Because an effective confining unit is lacking in the 44th Street area, the Ocean City aquifer is more susceptible to upconing of brackish water from the Manokin aquifer than it is elsewhere along the island.

Manokin Aquifer

At Ocean City and throughout most of the lower Eastern Shore, the Manokin aquifer is essentially equivalent to the Manokin formation. Individual sands within the Manokin average about 10 to 20 feet thick and the cumulative sand thickness of the aquifer ranges from about 90 to 195 feet in Worcester County (pls. 1–3 and fig. 10). The Manokin aquifer subcrops beneath the Columbia aquifer in the vicinity of Salisbury, Maryland. Transmissivities of the Manokin aquifer range from about 2,500 to 10,000 ft^2/d (Weigle, 1974; Weigle and Achmad, 1982; Whitman, Requardt and Associates, 1989). The Manokin aquifer is predominantly brackish from the 44th Street area north to 61st Street.

Internal confining units within the Manokin aquifer are common at Ocean City (pl. 1). These confining units are well developed in the southern part of Ocean City, but become more discontinuous in the central part of the island. Further north, internal confining units are common between 100th and 130th Streets, but are absent in the Gorman Avenue area (137th to 141st Streets) (pl. 1).

The St. Marys Formation forms the confining unit that underlies the Manokin aquifer throughout the lower Eastern Shore of Maryland. The St. Marys is a clayey, thick, relatively impermeable confining unit. The St. Marys separates the Manokin aquifer from the underlying Choptank aquifer. At Ocean City the Choptank is brackish.

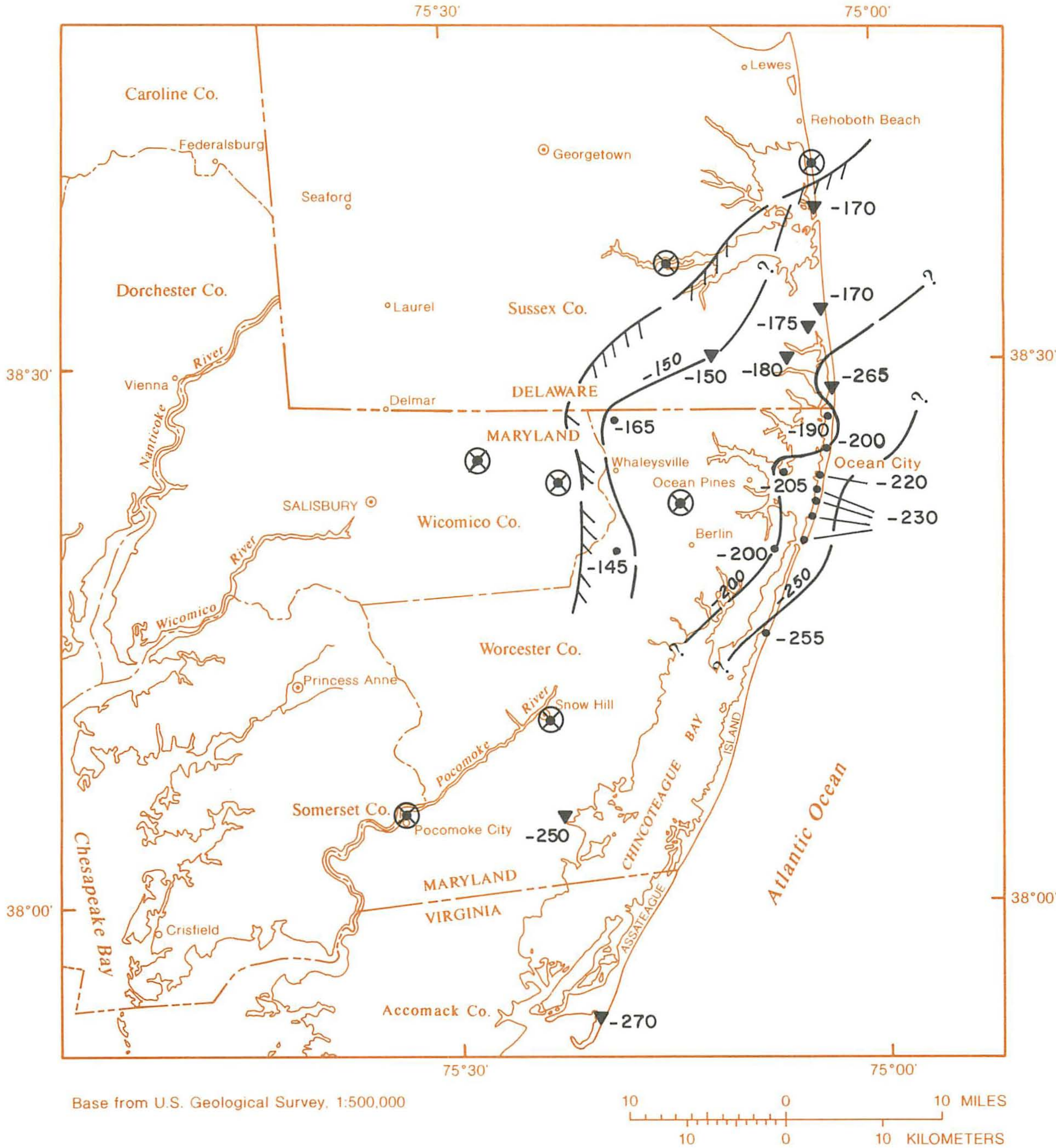
Choptank Aquifer

The Choptank aquifer underlies the middle and lower parts of the Delmarva Peninsula. At Ocean City, the top of the Choptank Formation coincides with the top of the Choptank aquifer. In well Ah 6 (pl. 1) at the northern end of Ocean City, the upper sand of the Choptank aquifer is about 165 feet thick (from 665 to 830 feet below sea level). A deeper sand, also considered part of the Choptank aquifer occurs from 875 to 935 feet below sea level in Ah 6. Below 935 feet below sea level, the Choptank becomes finer grained and increasingly clayey.

Transmissivity values of the Choptank aquifer range from 500 to 1,400 ft^2/d (Hansen, 1972; Cushing, Kantrowitz, and Taylor, 1973; and Vroblesky and Fleck, 1991). The Choptank aquifer contains brackish water (chlorides greater than 250 mg/L) throughout Worcester and Somerset Counties, and also in central and eastern Wicomico County, Maryland. At Ocean City, chloride concentrations range from 2,700 to 2,900 mg/L in the upper part of the Choptank aquifer (app. B). In Delaware, the Choptank contains brackish water in the eastern part of Sussex County (Woodruff, 1969; Talley, 1990).

PUMPAGE

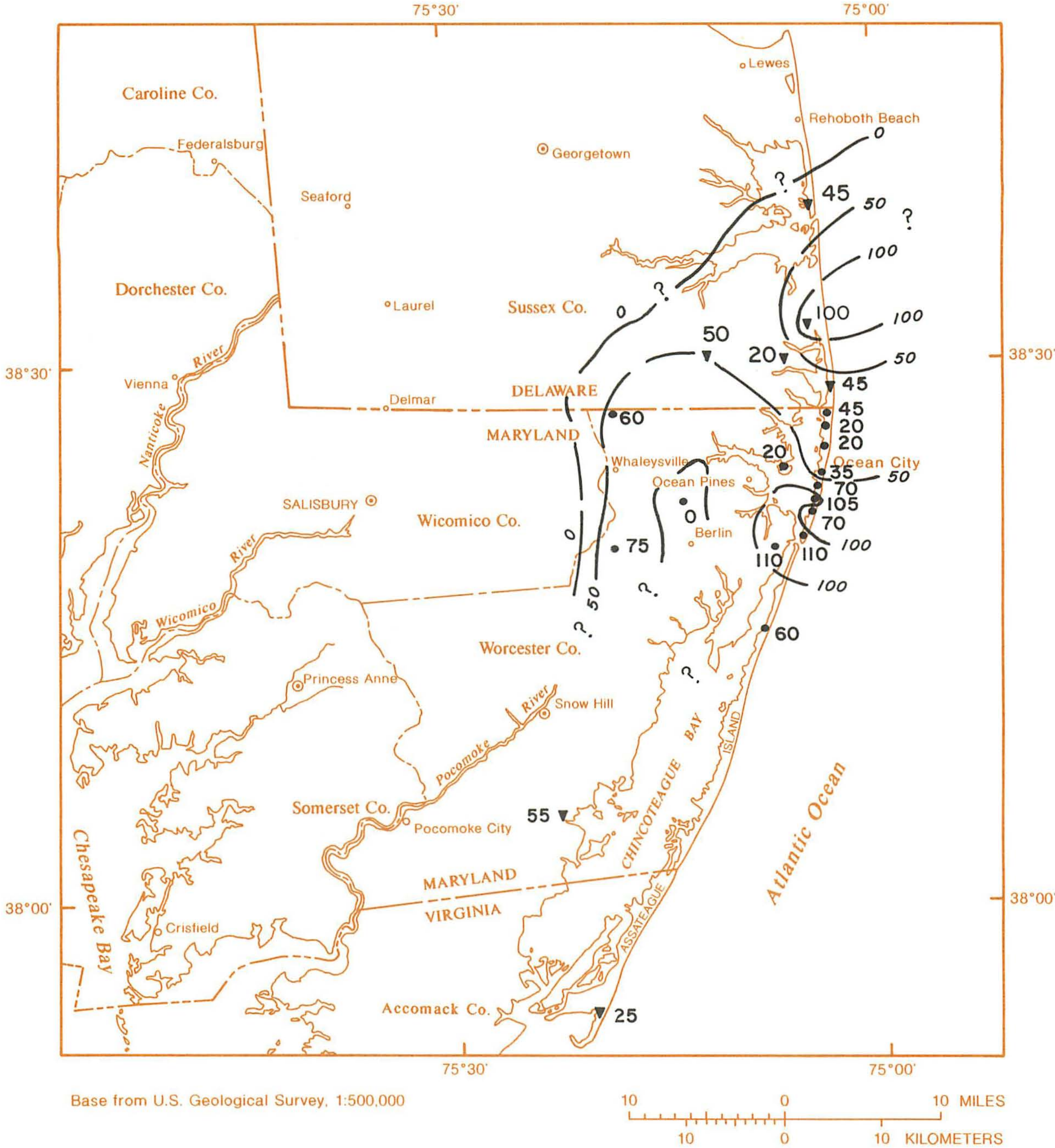
During the last century, Ocean City developed new well fields to meet an increasing demand for water by the town's year-round and summer population. Demand for ground water at Ocean City has increased from an annual average of about 1.3 Mgal/d in the early 1950's to an annual average of about 5.65 Mgal/d in 1990 (tab. 4). Total pumpage at Ocean City has increased from 475 Mgal (million gallons) in 1955 to 2,063 Mgal in 1990 (fig. 17). The demand for water is seasonal in Ocean City. Approximately fifty-eight percent of the annual pumpage occurs from June to September during the summer tourist season. The greatest demand is in August when about one fifth of the annual pumpage occurs. The maximum daily pumpage during periods of peak demand is 2 to 3 times the annual average pumpage for a given year (tab. 4).



EXPLANATION

● -250	Data point and altitude in feet below sea level.
▼-270	Data point and altitude of hydraulically equivalent sand.
⊗	Sites where the Ocean City aquifer is absent.
-150 ——?—	Line of equal altitude; queried where uncertain.
	Approximate updip limit of the Ocean City aquifer.
	Contour interval is 50 feet.

Figure 15.—Altitude of the top of the Ocean City aquifer and equivalent sands.



EXPLANATION

● 60 — Data point and thickness in feet of the Ocean City aquifer.

▼ 25 — Data point and thickness in feet of hydraulically equivalent sand.

50 ——— ? – Line of equal thickness; queried where uncertain.

Contour interval is 50 feet.

Figure 16.—Cumulative sand thickness of the Ocean City aquifer and equivalent sands.

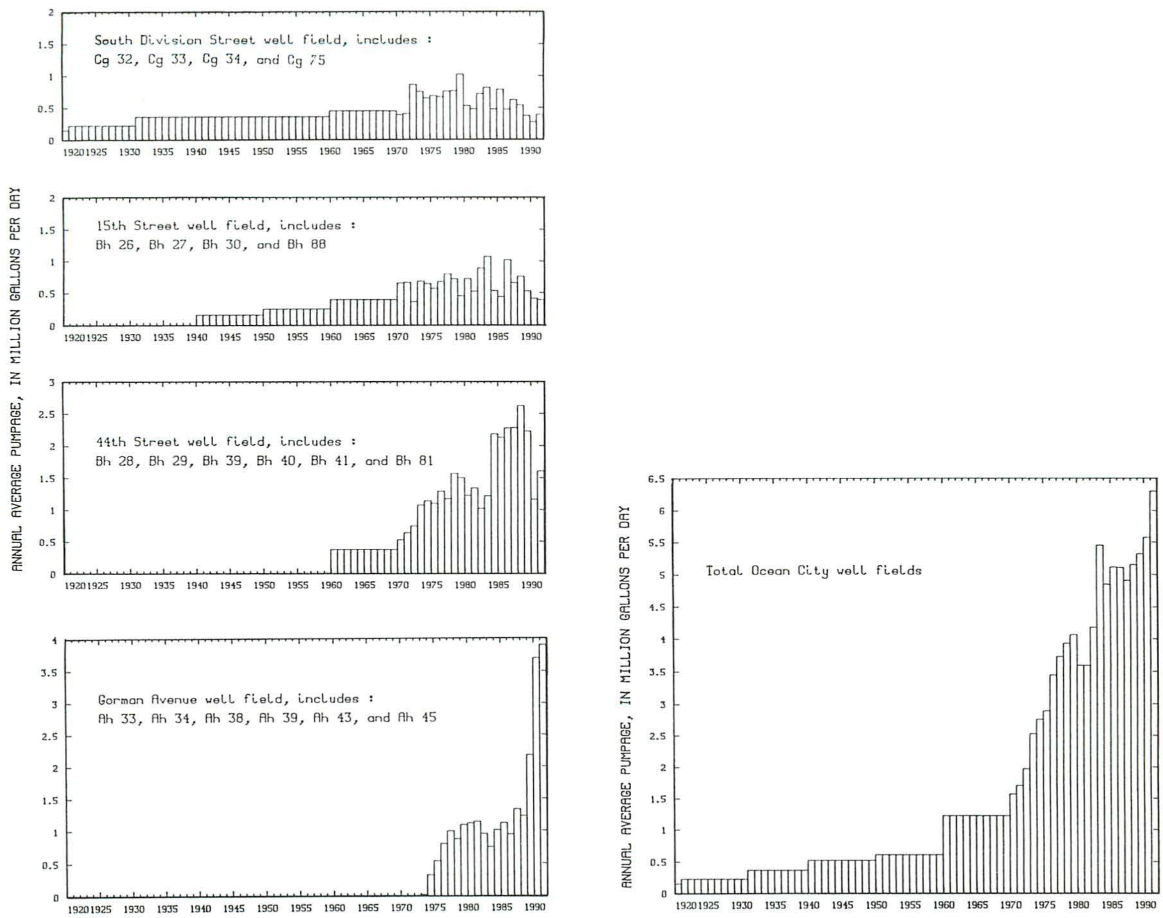


Figure 17.—Annual average pumpage from the Ocean City well fields during 1921–91.

Table 4.—Comparison of maximum daily pumpage and annual average pumpage at Ocean City, Maryland

[in million gallons per day (Mgal/d)]

Year	Annual average pumpage (Mgal/d)	Maximum daily pumpage (Mgal/d)
1970	1.57	4.3
1975	2.89	7.1
1980	3.59	10.3
1985	4.48	10.2
1990	5.65	12.1

The first well field in Ocean City, the Old North well field was located on Philadelphia Avenue between 12th and 15th Streets. The modern 15th Street well field is located at the northern end of the Old North well field (fig. 2). The first wells drilled at the Old North well field were drive-point wells about 90 feet deep that produced from near the base of the Columbia aquifer. These wells were used from 1890 to about 1930 when the wells were abandoned because of saltwater contamination. Saltwater entered these wells from the surface during periods of high-tides and flooding because the wells were set in pits with unprotected surface casings (Andreasen and Rasmussen, 1952).

Five wells (Bh 1 to Bh 5) were drilled at the Old North well field in 1939. These wells were screened in the Ocean City aquifer and together could produce 400 gal/min (gallons per minute). In 1949, three additional production wells (Bh 6, 7, and 8), together capable of producing 600 gal/min, were completed in the Pocomoke aquifer (Rasmussen and Slaughter, 1955). None of the production wells drilled prior to 1950 are used today. In 1957 the first well (Bh 26) of what is now the 15th Street well field was drilled to the Ocean City aquifer at the northern end of the Old North well field. Two more Ocean City aquifer production wells (Bh 27 and 30) were drilled at the 15th Street well field in 1960 and 1967. In 1984, a Manokin aquifer production well (Bh 88) was drilled (tab. 5).

Between 1900 and 1930 another well field, the South well field, was developed. The South well field was located between Dorchester and Wicomico Streets about 1,000 feet north of the present-day South Division Street well field (fig. 2). Most of the

Table 5.—Production wells and well fields in Ocean City, Maryland (1991)

Maryland Geological Survey Well Number	Town of Ocean City Well Designation+	Aquifer	Street Location	Date Drilled
		South Division Street well field		
WO Cg 32	A	Ocean City	Worcester St.	1955
WO Cg 33	C	Ocean City	Worcester St.	1955
WO Cg 34	B	Ocean City	South Division St.	1967
WO Cg 75	D	Manokin	South Division St.	1984
		15th Street well field		
WO Bh 26	A	Ocean City	15th St.	1957
WO Bh 27	B	Ocean City	14th St.	1960
WO Bh 30	C	Ocean City	14th St.	1967
WO Bh 88	D	Manokin	14th St.	1984
		44th Street well field		
WO Bh 28	A	Ocean City	44th St.	1963
WO Bh 29	B	Ocean City	45th St.	1963
WO Bh 39*	F	Ocean City	39th St.	1969
WO Bh 40*	E	Ocean City	42nd St.	1969
WO Bh 41	C	Ocean City	42nd St.	1969
WO Bh 81	D	Ocean City	42nd St.	1971
		Gorman Avenue well field		
WO Ah 33	B	Manokin	Gorman Avenue	1972
WO Ah 34	A	Manokin	137th St.	1972
WO Ah 38	C	Manokin	137th St.	1975
WO Ah 39	D	Manokin	141st St.	1975
WO Ah 43	E	Manokin	130th St.	1989
WO Ah 45	F	Manokin	125th St.	1990

+ The town of Ocean City uses both the well field name and a letter to designate the individual production wells; for example, the 44th Street A well, the Gorman Avenue D well.

* Bh 39 and Bh 40 were originally drilled to supply the Ocean City Convention Center's cooling and heating systems. These wells were taken over by the Ocean City Water Department in 1986.

wells at the South well field were screened in the Ocean City aquifer, although at least two production wells were screened in the Pocomoke aquifer and one in the Columbia aquifer. The South well field was used until the mid-1950's when it was replaced by the South Division Street well field (tab. 5).

The South Division Street and 15th Street well fields each produced an average pumpage of 0.65 Mgal/d during the 1950s (fig. 17). In 1990, the annual average pumpage from each of these well fields ranged from 0.5 to 1.0 Mgal/d. Present plans for development of the South Division Street and 15th Street well fields restrict the maximum annual pumpage from each field to 365 million gallons (1.0 Mgal/d) (Whitman, Requardt and Associates, 1989).

Development of the 44th Street well field began in 1963. Between 1963 and 1971 four public supply wells were drilled and screened in the Ocean City aquifer at 44th Street (tab. 5). The annual average pumpage from the 44th Street well field reached a high of 2.6 Mgal/d in 1988. In order to control rising chloride concentrations in the Ocean City aquifer at the 44th Street well field, the annual average pumping rate was reduced to 2.2, 1.2, and 1.6 Mgal/d in 1989, 1990, and 1991 respectively (figs. 17 and 18).

Development of the Gorman Avenue well field began in 1972 when it became apparent that the existing well fields could not meet the future water-supply demands of Ocean City. The first two wells drilled at Gorman Avenue were Ah 33 and Ah 34. These wells were screened in the Manokin aquifer from 350 to 450 feet below land surface. In 1976, two additional production wells were drilled, Ah 38 and Ah 39. The Gorman Avenue well field was expanded in 1989 with the drilling of Ah 43 and again in 1990 when Ah 45 was drilled (tab. 5).

Annual average pumpage at the Gorman Avenue well field has increased from 0.8 Mgal/d in 1976 to about 3.9 Mgal/d in 1991. From 1976 to 1989, however, the pumpage was relatively low, less than 1.5 Mgal/d and seasonal (fig. 17). In 1989, pumpage from the Gorman Avenue well field was increased to more than 2.0 Mgal/d and the well field was pumped year round. In 1990 and 1991, year round pumpage from the well field was increased to an annual average of over 3.8 Mgal/d (fig. 17). Of the total 1991 pumpage of 3.9 Mgal/d, about 2.4 Mgal/d was pumped from wells at 137th and 141st Streets, and 1.5 Mgal/d was pumped from the wells at 130th and 125th Streets. Individual well pumpage is estimated because Ocean City only collects pumpage data for entire well fields. The production well at 130th Street (Ah 43) came online in 1989 and the well at 125th Street (Ah 45) came online in 1990. Future expansion of the Gorman Avenue well field will include public-supply wells at 121st, 115th, 105th, and 95th Streets (Whitman, Requardt and Associates, 1989).

Pumpage by users of more than an annual average of 0.01 Mgal/d who are located in Worcester County outside of Ocean City was simulated in the ground-water-flow model (tab. 6). The decrease in the 1990 pumpage by these users was due to a decrease in farm and industrial water use in the area. Pumpage data were obtained from Wheeler and Wilde (1989), Phelan (1987), J.C. Wheeler (personal communication, 1991), and D.A. Bringman (personal communication, 1991).

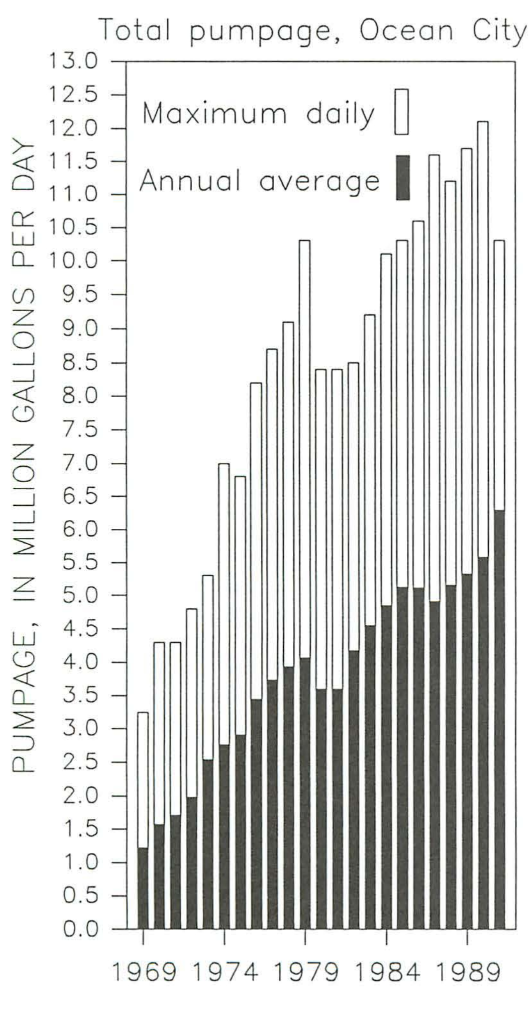


Figure 18.—Comparison of annual average and maximum daily pumpages from the Ocean City well fields during 1970–91.

Table 6.—Estimated annual average pumpage in Worcester County (excluding Ocean City) by users of more than 0.01 million gallons per day (Mgal/d)

Year	Annual average pumpage (Mgal/d)
1875	0.65
1930	1.8
1940	1.5
1950	1.6
1960	2.9
1970	4.4
1980	4.7
1990*	2.8

*List of ground-water users in 1990.

Towns and communities: Berlin, Eagle's Nest, Mystic Harbor, Newark, Ocean Pines, Pocomoke City, and Snow Hill.

Parks: Pocomoke State Park.

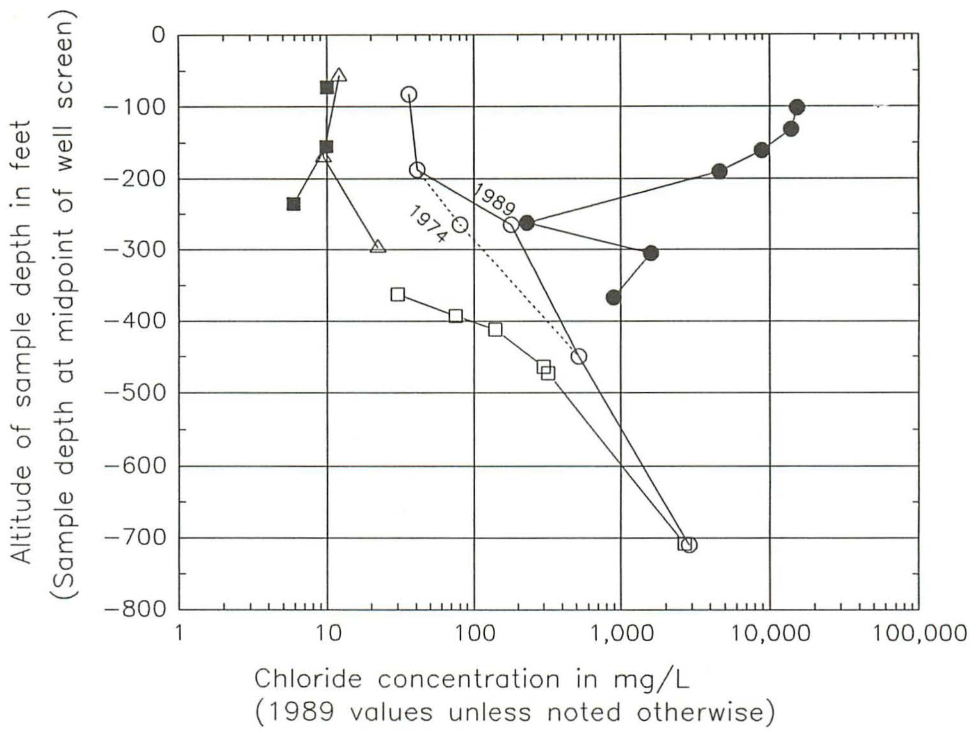
Commercial: Campbell Soup, Chesapeake Foods, General Motors Inn, Holly Farms, Ocean City Golf Course, Ocean Downs Race Track, Pine Shores Golf Course, Purdue Farms, Inc., Quality Inn, Savage Ice Co., Showell Farms, and Ross-Wells (Beatrice Foods).

CHLORIDE CONCENTRATIONS, DISTRIBUTIONS AND TRENDS

The Freshwater-Saltwater Mixing Zone

Saltwater intrusion to the freshwater aquifers at Ocean City is occurring in three ways: 1) shoreward encroachment of the freshwater-saltwater mixing zone caused by long-term head-gradient changes as a result of rising Holocene sea levels and recent head-gradient changes caused by pumpage, 2) upconing of brackish water to the Ocean City aquifer at the 44th Street well field because of head differences between the freshwater-bearing Ocean City aquifer and the Manokin aquifer which contains brackish water at 44th Street, and 3) intrusion to the unconfined to semiconfined Columbia aquifer from the ocean and back bays.

The freshwater-saltwater mixing zone at Ocean City is a broad interface. Profiles of chloride concentration as a function of depth at several well clusters in Worcester County (located at Whaleysville, Ocean Pines, Isle of Wight, and Ocean City) show chloride concentrations increasing as a function of increasing depth and as a function of increasing proximity to the coast (fig. 19, pl. 2). Chloride concentrations for the onshore segment of the freshwater-saltwater mixing zone are also shown on the regional dip section (pl. 2) which parallels the regional direction of ground-water flow. A profile of chloride concentration as a function of depth offshore of Ocean City in test hole 6008 is also shown on figure 19. Test hole 6008 is a core hole drilled to 370 feet below sea level 8.8 miles off the coast of



EXPLANATION

Profile at Whaleysville (Ae 23, 24 and 25).

Profile at Ocean Pines (Bg 15, 45 and 46).

Profile in the central part of Ocean City (44th St. well field: For Bh 28, the 1974 and 1989 values are shown; for Bh 84, 85 and 89, only 1989 data is shown. The Choptank data is from Bh 90 at 28th St.).

Profile at Gorman Avenue and 137th Sts. (WO Ah 34, 36, 37, and 1969 values for Ah 6).

Profile at test hole 6008 (1976 values) 8.8 miles offshore of Ocean City.

Figure 19.—Chloride concentrations as a function of depth in northeastern Worcester County and in test hole 6008.

Ocean City in 1976. Core descriptions indicate the boring reached the upper part of the Ocean City-Manokin aquifer system (app. D). Chloride determinations made on pore-water squeezed from the core samples show that relatively low chloride concentrations, 231 mg/L at 262 feet and 896 mg/L at 367 feet below sea level, occur offshore in the ground-water system (F. A. Kohout, written communication, 1976; app. C). The low chloride levels also suggest that a plume of fresh to brackish ground water extends from the coast at least 8.8 miles offshore. The shape of the freshwater-saltwater mixing zone offshore of Ocean City, Maryland may be similar to the mixing zone offshore of Atlantic City, New Jersey, where freshwater occurs up to 12 miles offshore (Hathaway and others, 1976; Meisler, 1989). The conceptual model of the freshwater-saltwater mixing zone (fig. 20) assumes the presence of a fresh to brackish ground-water plume. A cross-sectional solute-transport model that simulated a fresh to brackish ground-water plume is discussed in a subsequent section of this report.

Chlorides in the Ocean City-Manokin Aquifer System

Chloride concentrations in the Ocean City-Manokin aquifer system range from a low of 23 mg/L in the Ocean City aquifer at 33rd Street in Bh 99 to a high of 1,030 mg/L in the lower part of the Manokin aquifer at 44th Street. Data from observation and production wells showing the vertical distribution of chloride concentrations in Ocean City is shown on plate 1. Plate 1 is a slice through the freshwater-saltwater mixing zone approximately perpendicular to the southeasterly direction of regional ground-water flow.

The areal distribution of chlorides in the Ocean City and Manokin aquifers in 1989–90 is shown in figures 21 and 22. To date, the 44th Street well field is the only well field where brackish water intrusion presents an imminent danger to the water quality. Chloride concentrations in the Ocean City aquifer at the 44th Street well field have risen from about 70 mg/L in 1975 to about 215 mg/L in 1988. Plots of the chloride data for two of the

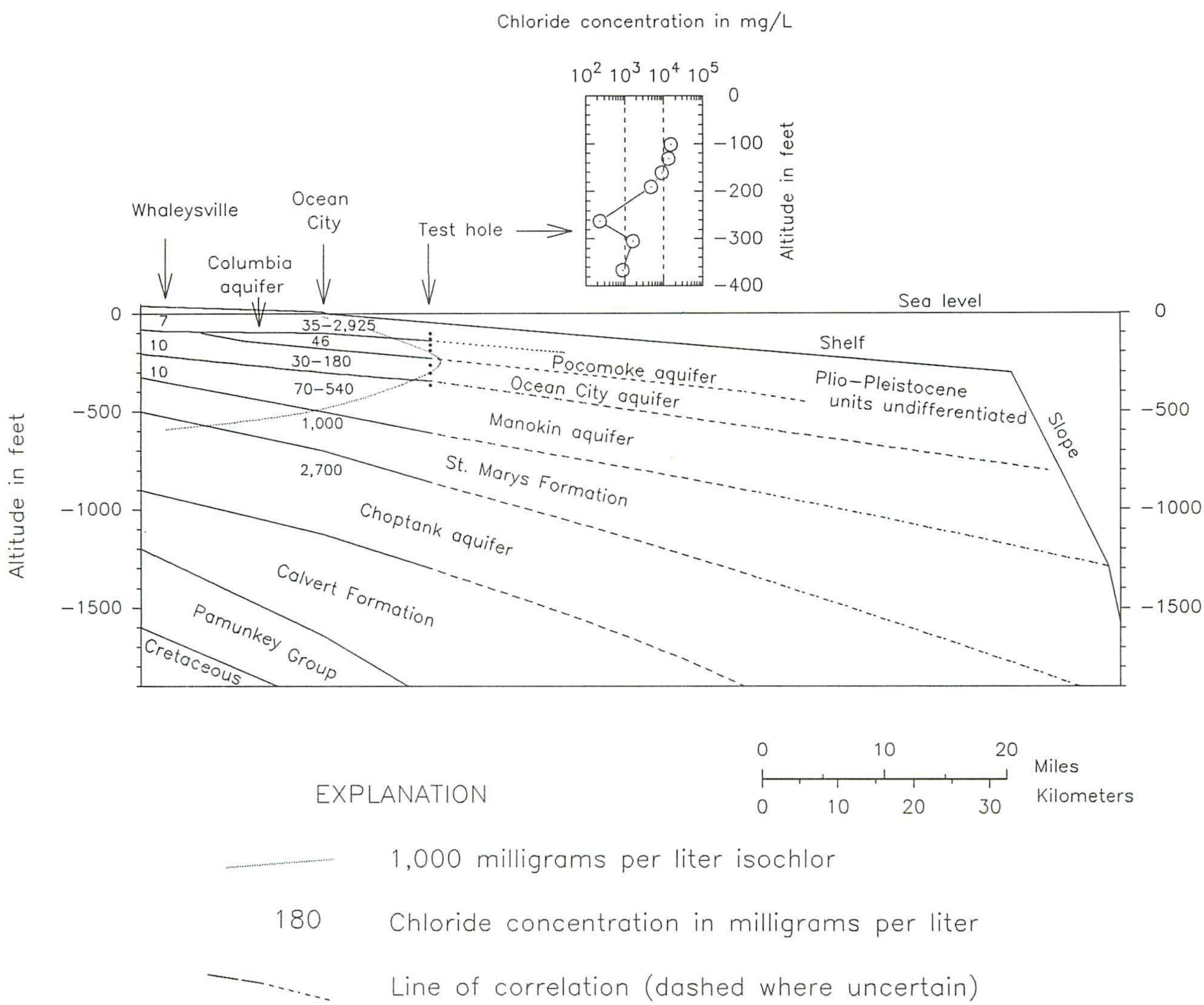


Figure 20.—Conceptual model of the hydrogeologic framework and position of the 1,000 mg/L isochlor from Whaleysville, Maryland, to the continental slope.

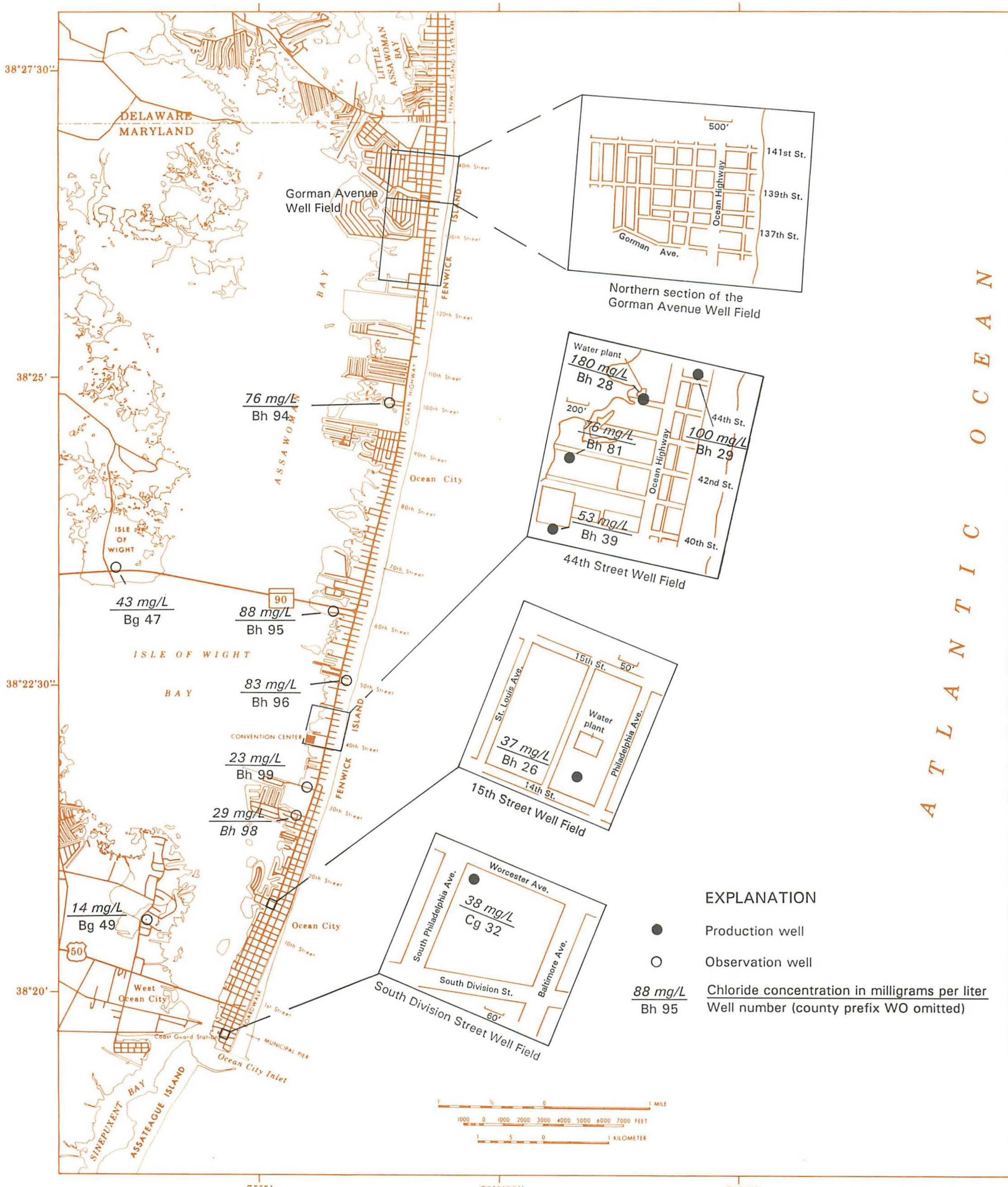


Figure 21.—Chloride concentrations in the Ocean City aquifer during 1989–90 at Ocean City, Maryland.

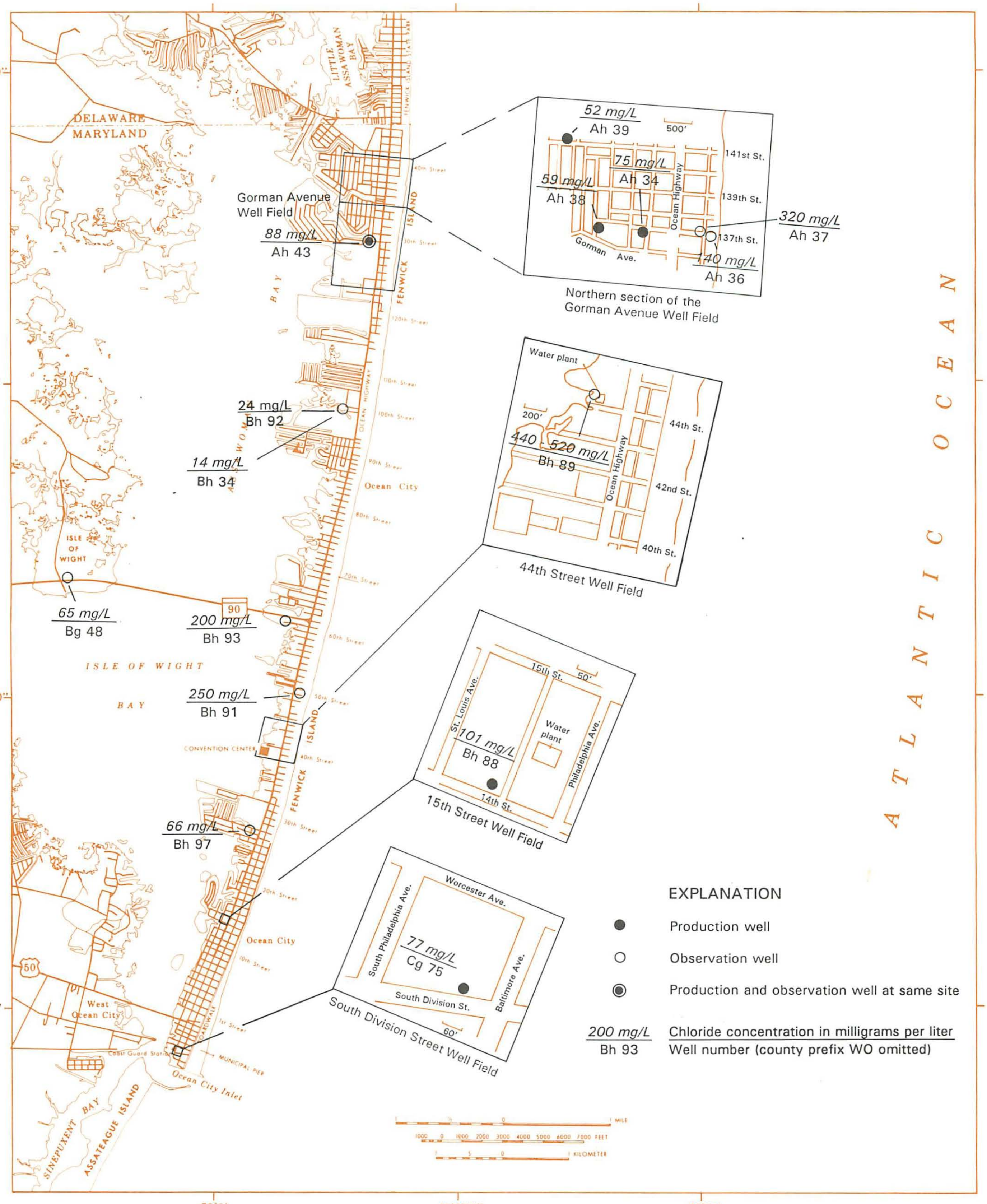


Figure 22.—Chloride concentrations in the Manokin aquifer during 1989–90, at Ocean City, Maryland.

major production wells (Bh 28 and 81) at the 44th Street well field are shown in figure 23.

Initial and Present Distribution of Chlorides at Ocean City

Three aspects of the hydrogeologic framework influence the distribution of chlorides in the Ocean City-Manokin aquifer system: 1) the altitude of the basal silty sand facies of the Manokin aquifer; 2) the effectiveness of the confining units within the Manokin aquifer; and 3) the effectiveness of the confining unit between the Manokin and Ocean City aquifers.

The development of Ocean City generally proceeded from the southern end of the island north to the Maryland–Delaware line. The initial distribution of chlorides (fig. 24) is based on historical and current data (app. B). The 250 mg/L isochlor in figure 24 shows the probable prepumping distribution of

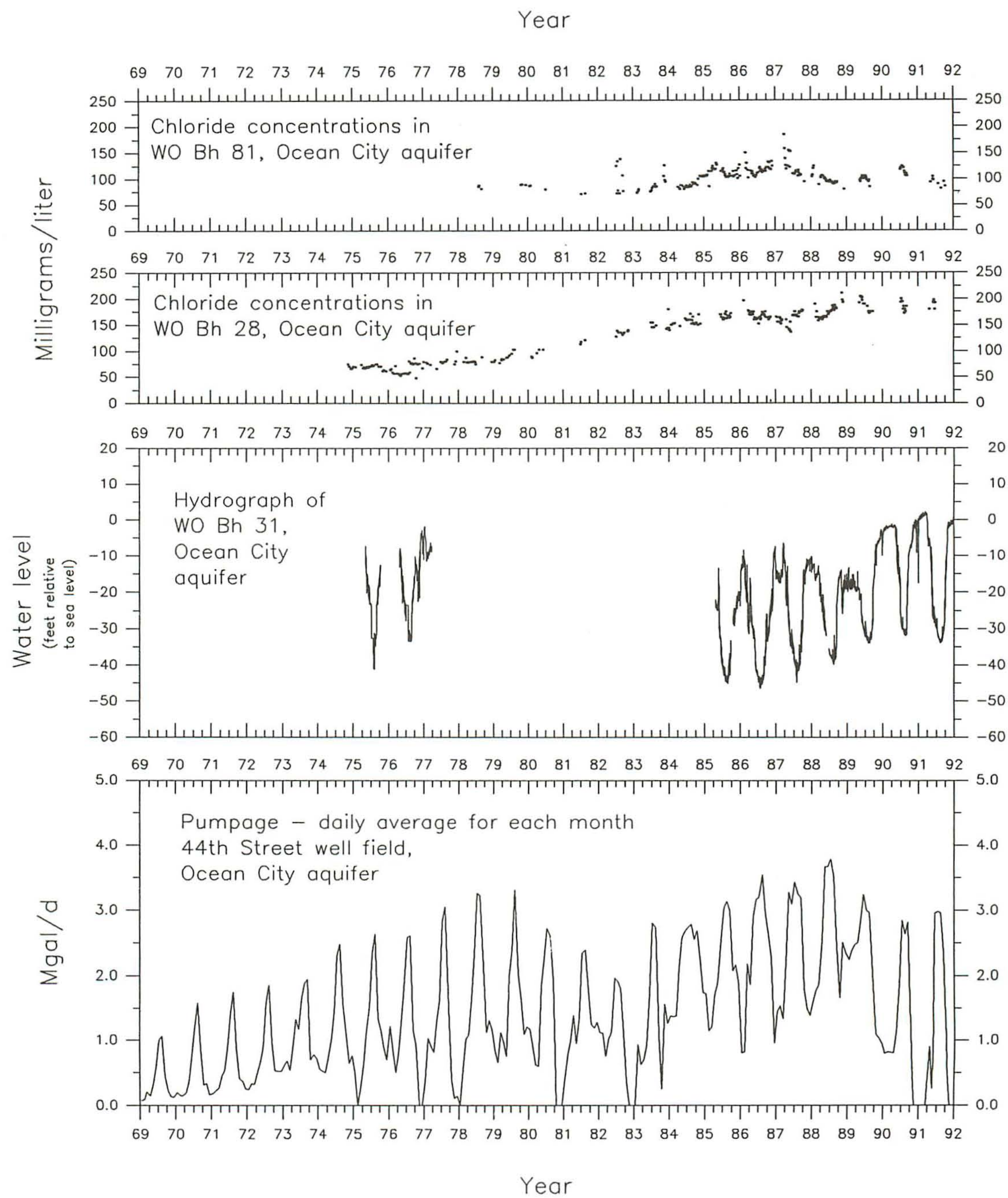


Figure 23.—Chloride concentrations in Bh 28 and Bh 81, and average daily pumpage per month and water levels at the 44th Street well field from 1969 to 1992.

brackish water in the Manokin aquifer. Historical data for the Ocean City aquifer indicates that the initial chloride concentrations in the Ocean City aquifer increased from about 30 mg/L in the region between South Division and 33rd Streets to about 80 mg/L at 66th Street (app. C).

44th Street Well Field

Comparison of the estimated initial and present day chloride distribution (figs. 24 and 25) shows the change in the distribution of chlorides at the 44th Street well field. Upconing of brackish water from the Manokin aquifer to the pumping sites at 44th Street is illustrated schematically in figure 25. In the Manokin and Ocean City aquifers, the change in chloride distribution is areally restricted to the regions surrounding production wells Bh 28, 29, 41, and 81 (fig. 2).

From 1988 to 1990, chloride concentrations in the Manokin aquifer at the 44th Street well field ranged from 440 to 520 mg/L in samples from Bh 89 that were representative of the entire aquifer (app. B). Chlorides as high as 1,030 mg/L were sampled opposite the deepest screen in Bh 89 (490 to 505 feet below sea level) (Whitman, Requardt and Associates, 1989). The chloride data from Bh 89 indicate that brackish-water contamination in the Manokin occurs farthest inland in the 44th Street area. One factor contributing to the greater brackish-water contamination at 44th Street is the greater depth of the Manokin aquifer–St. Marys Formation contact in that region (pl. 1). The contact between the basal silty sand facies of the Manokin aquifer and the St. Marys Formation varies from about 480 feet below sea level at Gorman Avenue (Ah 6) to about 530 feet below sea level at 51st Street and about 510 feet below sea level at 28th Street. The basal, silty sand facies of the Manokin aquifer has an estimated vertical hydraulic conductivity of about 10^{-1} ft/d, which is 5 orders of magnitude greater than the confining unit formed by the St. Marys Formation (10^{-6} ft/d). Brackish water in the deeper, sandy facies of the Manokin aquifer in the 44th to 51st Street area can more readily diffuse upwards to shallower parts of the aquifer than brackish water present at the same depth in the St. Marys Formation elsewhere along the island (e.g., Gorman Avenue) (pl. 1).

The bulk of the Manokin aquifer from the 44th Street area north to 61st Street is shown to contain brackish or near-brackish water. The chloride levels in the Manokin from 42nd to 66th Streets are based on water analyses (app. C) and multi-point electric logs (pl. 1) from the 44th Street well field and from observation-well sites, at 51st and 61st Streets, where the Manokin is undeveloped. In this region, confining units within the Manokin aquifer are thinner and sandier than south of the 44th Street well field. Chloride concentrations in samples from the Manokin aquifer ranged from 200 mg/L at 61st Street to between 440 and 520 mg/L in Bh 89 at 44th Street (app. C).

The chloride distribution in the Ocean City aquifer is strongly influenced by the following factors: 1) the effectiveness of the confining unit between the Manokin aquifer and the Ocean City aquifer, 2) the chloride distribution in the sands of the Manokin aquifer that underlie the Ocean City aquifer, and 3) head differences between the Ocean City aquifer and the Manokin aquifer caused by pumpage from the Ocean City aquifer.

Chloride concentrations in Bh 28, a production well screened in the Ocean City aquifer at the 44th Street well field rose from about 75 mg/L in 1975 to about 215 mg/L in 1988 (Phelan, 1987; D.J. Phelan, written communication, 1988). The increase in chlorides in the Ocean City aquifer at the 44th Street well field is caused by upconing of brackish water from the underlying Manokin aquifer. The trend of rising chlorides in Bh 28 and at other wells of the 44th Street well field correlate with the increase in pumpage from the 44th Street well field. The relationship between rising chloride concentrations at two of the production wells (Bh 28 and 81) and the average daily pumpage per month at the 44th Street well field is shown in figure 23. Chloride trends from individual wells cannot be correlated with pumpage because pumpage records are kept only for the entire well fields.

Upconing of brackish water at the 44th Street well field is caused by the absence of an effective confining unit between the Ocean City and Manokin aquifers in the 44th Street area, and water level (pressure head) differences between the Ocean City and Manokin aquifers caused by pumpage from the Ocean City aquifer. Gamma logs indicate that the section considered a confining unit between the Manokin aquifer and the Ocean City aquifer at the 44th Street well field by Weigle and Achmad (1982) and Weigle (1974) is about 70 percent sand. North and south of 44th Street, however, this part of the section becomes a confining unit as the percentage of clay and silt increases (pl. 1 and tab. 7).

Comparison of the trend of rising chlorides in Bh 28 from 1975–88 (fig. 23) with the stabilization of chlorides in 1989 and

Table 7.—Clay-silt percent and thickness of the confining unit between the Ocean City and Manokin aquifers based on gamma-ray log traces

Location and well number	Percent clay-silt	Thickness of interval (in feet)
South Division Street		
WO Cg 72	very high	10
28th Street		
WO Bh 90	high	48
44th Street		
WO Bh 89	low	50
51st Street		
WO Bh 91	medium	50
61st Street		
WO Bh 93	medium	26
100th Street		
WO Bh 92	high	25

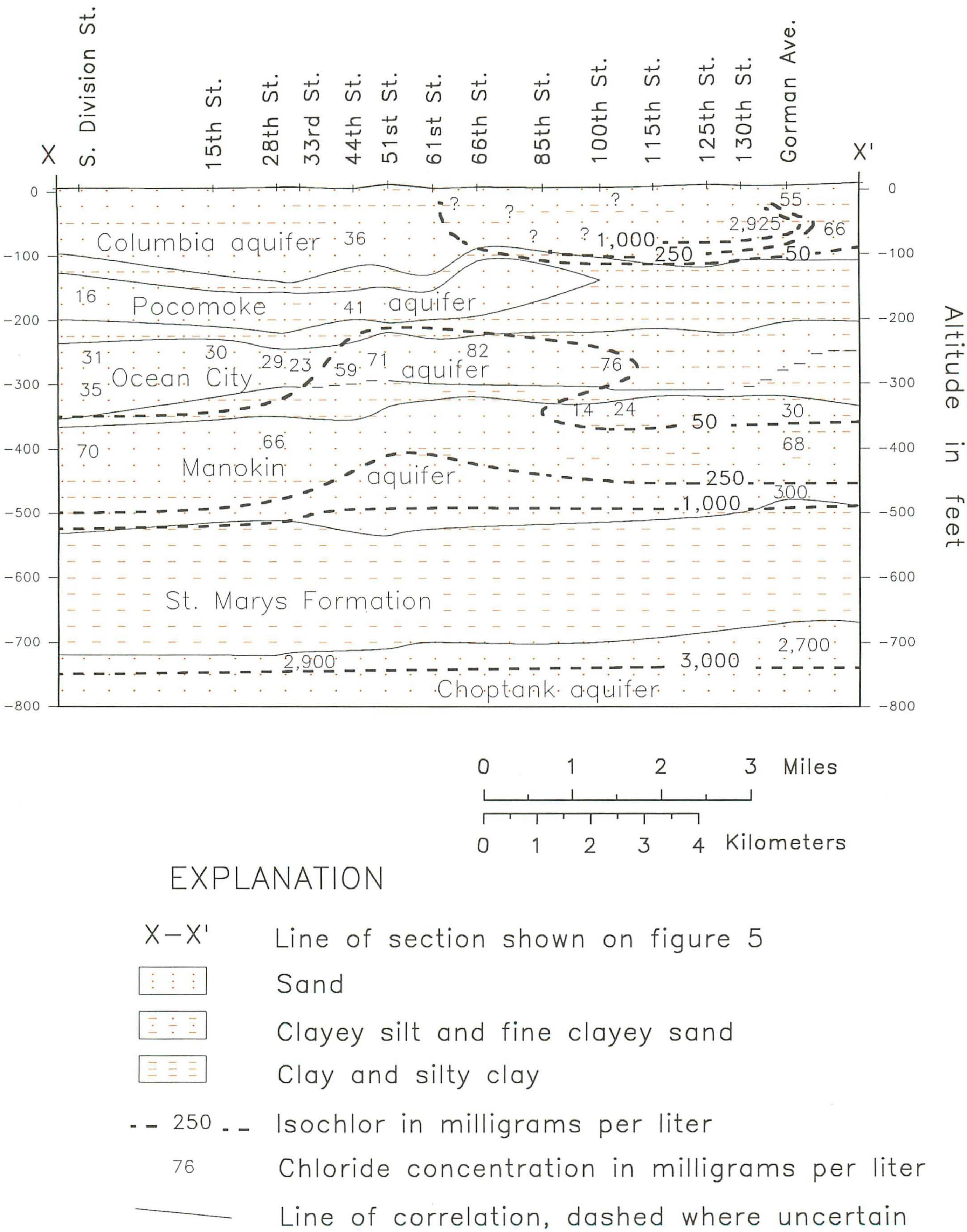


Figure 24.—Probable initial prepumping distribution of chlorides at Ocean City, Maryland.

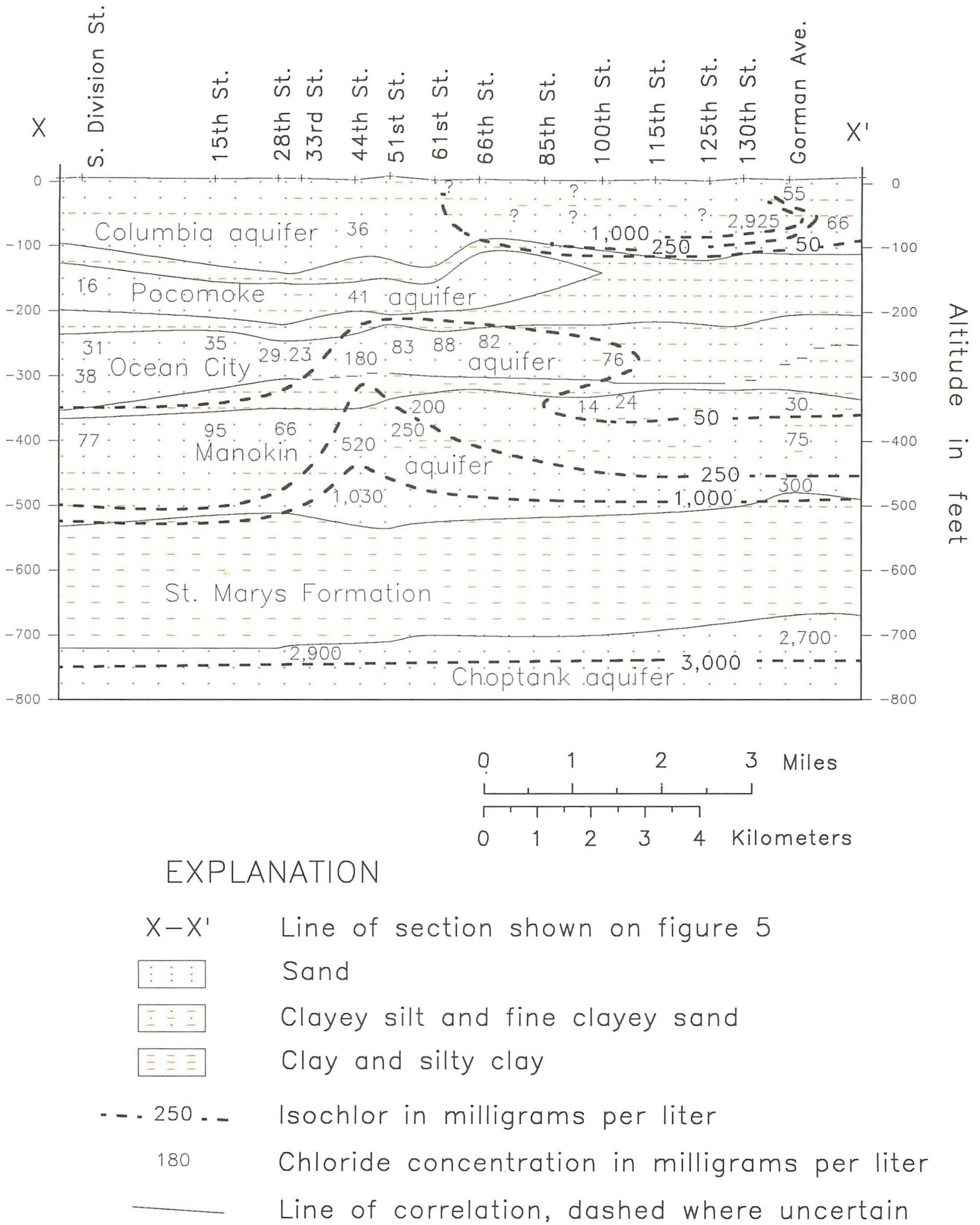


Figure 25.—The 1989–90 distribution of chlorides at Ocean City, Maryland.

1990 illustrates the relation among pumpage, water-level differences between the Ocean City and Manokin aquifers, and chloride concentrations at the 44th Street well field. Pumpage from the 44th Street well field was reduced in 1989 and 1990 in response to rising chloride concentrations in the Ocean City aquifer in Bh 28 (fig. 26). The reduction in pumpage at the 44th Street well field halted the rise in chloride concentrations at the 44th Street well field because the head differences between the Ocean City and Manokin aquifers were reduced (fig. 26). Figure 26 shows that water levels in the Ocean City aquifer were lower than water levels in the Manokin aquifer at this site year-round from 1986 through the summer of 1989. In the summers of 1989 and 1990, the maximum difference in water levels between the two aquifers was 2 to 3 feet less than in the summers of 1987 and 1988. From the fall of 1989 to the summer of 1990, the water levels in the Ocean City and Manokin aquifers were the same and the chloride concentrations in Bh 28 had stabilized at about 180 mg/L.

Gorman Avenue Well Field

At the Gorman Avenue well field ground water is pumped from the Manokin aquifer. The Manokin aquifer is thicker and more transmissive at Gorman Avenue than elsewhere in Ocean City. In observation well Ah 6 (fig. 2), the chloride concentration at 464 to 474 feet below land surface was 296 mg/L in 1969. In observation well Ah 37 (fig. 2), the chloride concentration at 468 to 478 feet below land surface was 320 to 360 mg/L in 1975, and 330 mg/L in 1990. In 1976, the annual average pumpage from the well field was 0.8 Mgal/d and the chloride concentrations in the two existing production wells, Ah 33 and Ah 34, were about 60 and 75 mg/L respectively. The well field was expanded in 1976 with the drilling of two additional public supply wells, Ah 38 and Ah 39 (fig. 2). In 1977, pumpage from the well field was increased to about 1.0 Mgal/d and chloride concentrations rose to 125 mg/L in Ah 33 and 100 mg/L in Ah 34. Since 1977, the chloride concentrations in Ah 33 and 34 have fluctuated within about 25 mg/L of their 1977 values. Figure 27 shows the chloride concentrations, water levels in observation well Ah 6, and average daily pumpage per month at the Gorman Avenue well field from 1970 to 1992.

Several factors have contributed to the relative stability of the chloride concentrations at the Gorman Avenue well field between 1972 and 1990. At 100th Street and 125th Street, the Manokin aquifer contains several internal confining units that impede the upward movement of brackish water. The geophysical logs for the sites indicate that freshwater sands are interstratified with clayey beds down to at least 440 feet below sea level (pl. 1). Ground water sampled from the upper part of the Manokin aquifer near 100th Street (Bh 34) in 1989 had a chloride concentration of 14 mg/L. Between 130th to 141st Streets, internal confining units in the Manokin aquifer are absent at the production well sites (fig. 2). These wells, however, produce water with less than 100 mg/L chlorides. This freshwater production is in part the result of the altitude of the contact between the basal silty sand facies of the Manokin and the St. Marys Formation. The contact is about 50 feet higher in the section at 137th Street than at 51st Street and the water in the basal facies of the Manokin at Gorman Avenue is less brackish than, for example, the water in the lower part of the Manokin from 44th to 61st Streets (pl. 1, app. C). Additionally, to avoid withdrawing brackish ground water from the base of the Manokin aquifer, public supply wells drilled at Gorman Avenue well field were screened 50 to 100 feet above the Manokin-St. Marys contact. For the same reason, production from individual wells is rotated to allow pumping water levels to recover. Recently drilled wells (Ah 43 and Ah 45) were located far enough away from existing wells to minimize the effects of well-interference and reduce the possibility of increasing the rate of brackish-water encroachment.

15th Street and South Division Street Well Fields

At the 15th Street well field, chloride concentrations range from 30 to 50 mg/L in the Ocean City aquifer and from 98 to 110 mg/L in the Manokin aquifer. At the South Division Street well field, chloride concentrations range from 30 to 65 mg/L in the Ocean City aquifer and from 80 to 90 mg/L in the Manokin aquifer. Chloride concentrations have not shown any significant increase over time in either the Ocean City or Manokin aquifer at the 15th Street or South Division Street well fields. Two reasons account for the stability of the chloride concentrations in the Ocean City and Manokin aquifer south of the 44th Street area. First, pumpage has remained relatively low and constant, between an annual average of 0.4 and 1.0 Mgal/d, since 1960. Secondly, the internal confining units of the Manokin aquifer are relatively thick and clayey in the region from South Division to 28th Streets. A 40 foot thick, clayey, confining unit separates freshwater in the upper part of the Manokin from water that is probably brackish (based on the multi-point electric log for Cg 72) in the lower part of the Manokin at the South Division Street well field (pl. 1). At 28th Street, this same confining unit is also 40 to 50 feet thick and the multi-point electric log at 28th Street suggests this confining unit separates freshwater in the upper Manokin from brackish water in the lower part of the Manokin (pl. 1).

Saltwater Intrusion to the Columbia Aquifer

Figure 25 illustrates the region where saltwater intrusion to the Columbia aquifer has occurred. Weigle (1974) mapped two areas of saltwater intrusion in the Columbia aquifer; at 66th and 137th Streets. Multi-point-electric logs of test holes made since 1974 suggest that parts of the Columbia aquifer from about 61st to 137th Streets are affected to some extent by saltwater intrusion from either the Atlantic Ocean, Assawoman Bay or both. The most likely cause of the intrusion is breached confining units in the upper part of the Columbia aquifer. Several historical inlets that are now infilled have been mapped in Ocean City (Truitt, 1963; Field, 1980). Saltwater intrusion to the Columbia aquifer from the ocean or back bays is not considered a serious problem because there is no pumpage from the Columbia or underlying Pocomoke aquifer at Ocean City, and multiple con-

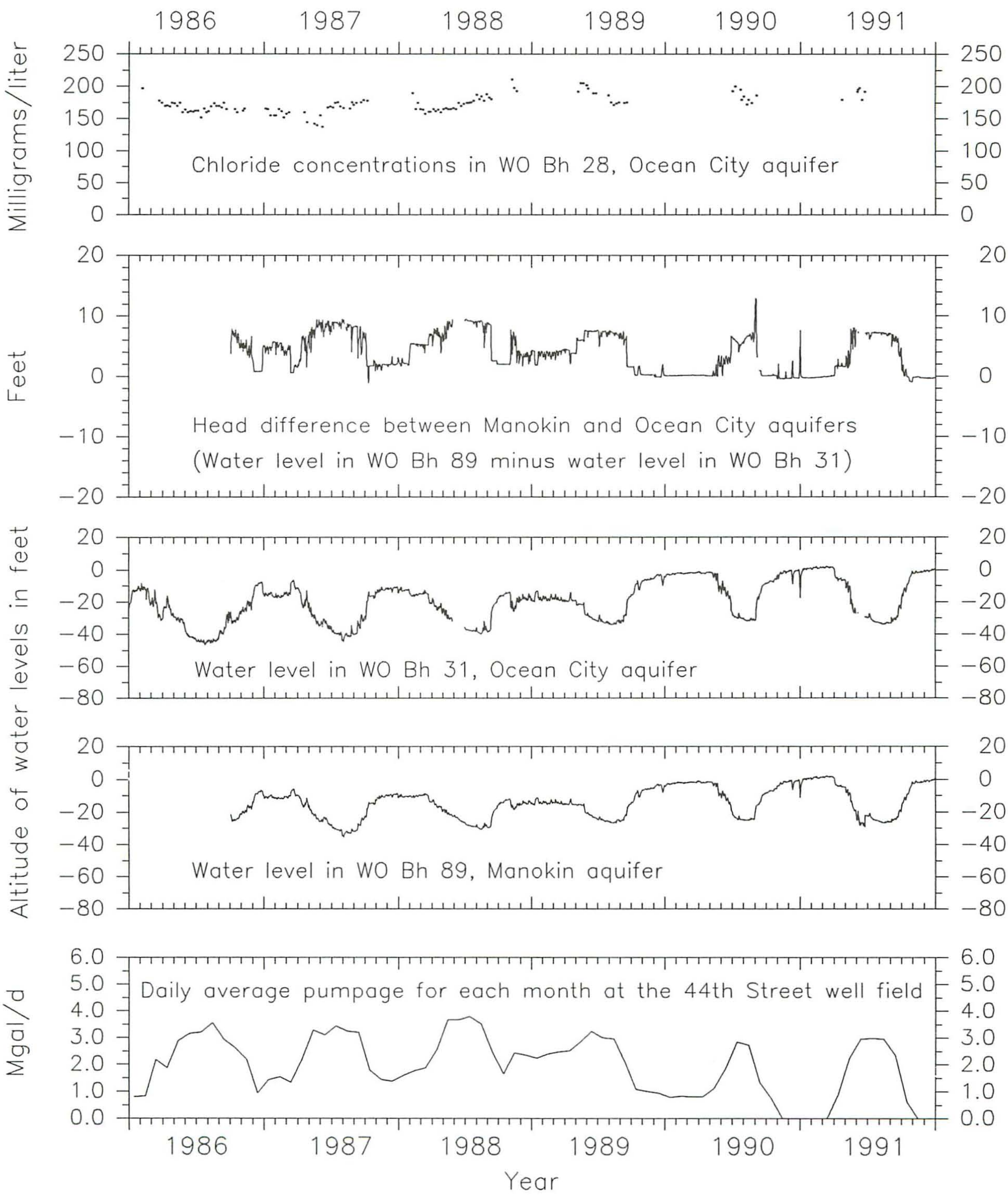


Figure 26.—Chloride concentrations in Bh 28, and average daily pumpage per month, water levels, and water level differences in the Ocean City and Manokin aquifers at the 44th Street well field from 1986 to 1990.

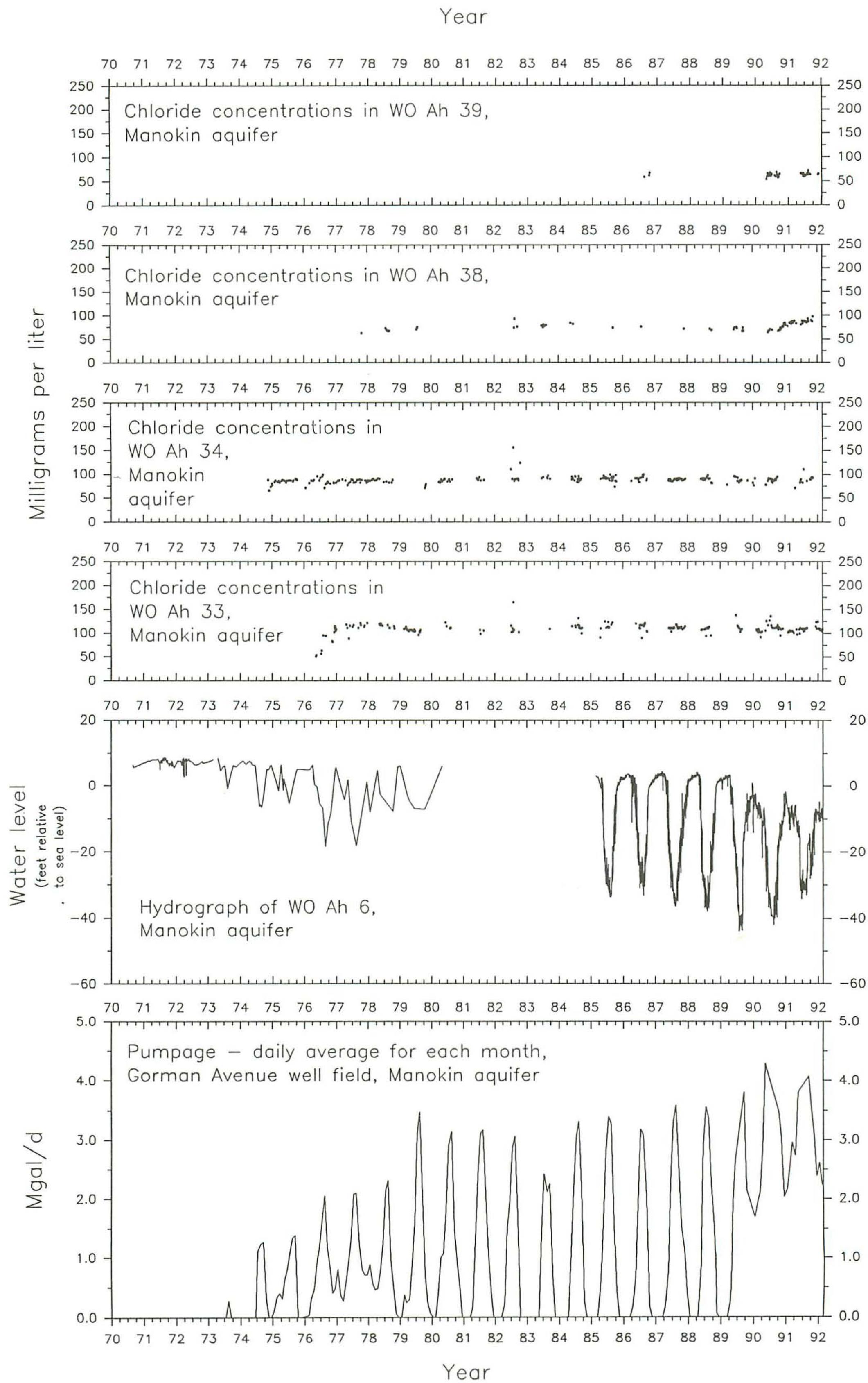


Figure 27.—Chloride concentrations in Ah 33, Ah 34, Ah 38, and Ah 39 and average daily pumpage per month and water levels at the Gorman Avenue well field from 1970–92.

fining units separate the Ocean City-Manokin aquifer system from the Columbia aquifer. Rising sea-level and new storm events will continue to make the Columbia aquifer susceptible to saltwater intrusion.

MODEL SIMULATION OF GROUND-WATER FLOW AND CHLORIDE DISTRIBUTION

SIMULATION OF GROUND-WATER FLOW

A ground-water flow model was developed to simulate the effects of future pumpage on water levels in the coastal aquifer system at Ocean City and to provide input data for a solute-transport model. The flow model integrates the components of the flow system by simulating the interaction between the aquifer's hydrologic properties, geometry, boundary conditions, recharge, discharge, and ground-water withdrawals. The U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1984) was used to solve for head distributions in the aquifer system. The flow equations used in the modular flow model describe a three-dimensional flow of ground water of constant density under non-equilibrium conditions in a heterogeneous and anisotropic medium with leakage across confining units.

Description of the Ocean City Flow Model

The ground-water flow model described in this report focuses on the Ocean City area. This model is based on an earlier model of the Ocean City area (Achmad and Weigle, 1979; Weigle and Achmad, 1982) that was updated and recalibrated with hydrologic data for the Ocean City area collected since the completion of the previous model. The model was expanded offshore to include the upper continental slope and vertically to include deeper brackish-water aquifers. The expanded model simulated more of the regional flow system and reduced the effects of artificial boundary conditions used in the earlier model. The areal coverage of the revised model is about 85.3 miles by 56 miles, which extends from 74°00′ W to 75°40′ W, and from 37°50′ N to 38°40′ N (fig. 28). The 4,777 square mile model area was discretized into a grid consisting of 40 columns and 44 rows with variable distances between the grid lines that range from 2,084 to 41,680 feet. The smallest elemental cell in the grid system is 2,084 feet by 2,084 feet, and the largest cell is 20,840 feet by 41,680 feet. The Ocean City area was divided into grid cells of 2,084 feet by 2,084 feet for better resolution of hydrologic properties and pumpage.

The flow model assumes uniform temperature, single density fluid, and advective flow. The assumptions and the finite-difference approximation restrict the application of the flow model to the simulation of water levels that represent the average level of freshwater in the model cell. The densities of the brackish water in the Ocean City area are not much greater than the density of freshwater; therefore, the model accurately simulated the water levels at Ocean City. Offshore, where saltwater is present, model heads are inexact. The density gradient offshore was simulated by converting the saltwater heads of the boundary nodes into equivalent freshwater heads.

Framework of the Conceptual Model

The flow model was constructed using five layers that represent a 1,900-foot thick section of Coastal Plain deposits underlying the study area (fig. 29). Each of the upper four layers of the model consist of an aquifer unit and an underlying confining unit. Layer 5, the lowermost layer of the model, is bounded on the bottom by no-flow boundary nodes. From top to bottom, the model layers correspond to the following hydrologic units: Layer 1 represents the Columbia aquifer and was assigned unconfined conditions. The onshore portion of layer 1 is modeled as an active water-table aquifer. Layers 2, 3, and 4 represent the Pocomoke, Ocean City, and Manokin aquifers respectively, and are assigned confined conditions. The St. Marys Formation is represented by the confining unit of layer 4. Layer 5 represents the Choptank aquifer and undifferentiated underlying hydrologic units (fig. 20) which in the model are simply referred to as the Choptank aquifer. Layer 5 was assigned confined conditions.

The confining units of layers 1, 2, 3, and 4 allow leakage between aquifers. The magnitude and direction of flow across a confining unit depends upon the differences in water levels between the aquifers, vertical hydraulic conductivity of the confining unit, and thickness of the confining unit. Inland the water levels of the upper aquifers are generally higher than the water levels of the lower aquifers and the flow across the confining units is downward (Weigle and Achmad, 1982, p. 5, fig. 2). At Ocean City the opposite condition exists; water levels of the lower aquifers are higher than water levels of the upper aquifers and flow across the confining units is upward.

Boundary Conditions

The flow model is enclosed by boundary surfaces that define the external geometry of the modeled aquifer system (fig. 29). The model boundaries are placed to correspond with natural hydrologic boundaries. At locations where an aquifer intercepts a large surface water body a constant-head boundary is assigned to the boundary cells, and where an aquifer is terminated, a no-flow boundary is usually assigned to the boundary nodes. At locations in the model area where the Pocomoke and Ocean City aquifers terminate, a low transmissivity value was assigned so that leakage from adjacent aquifers could occur, but horizontal flow in the aquifer would be prevented. Where an aqui-

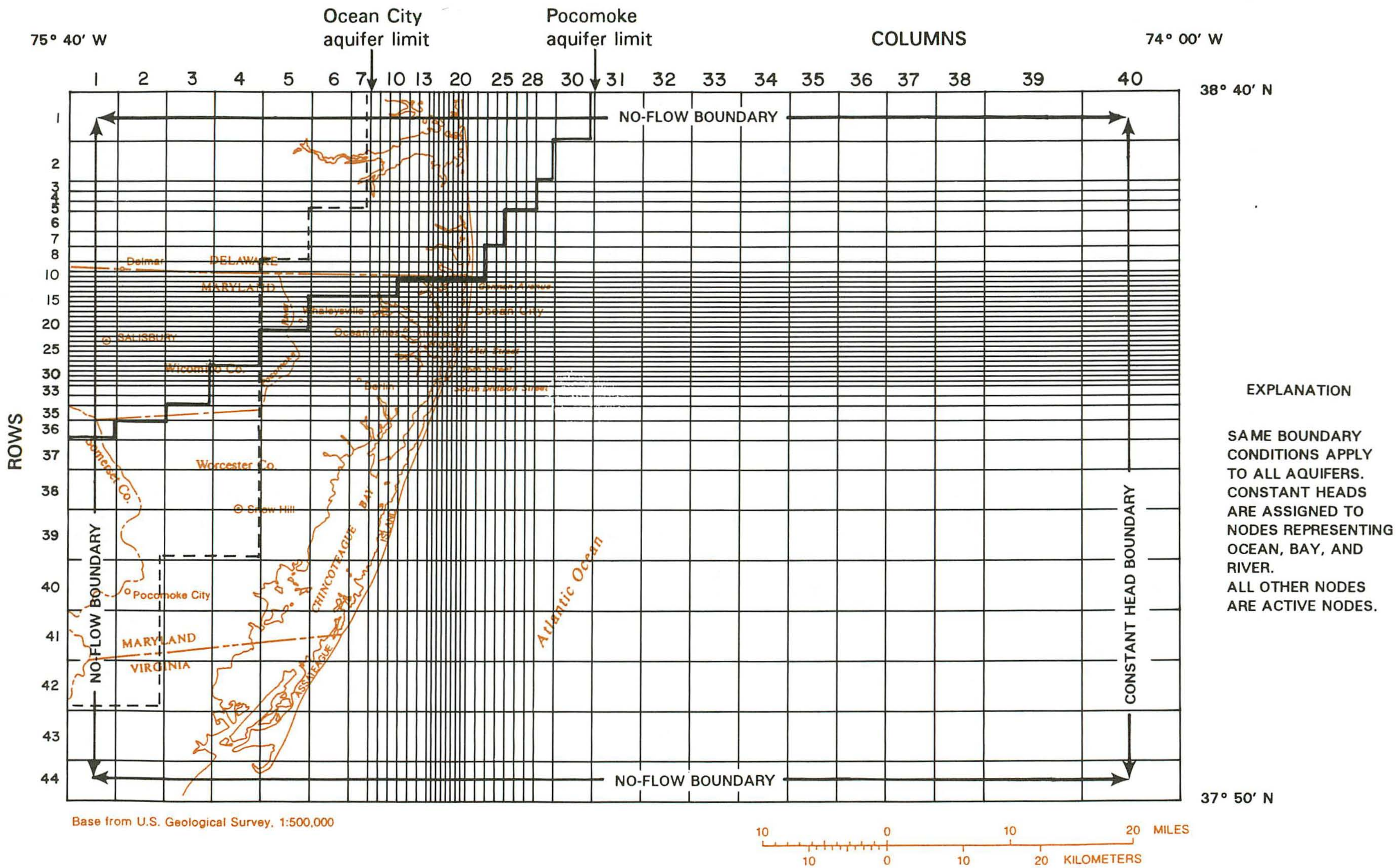


Figure 28.—Finite-difference grid and boundary conditions of the model area.

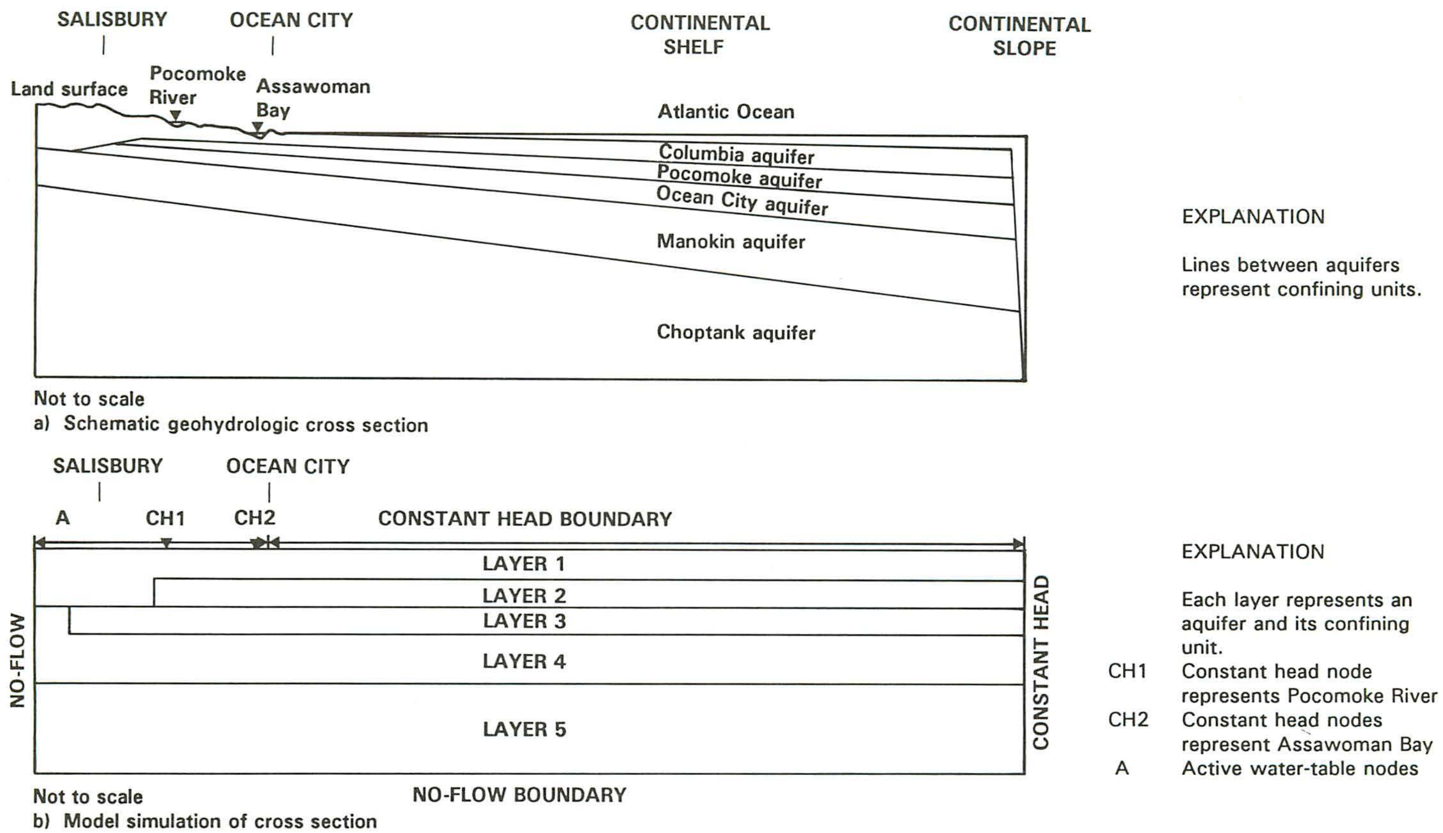


Figure 29.—Schematic cross section of the geohydrologic system and boundary conditions as simulated in the flow model.

fer continues beyond the boundaries of the model, specified-head or specified-flux boundary conditions are assigned to the boundary cells in order to provide flow across the boundary. The boundary conditions assigned to the model were specified on the basis of flow characteristics that prevail at each boundary surface (Franke, Reilly, and Bennett, 1984).

Layer 1 of the model was assigned a specified-flux boundary condition to represent recharge from precipitation. The cells of layer 1 that correspond to the Pocomoke River, the back bays (Assawoman, Isle of Wight and Chincoteague Bays), and the Atlantic Ocean were assigned constant-head boundaries (fig. 29). A constant-head of zero, representing sea level, was assigned to cells representing the back bays and ocean. The constant heads assigned to the stream cells were estimated from topographic maps. In this study, the simulated stream baseflow was not calibrated and no attempt was made to rigorously calibrate the water-table aquifer. Using constant-head boundaries to simulate stream cells is appropriate because the water table and stream elevations in the model area have not changed significantly during the simulation period. The base of layer 5 was assigned a no-flow condition because any flux across the lower boundary would have a minimal effect on the flow in the upper section of the model.

The western boundary nodes of the model were assigned no-flow conditions at subcrop locations where the confined aquifers terminate (fig. 28). The southern and northern boundaries of the model align approximately parallel to the general ground-water divide and were made no-flow boundaries. The southern and northern no-flow boundary conditions were tested after the model was calibrated by substituting a constant-head condition. Simulations using higher pumping rates did not show significant head differences in the Ocean City area when using no-flow or constant-head flow conditions because the boundaries are located far from the pumping centers.

The eastern boundary of the model was made a constant-head boundary. The eastern boundary of the model is located near the continental slope where the aquifer layers are exposed to the ocean. The validity of assuming constant-head conditions at the eastern boundary of the model was tested after the model was calibrated by substituting a no-flow boundary for the constant-head boundary. A pumping rate of 9.1 Mgal/d, the highest simulated by the model, did not cause any significant head changes at the eastern boundary of the model. The effects of the eastern boundary on the model were minimal. The hydraulic stresses imposed during the simulations did not reach the eastern boundary because the boundary is located far from the pumping centers on the downgradient side of the flow regime.

Hydrologic Properties

Hydrologic data supplied to the model include transmissivity and storage coefficient of the aquifers and vertical hydraulic conductance of the confining units (tab. 8). Vertical hydraulic conductance is defined as vertical hydraulic conductivity divided by thickness. Transmissivities and storage coefficients of the Columbia, Pocomoke, Ocean City, and Manokin aquifers and the vertical hydraulic conductivities of the corresponding confining units were obtained from an earlier model (Weigle and Achmad, 1982) and updated for the Ocean City area using information provided by Whitman, Requardt and Associates (1989). Transmissivity and storage coefficient data for the Choptank aquifer were obtained from earlier studies (Hansen, 1972; Cushing, Kantrowitz, and Taylor, 1973; and Vroblesky and Fleck, 1991).

Layer 1 (the Columbia aquifer) was assigned hydraulic conductivity values ranging from 25 to 75 ft/d, a storage coefficient of 0.15, and an average saturated thickness in the Ocean City area of 100 feet. The actual saturated thickness at each model cell was calculated as the difference between the water level and the altitude of the bottom of layer 1. The confining unit underlying layer 1 was assigned a vertical hydraulic conductance of $1.0 \times 10^{-6}d^{-1}$ (1/day).

Layer 2 (the Pocomoke aquifer) was assigned transmissivities ranging from 2,000 to 4,000 ft^2/d in the Ocean City area to 8,000 ft^2/d in the Snow Hill area. At locations where the Pocomoke aquifer is absent, a low transmissivity of 0.02 ft^2/d was assigned to layer 2. A transmissivity of 0.02 ft^2/d allowed vertical leakage across the confining units but prevented horizontal flow within the aquifer. The storage coefficient used for layer 2 was 0.00012. The underlying confining unit was assigned a vertical hydraulic conductance of $1.0 \times 10^{-6}d^{-1}$.

Layer 3 (the Ocean City aquifer) was assigned transmissivities ranging from 2,500 ft^2/d in the southern part of the model area to 7,500 ft^2/d in the Ocean City area. At locations where the Ocean City aquifer is absent a low transmissivity of 0.02 ft^2/d was assigned to layer 3. A storage coefficient of 0.00009 was assigned to layer 3. The underlying confining unit was assigned a vertical hydraulic conductance of $0.6 \times 10^{-4}d^{-1}$.

Layer 4 (the Manokin aquifer) was assigned transmissivities ranging from 2,500 ft^2/d in the southern part of the model to 10,000 ft^2/d at the Gorman Avenue well field. A storage coefficient of 0.00012 was assigned to layer 4. The vertical hydraulic conductance assigned to the confining unit underlying layer 4, the St. Marys Formation, was $2.0 \times 10^{-9}d^{-1}$; this value was obtained through model calibration.

Layer 5, (the Choptank aquifer) was assigned a transmissivity ranging from 500 to 1,400 ft^2/d and a storage coefficient of 0.0001 (Cushing, Kantrowitz, and Taylor, 1973, p. 44).

Ground-Water Recharge and Evapotranspiration

Ground-water recharge for a drainage basin can be calculated by summing up incremental increases in the water table (Rasmussen and Andreasen, 1959; Achmad, 1991), or by baseflow separation of streamflow hydrographs (Johnston, 1976; Achmad, 1991). Ground-water recharge in the model was applied as a uniform flux distributed evenly throughout the model area. A ground-water recharge of 18 in./yr was specified in the model based on average values previously reported for the model area and from adjacent areas with similar hydrologic

Table 8.—Hydrologic properties used in the flow model

Layer	Aquifer			Underlying confining unit
	Name	Transmissivity, in feet squared per day	Storage coefficient, dimensionless	Vertical hydraulic conductance, in day^{-1}
1	Columbia	25 to 75 feet per day times saturated thickness of 20 to 100 feet[1/]	0.15	1.0×10^{-6}
2	Pocomoke	2,000 - 8,000 where absent, transmissivity is .02 feet squared per day	.00012	1.0×10^{-6}
3	Ocean City	2,500 - 7,500 where absent, transmissivity is .02 feet squared per day	.00009	$.6 \times 10^{-4}$
4	Manokin	2,500 - 10,000	.00012	2.0×10^{-9}
5	Choptank	500 - 1,400	.0001	(No-flow boundary)

[1/] Saturated thickness is calculated as the difference between the water level and the altitude of the bottom of Columbia aquifer.

conditions (Rasmussen and Andreasen, 1959; Johnston, 1976; Achmad, 1991).

Evapotranspiration (ET) is the part of the water budget that is lost to the atmosphere by evaporation and by transpiration through plants. The ET rate varies with seasonal changes in air temperature, depth to the water table, and the type of vegetation in a region. The total evapotranspiration rate includes soil ET plus ground-water ET. The ground-water ET is the portion of total ET that is released from the water table. An average value of 18 in./yr ground-water ET was assigned to the model based on values reported in previous studies done in the model area (Rasmussen and Andreasen, 1959; Johnston, 1976), and in adjacent areas with similar hydrologic conditions (Achmad, 1991).

The effective ground-water evapotranspiration rate is a function of the depth to the water table (Ripple, Rubin, and van Hylckama, 1972). From land surface down to a certain depth the ground-water ET rate is at a maximum. As the water table approaches a minimum elevation, the ground-water ET rate decreases to zero. Field studies of the changes in the ground-water ET rate with depth are difficult to obtain. However, by assuming that the limit to evaporation is 3 feet below land surface and that transpiration is limited to an average depth of 8 feet below land surface, the extinction-depth interval for ground-water ET is from 3 to 8 feet below land surface (Wilson and Wiser, 1974). The model calculates ground-water ET for each cell in the water-table layer at a rate of 18 in./yr when the water table is at a depth of 3 feet below land surface or above. For water-table depths between 3 and 8 feet below land surface, ground-water ET is reduced linearly to zero in proportion to the increase in water-table depth.

Average annual ground-water recharge and evapotranspiration rates were used to simulate one-year stress periods. The average net recharge to the model calculated for the steady-state simulation was 1.4 in./yr.

Simulation of Historical Pumpage

The ground-water flow model must be calibrated by matching simulated water levels with the historical record under both steady-state and transient-flow conditions before the model can be used to predict the effects of pumpage on water levels at Ocean City. Model calibration is a trial-and-error method that consists of matching simulated water levels with measured water levels by adjusting the hydrologic properties used as model input. The steady-state and transient calibrations of the flow model are inseparable because a steady-state condition is essential for the initiation of the transient simulation. When both the steady-state and transient-flow calibration criteria are satisfied, the flow model is considered reasonably representative of the actual ground-water flow in the modeled area.

Steady-State Calibration

Under steady-state conditions inflow is equal to outflow and water levels do not change with time. By using the hydrologic properties and boundary conditions described earlier, the Ocean City model was run with a zero storage coefficient to simulate the water-level distribution of 1900. The year 1900 was chosen as the initial time to start the simulation because at that time development of the aquifers in the Ocean City area was minimal, and the flow system was in equilibrium. Only minor adjustments were made to the hydrologic parameters initially input to the model because this model was built using the hydrologic properties obtained from a previously calibrated model (Weigle and Achmad, 1982). Some trial-and-error adjustments of hydrologic properties were made for areas of the model that were outside of the area covered by the previously calibrated model. Since water-level data prior to the development of the aquifers are limited, the steady-state calibration was primarily a process of obtaining reasonable ground-water-flow patterns in the model simulations. Criteria for a reasonable flow pattern include higher water levels in the upper layers that cause a downward flow in the northwestern portion of the model and lower water levels in the upper layers near the coast that cause an upward flow discharging to the ocean. The simulated water levels obtained after several steady-state trial runs depict reasonable flow conditions (figs. 30–34).

The sensitivity analysis of the model input parameters indicates that simulated water levels were more sensitive to changes in the transmissivity of the aquifers than to the vertical hydraulic conductivity of the confining units. At steady state, multiplying the aquifer transmissivity by a factor of 2 reduced the drawdown in pumping cells by a factor of 2. Simulated water levels were not sensitive to changes in vertical hydraulic conductivity of the confining unit. A change of hydraulic conductivity of one order of magnitude caused only a fraction of a foot head change in the aquifer. Also at steady state, increasing the well pumpage by a factor of 2 produced twice as much drawdown. A change in the value of the storage coefficient affects the early stages of the transient simulation, but not the later stages when the water levels are stabilizing.

Transient Calibration

Using the 1900 steady-state water levels for initial conditions, the model simulated transient conditions by adding pumpage for the period 1900 to 1990 (fig. 17). During the transient calibration, the hydrologic properties and boundary conditions used to obtain the steady-state calibration were not changed. The simulations were arbitrarily divided into four segments, namely 1900–20, 1921–50, 1951–80, and 1981–90. Each simulation segment was divided into one-year stress periods and each stress period was divided into seven time steps with a multiplication factor of 1.2. Thus, each stress period started with a time step of 28 days; subsequent time steps increased by a factor of 1.2 until the seventh time step was 83 days. The pumpage used in the model is the annual average pumpage obtained by summing the daily pumpage over a year and dividing it by the number of days in the year. Consequently, the simulated water levels are annual average water levels. The simulated water lev-

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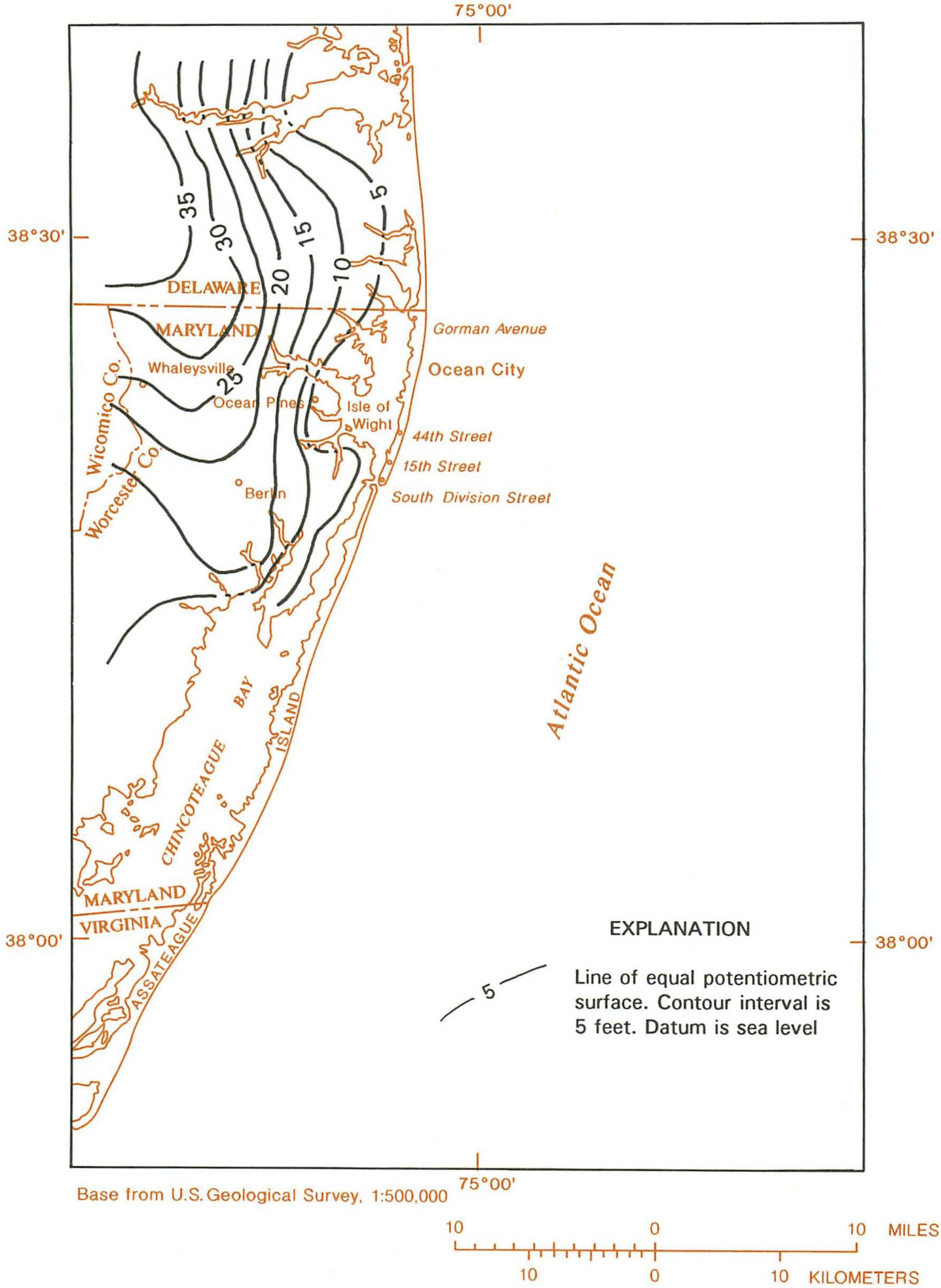

Figure 30.—Simulated potentiometric surface of the Columbia aquifer depicting the 1900 steady-state flow conditions.

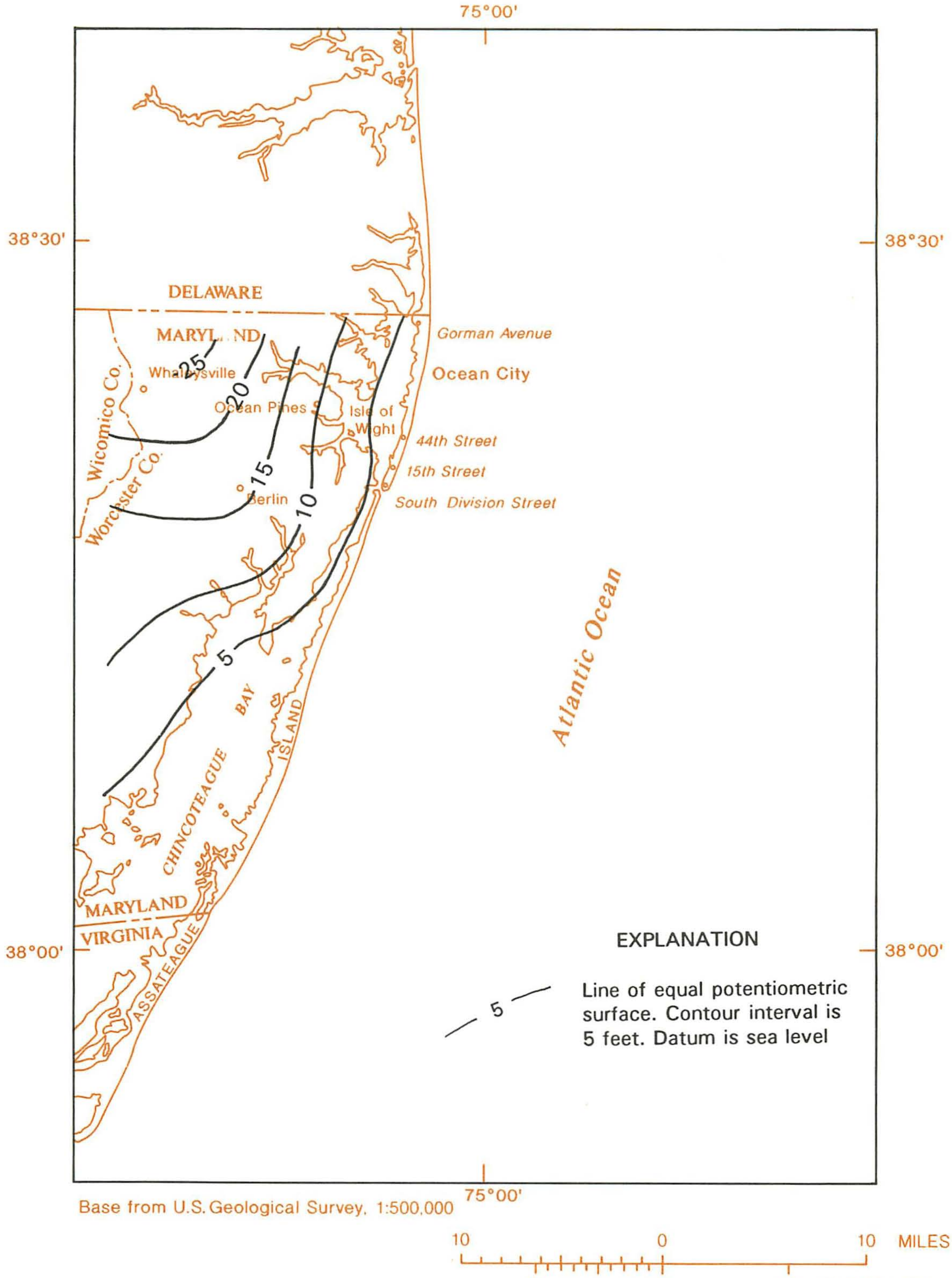

Figure 31.—Simulated potentiometric surface of the Pocomoke aquifer depicting the 1900 steady-state flow conditions.

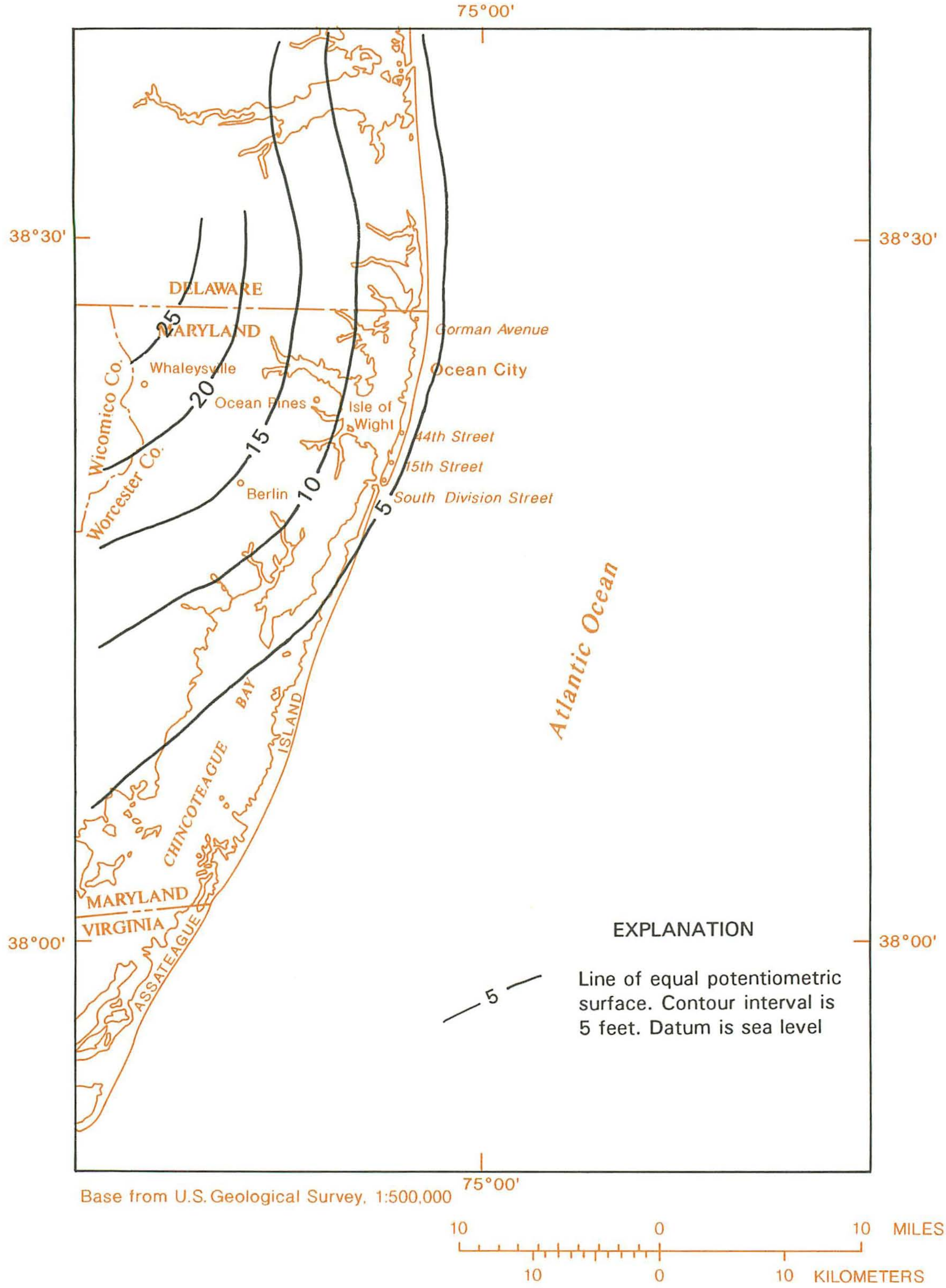

Figure 32.—Simulated potentiometric surface of the Ocean City aquifer depicting the 1900 steady-state flow conditions.

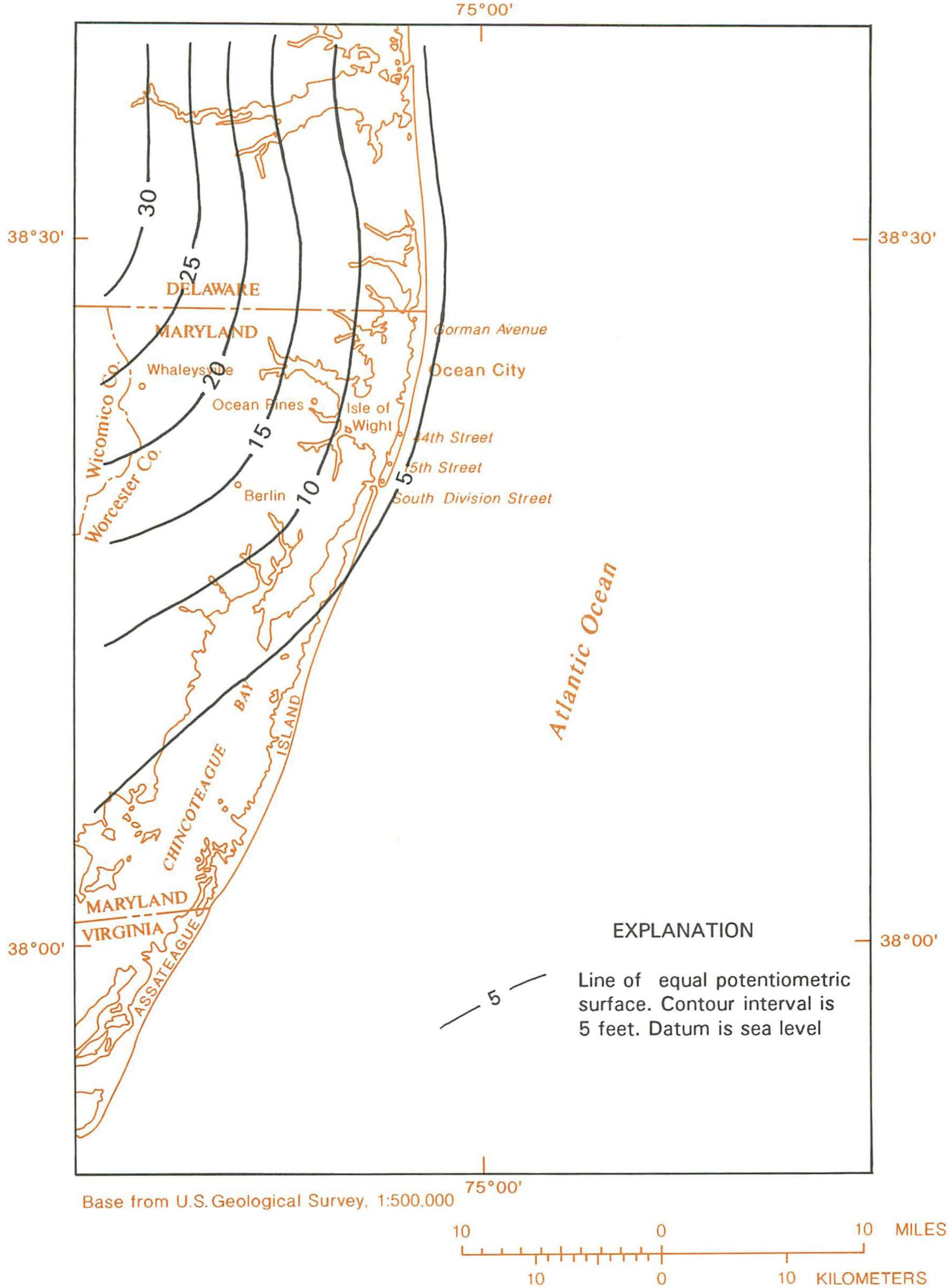

Figure 33.—Simulated potentiometric surface of the Manokin aquifer depicting the 1900 steady-state flow conditions.

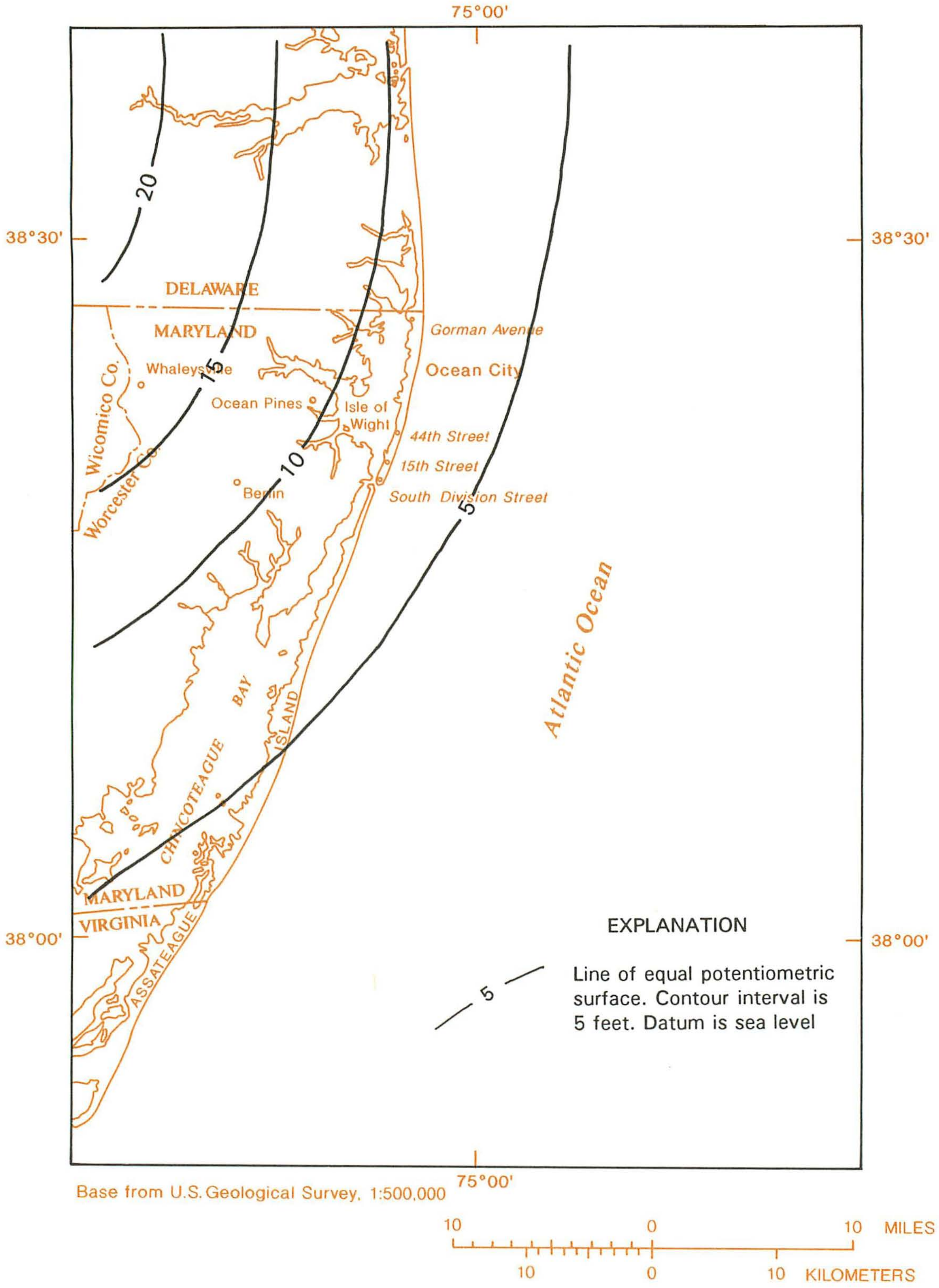

Figure 34.—Simulated potentiometric surface of the Choptank aquifer depicting the 1900 steady-state flow conditions.

els match reasonably well with the average of measured water levels for a given year (fig. 35). The average difference between simulated and measured water levels for all the aquifers simulated was 0.9 feet and the maximum difference was 5 feet. Ninety-four percent of the simulated water levels differed by 3 feet or less from the corresponding measured water levels. The 1900–1990 transient simulation provided a satisfactory calibration of the model.

At Ocean Pines, simulated annual average water levels in the Columbia and Pocomoke aquifers matched within 1 foot the measured annual average water levels. Figure 35 compares the simulated water levels with water-level hydrographs of Bg 45, which is screened in the Columbia aquifer. The measured and simulated water levels of the Columbia aquifer remained unchanged throughout the transient calibration. Simulated annual average water levels in the Pocomoke, Ocean City, and Manokin aquifers at the 44th Street well field, matched within 2 feet the measured annual average water levels (fig. 35). The observation wells used for calibration at the 44th Street well field were: Bh 85, screened in the Pocomoke aquifer; Bh 31, screened in the Ocean City aquifer; and Bh 89, screened in the Manokin aquifer. At the Isle of Wight, simulated annual average water levels in the Ocean City aquifer matched within 2 feet with the measured annual average water levels of well Bg 47. At the Gorman Avenue well field, the simulated annual average water levels of the Manokin aquifer matched within 5 feet the measured annual average water levels of the Manokin aquifer in Ah 37 (fig. 35) and in Ah 6. For the Choptank aquifer at the Gorman Avenue well field, the simulated annual average water levels matched within 5 feet the measured annual average water levels of Ah 35 (fig. 35).

First order linear regression analyses ($Y = aX + b$) indicated that the goodness of fit of the simulated and measured water levels was acceptable for water levels simulated in the Pocomoke, Ocean City, and Manokin aquifers; for those three aquifers, the linear slopes (b) ranged from 0.993 to 1.07 and the coefficient of correlations (r) ranged from 0.991 to 0.999 (tab. 9). The goodness of fit for water levels simulated in the Columbia and Choptank aquifers was reasonable; the linear slopes were 0.807 and 0.952 and the coefficients of correlation were 0.950 and 0.976 respectively.

The Pocomoke, Ocean City, Manokin, and Choptank aquifers showed the effects of pumpage. A cone of depression in the Pocomoke aquifer (fig. 36) formed at the 44th Street well field. In the Ocean City and Manokin aquifers (figs. 37 and 38), distinct cones of depression formed at the 44th Street and Gorman Avenue well fields. A cone of depression did not form in the Choptank aquifer, but the 5-foot water-level contour in the Choptank aquifer moved about 1 mile inland. The cones of depression of the Pocomoke, Ocean City, and Manokin aquifers are elongated in the seaward direction indicating that flux from the landward direction replenishes the cones faster than flux from the seaward direction. Water levels in the Columbia aquifer remained unchanged during the 1900 to 1990 simulation. The simulated water levels shown on the potentiometric surface maps are annual average water levels for each model cell and are not the water levels in individual pumping wells.

Simulation of Projected Pumpage at Ocean City

Projected water demand for Ocean City is expected to increase from about 5.6 Mgal/d in 1990 to 9.1 Mgal/d in 2010. One half of the total projected pumpage, about 4.5 Mgal/d, is to be supplied by the Gorman Avenue well field (Whitman, Requardt and Associates, 1989). The chief concern with developing the Ocean City-Manokin aquifer system is the potential increase in chloride concentrations of the ground water as pumpage increases. In 1988, an average daily pumpage of 2.62 Mgal/d from the Ocean City aquifer at the 44th Street well field caused chloride concentrations in well Bh 28 to reach 215 milligrams per liter (mg/L). Because chloride concentrations were approaching brackish levels, pumpage from the 44th Street well field was lowered significantly in 1989 and was maintained at comparatively low rates of 1.2 and 1.6 Mgal/d in 1990 and 1991. Reducing the average daily pumpage to about 60 percent of the 1988 levels has halted the rise in chlorides at the 44th Street well

Table 9.—Comparison of water levels using linear regression, $Y = a + bX$ for transient model verification

Aquifer	Y intercept a (feet)	Linear slope b (dimensionless)	Coefficient of correlation r (dimensionless)
Columbia	1.437	0.807	0.950
Pocomoke	0.007	1.002	0.999
Ocean City	-1.662	1.070	0.991
Manokin	0.387	0.993	0.994
Choptank	0.334	0.952	0.976

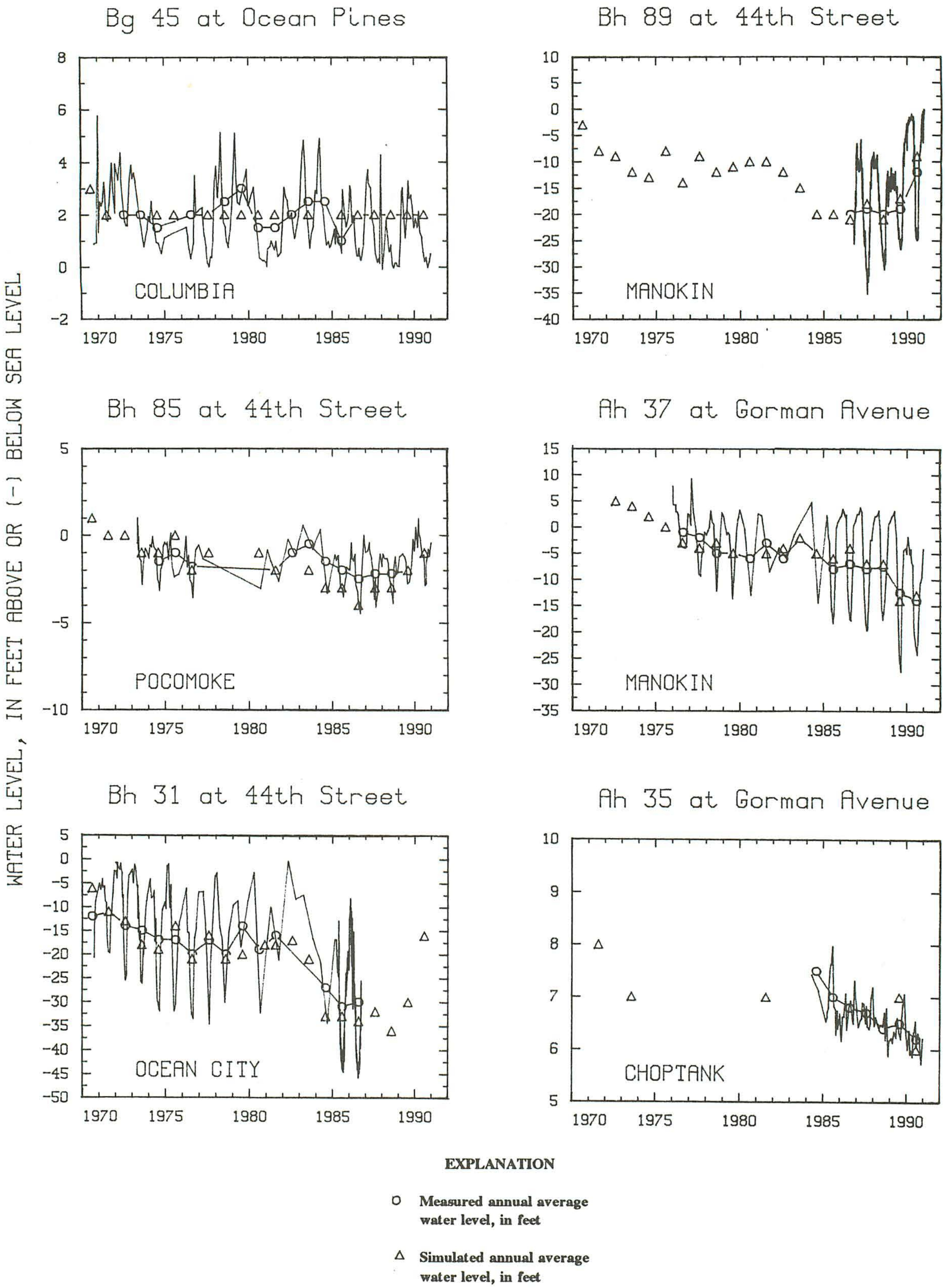

Figure 35.—Comparison of simulated annual average water levels and water-level hydrographs of the Columbia, Pocomoke, Ocean City, Manokin, and Choptank aquifers used for transient model calibration.

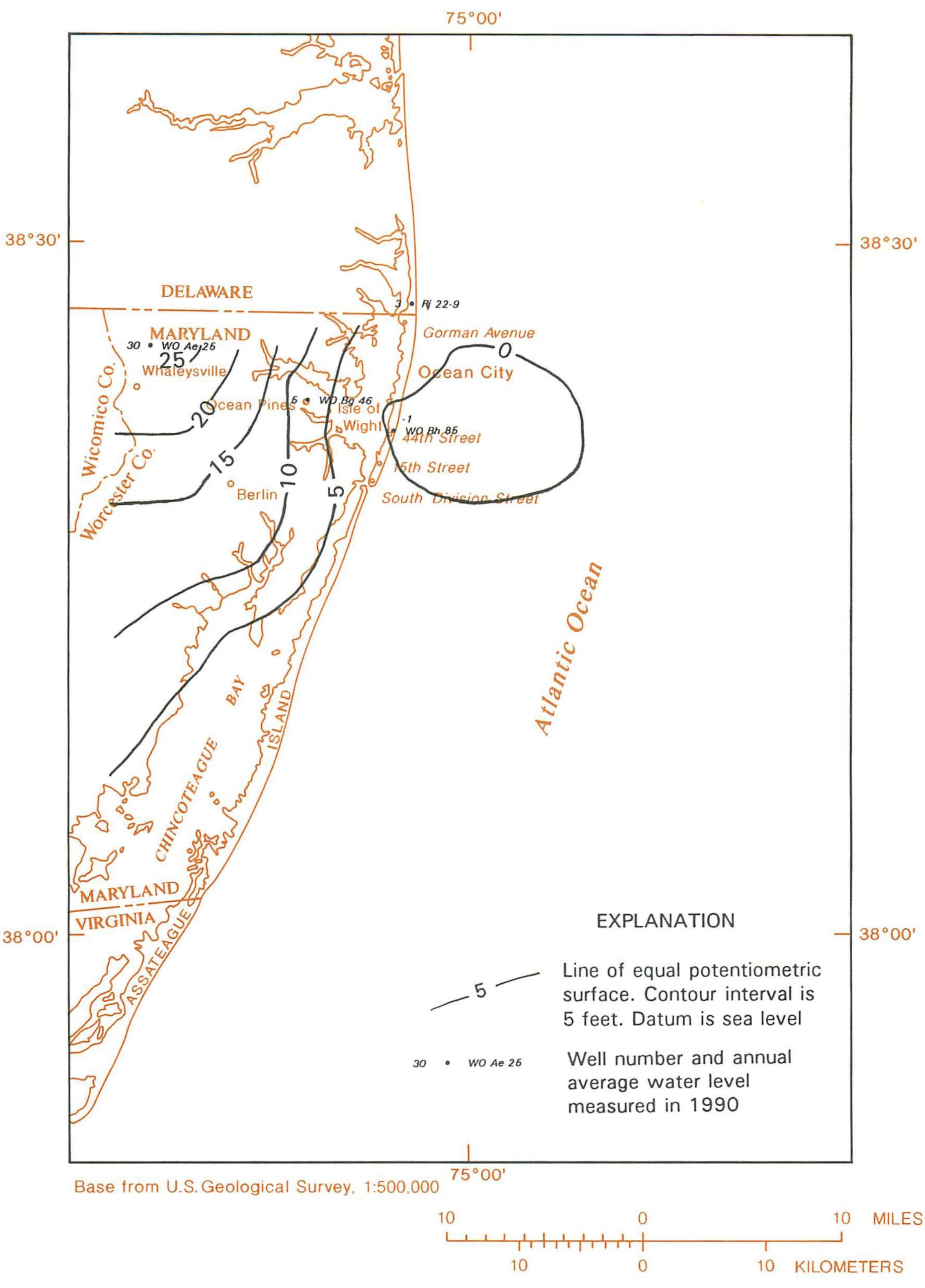

Figure 36.—Simulated potentiometric surface of the Pocomoke aquifer depicting the 1990 annual average water levels.

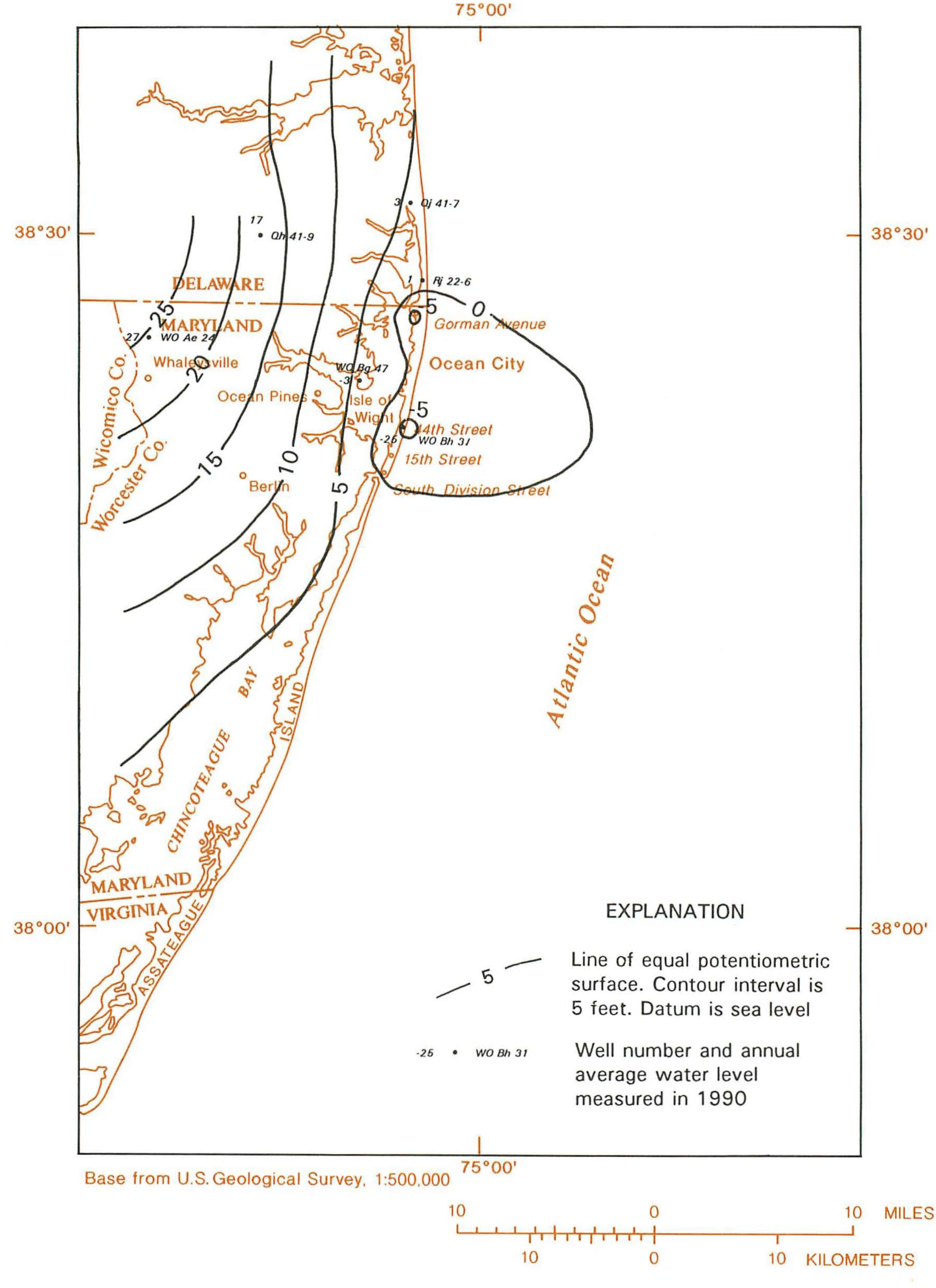

Figure 37.—Simulated potentiometric surface of the Ocean City aquifer depicting the 1990 annual average water levels.

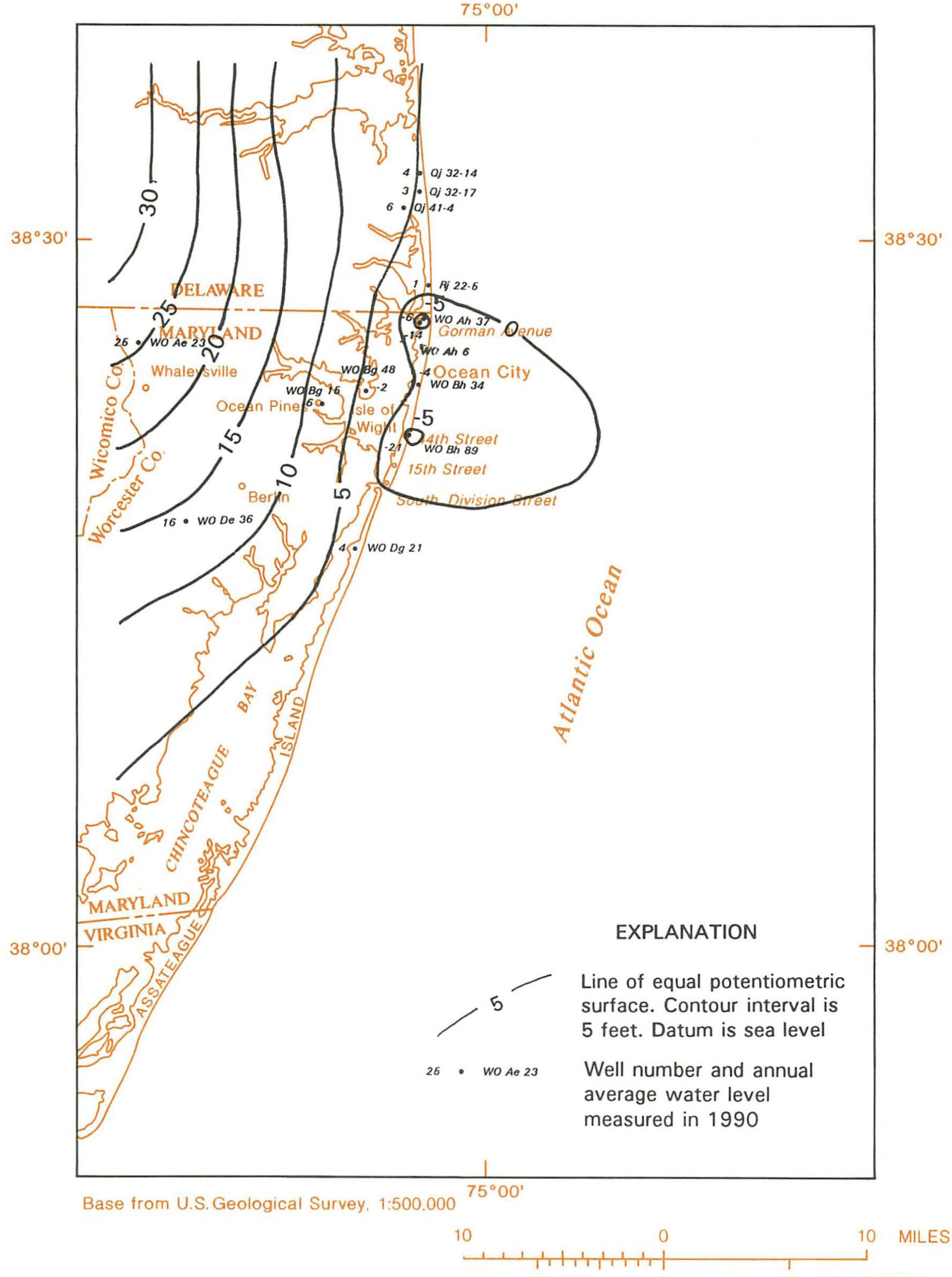

Figure 38.—Simulated potentiometric surface of the Manokin aquifer depicting the 1990 annual average water levels.

field, but has not reduced the chloride concentrations in the 44th Street well field production well Bh 28 by an equal amount. In 1990 and 1991, chloride concentrations in Bh 28 ranged from 172 to 200 mg/L. In comparison, in 1979 when the pumpage was 1.6 Mgal/d, the chloride concentration in well Bh 28 was 125 mg/L.

The effect of increased pumpage on water levels in the Ocean City-Manokin aquifer system is less of a constraint to continued aquifer development than the effect of increased pumpage on chloride concentrations in the aquifers. The deepest water level measured in 1990 in well Bh 31 (the Ocean City aquifer) at 44th Street was about 45 feet below sea level. The deepest water level measured in well Ah 6 (the Manokin aquifer) at Gorman Avenue was about 35 feet below sea level. These water levels are 200 feet above the top of the Ocean City aquifer and 300 feet above the top of the Manokin aquifer and indicate that a large amount of additional drawdown is available. Also, water levels recover during the winter months when pumpage is much lower (fig. 35).

The water-development plan for Ocean City (Whitman, Requardt and Associates, 1989) was updated with the actual pumpages for 1990 and 1991. The plan was used as a guide in developing scenarios for model simulation of projected pumpage from 1991 to 2010 (tab. 10). Actual pumpage from the South Division Street well field was 0.39 Mgal/d in 1991. In the model simulations, the pumpage from the South Division Street well field was increased to 0.75 Mgal/d for the period from 1992 to 1999, 0.88 Mgal/d for 2000, and 1.0 Mgal/d for the period from 2001 to 2010. Pumpage from the 15th Street well field was 0.39 Mgal/d in 1991. Pumpage from the 15th Street well field was increased in the model simulations to 0.86 Mgal/d for the period from 1992 to 1999, 0.88 Mgal/d for 2000, and 1.0 Mgal/d for the period from 2001 to 2010. The pumpage from the 44th Street well field was 1.6 Mgal/d in 1991. In the model simulations pumpage from the 44th Street well field was increased to a maximum of 2.6 Mgal/d for the period from 1992 to 2010. The pumpage from the Gorman Avenue well field was 3.9 Mgal/d in 1991. Simulated pumpage from the Gorman Avenue well field was kept at 3.9 Mgal/d for the period from 1992 to 2005 and increased to 4.5 Mgal/d for the period from 2006 to 2010. Pumpage from other production wells in Worcester County outside of Ocean City was 2.8 Mgal/d in 1990. In the model simulations this pumpage was kept at 2.8 Mgal/d for the period 1991 to 2010.

The simulated 2010 water levels for the Columbia aquifer were only slightly changed from the 1900 water levels with the exception of areas near well fields on the mainland where pumpage is from the Columbia aquifer. Simulated 2010 potentiometric surfaces in the Ocean City area for the Pocomoke, Ocean City, Manokin, and Choptank aquifers indicated the effects of increased pumpages. The simulated 9.1 Mgal/d total pumpage from the Ocean City and Manokin aquifers expanded and deepened the cones of depression in the Manokin, Ocean City, and Pocomoke aquifers at the 44th Street and Gorman Avenue well fields (figs. 39–41). Increased pumpage from the Ocean City and Manokin aquifers also affected water levels in the Choptank aquifer. The 5-foot water-level contour moved farther inland in the 2010 pumpage simulation than it did in the 1990 pumpage simulation.

A mass balance of the flow components helps determine the sources and effects of pumpage. The volumetric budgets for the 1900 steady-state simulation, and the 1950, 1980, 1990 and 2010 transient simulations are shown in table 11. In the model simulations, no recharge and no evapotranspiration were allocated to the constant-head nodes representing the ocean, bays, and rivers because recharge and evapotranspiration are intercepted by the constant head boundary (McDonald and Harbaugh, 1984, p. 242, 243, and 320). In order to relate the pumpage to the other flow components, the flow components in table 11 are expressed in Mgal/d, in./yr, and percentage of the net ground-water recharge. Net ground-water recharge is recharge minus effective evapotranspiration calculated for the total number of cells in the

Table 10.—Pumpage scenario based on projected future demand

Projected average daily pumpage in million gallons per day

Well field	1992	2000	Year 2001	2005	2010
South Division Street	0.75	0.88	1.00	1.00	1.00
15th Street	0.86	0.88	1.00	1.00	1.00
44th Street	2.60	2.60	2.60	2.60	2.60
Gorman Avenue	3.90	3.90	3.90	4.50	4.50
Total	8.11	8.26	8.5	9.10	9.10

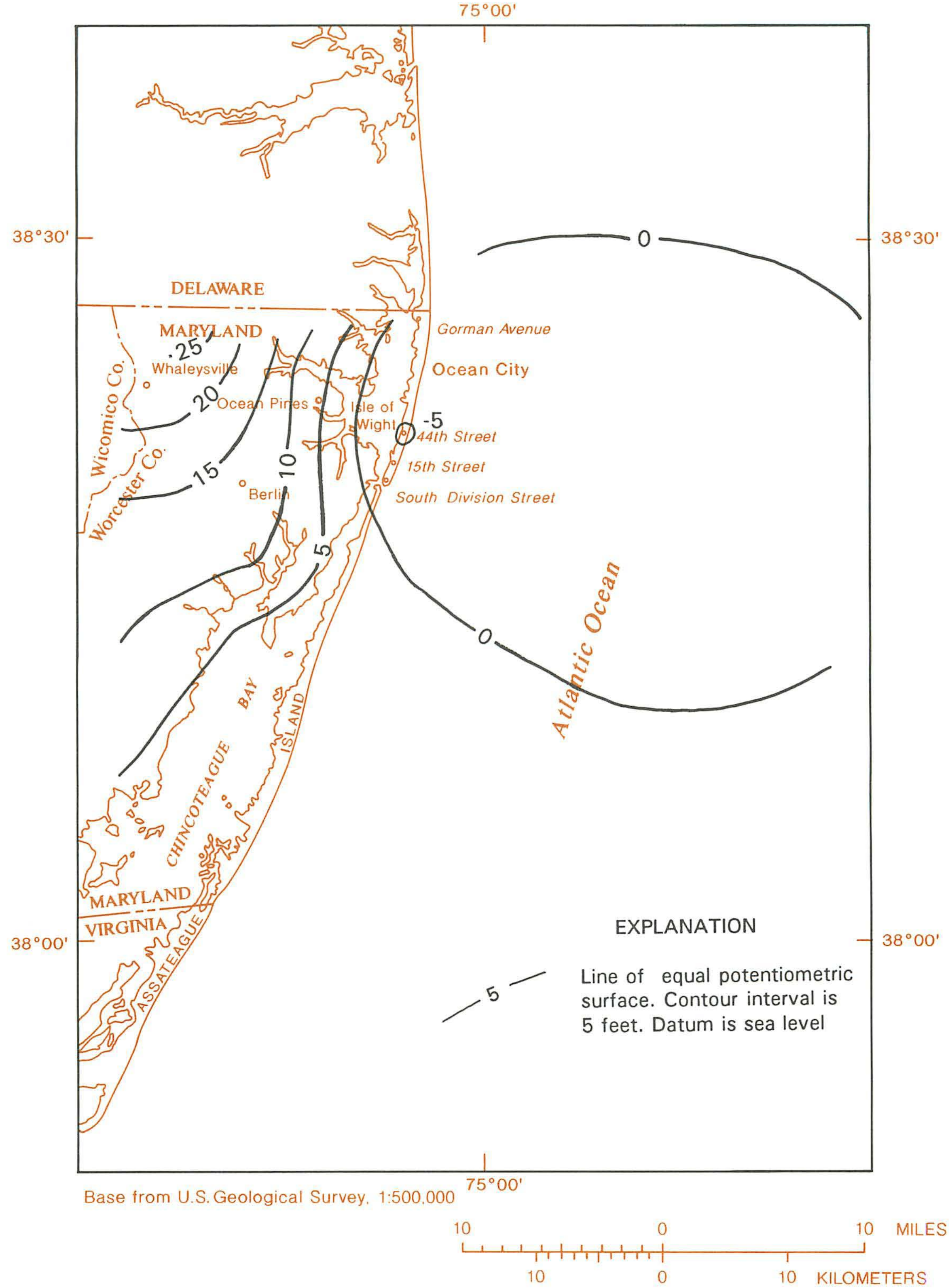

Figure 39.—Simulated 2010 annual average potentiometric surface of the Pocomoke aquifer using a pumping rate of 9.1 Mgal/d.

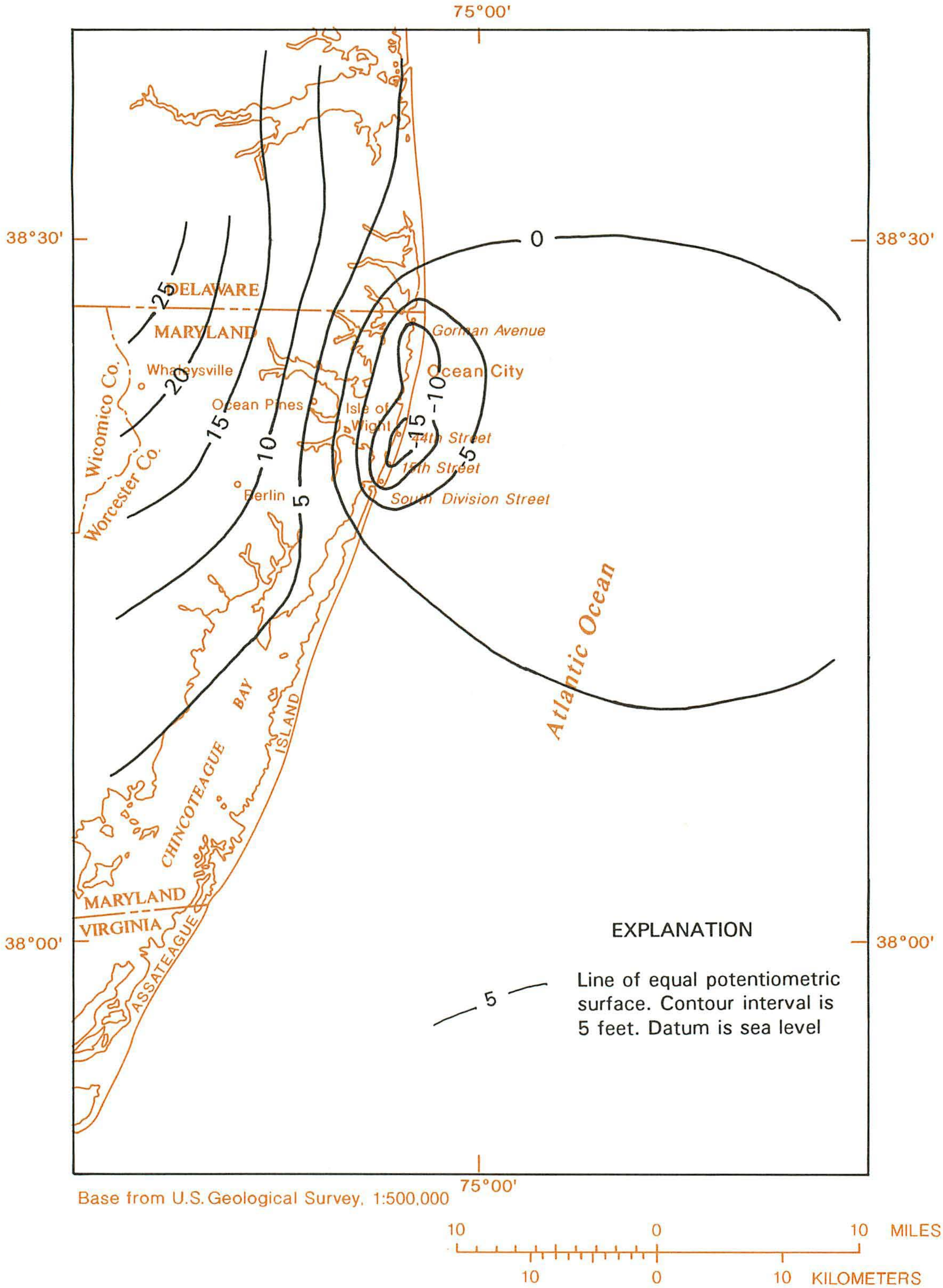

Figure 40.—Simulated 2010 annual average potentiometric surface of the Ocean City aquifer using a pumping rate of 9.1 Mgal/d.

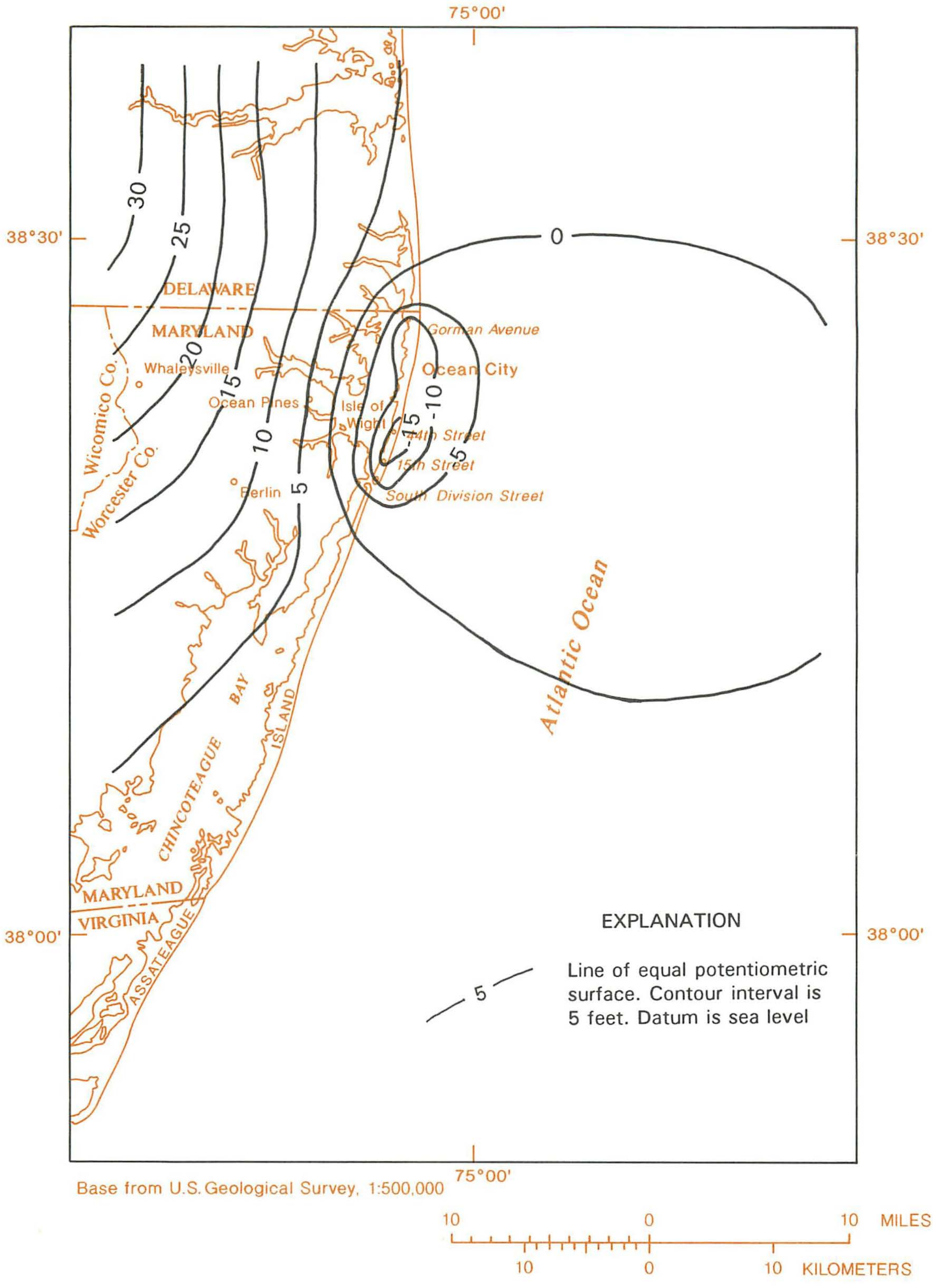

Figure 41.—Simulated 2010 annual average potentiometric surface of the Manokin aquifer using a pumping rate of 9.1 Mgal/d.

Table 11.—Mass balance of flow components for 1900, 1950, 1980, and 2010 simulations compared to net recharge

[Mgal/d = million gallons per day; in./yr = inch per year; % = percentage]

	Flow rates at the last time step in year:											
	1900			1950			1980			2010		
Inflow:	Mgal/d	in./yr	%	Mgal/d	in./yr	%	Mgal/d	in./yr	%	Mgal/d	in./yr	%
Net recharge[1/]	66.0	1.4	100	67.3	1.5	100	72.6	1.6	100	74.4	1.6	100
Outlfow:												
Well pumpage				2.0	.0	3	8.1	0.2	11	12.1	.3	16
Constant head boundary	66.0	1.4	100	65.3	1.5	97	64.5	1.4	89	62.3	1.3	84

[1/] Net recharge = ground-water recharge - effective evapotranspiration

model. The mass balance (tab. 11) for the steady-state simulation of 1900 indicates that a net recharge of 1.4 in./yr percolates into the water table. In steady-state conditions, there is no change in storage and water levels are in equilibrium. The steady-state mass balance, therefore, indicates that the net recharge of 1.4 in./yr is totally discharged through the constant head nodes representing the back bays and the ocean.

Water-level declines caused by pumpage reduce the loss to evapotranspiration and increase net recharge. The mass balance for the simulations of 1950 (2 Mgal/d), 1980 (8.1 Mgal/d), and 2010 (12.1 Mgal/d) indicate that net recharge is 1.3, 6.6, and 8.4 Mgal/d greater than net recharge for the 1900 simulation (tab. 11). The balance of the volume supplying pumpage (0.7, 1.5, and 3.7 Mgal/d respectively) is intercepted from discharge to the constant head boundaries.

PARTICLE-TRACKING ANALYSIS OF GROUND-WATER FLOW

A particle-tracking program (Pollock, 1989) was applied to the results of the flow model simulations to determine the origin and three-dimensional pathlines of recharge supplying the pumpage at Ocean City. The particle-tracking program calculates particle paths in a steady-state flow field. Particle tracking is an advective method that is solely based on flow velocity, and therefore does not account for the effects of mixing caused by diffusion or dispersion. The particle-tracking method assumes that the velocity component in each of the three principal directions of flow in a cell varies linearly with the flux across each face of the cell. Porosities and thicknesses are assigned to each cell of the flow model so that velocities and traveltimes can be calculated. All the aquifers were assigned a porosity of 30 percent and all the confining units were assigned porosity of 50 percent. The thickness of the layers used in the particle-tracking program were calculated from the altitudes of tops and bases of the aquifers (figs. 6–10 and 12–16).

Used as a post processor to the flow model, the particle-tracking program adds new insight to the flow-model simulations. The particle-tracking program is a useful tool for determining recharge areas and time-specified capture zones by backtracking recharge particles from a pumping well. The mass balance of a pumping cell estimates the distribution of fluxes that contribute to the pumpage passing through the six faces of the model cell (fig. 42). The particle-tracking program used in conjunction with the pumping cell mass balance provides an estimate of the magnitude of the flow components supplying the pumpage at Ocean City and the source of ground-water recharge to the well fields.

Particle tracking was applied to steady-state simulations using the 1972 and 1990 pumpages at the 44th Street well field and the 1990 pumpage at the Gorman Avenue well field in order to identify sources of recharge. Particle tracking was also applied to the projected 2010 pumpages at the 44th Street and Gorman Avenue well fields in order to assess the sources of brackish-water encroachment at higher pumping rates. A steady-state simulation is achieved in a single time step by assigning zero aquifer storage. In reality, a steady-state equilibrium is reached when hydraulic heads remain unchanged with time; an extended period of time is often necessary for this condition to be achieved.

The particle-tracking analyses were made by releasing 27 to 125 particles per pumping cell. The particles were backtracked from the pumping cell using the weak-sink option, in which particles are not captured as they pass through other pumping cells in the flow region. Backward tracking the particle pathlines from the pumping cell to their endpoints at the water table determines the recharge area for the pumping cell. The steady-state capture zone for the pumping cell is the paths followed by the backtracked particles from the pumping cell to the recharge area after steady-state flow conditions are established. The traveltimes for backtracked particles to reach the recharge area from the pumping cells that simulated the Ocean City pumpage

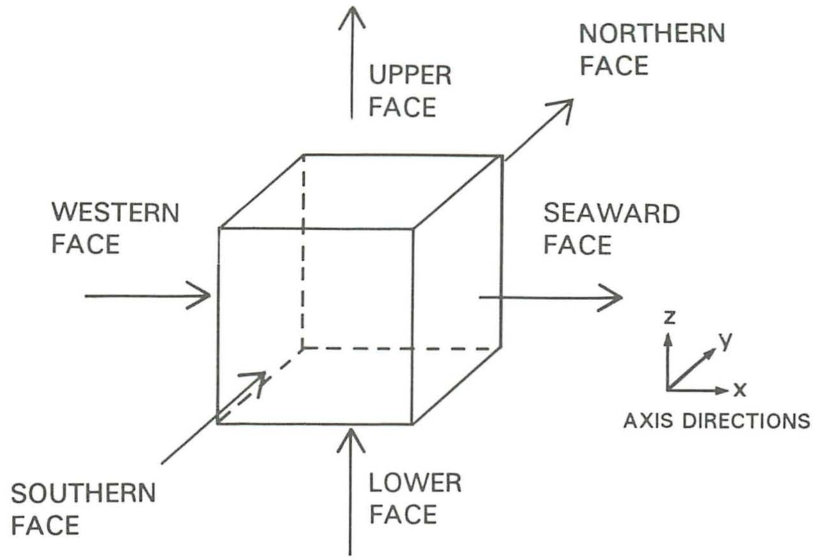

Figure 42.—Schematic diagram naming the six faces of a model pumping cell.

ranged from 10,000 to 370,000 years. The 30-year capture zone for a pumping cell is the zone covered by the end points of the pathlines generated after 30 years of backtracking particles.

Releasing 27 to 125 particles per cell produced pathlines that represented the particle tracks clearly. Releasing more than 125 particles per cell resulted in a cluttered graph that was difficult to interpret. The use of a large number of particles per cell increased the density of the pathlines and endpoints, but the area and shape of the capture zone remained the same. In order to illustrate the three-dimensional aspect of the ground-water-flow system, the pathlines are shown in areal and cross-sectional views along a row and column of the model grid. The pathlines and endpoints were projected onto the viewing plane.

44th Street Well Field

The production wells in the 44th Street well field are screened in the Ocean City aquifer. In 1972, the average total pumpage of the 44th Street well field was about 0.74 Mgal/d. Pathline endpoints backtracked from the pumping cell simulating 1972 pumpage indicated that most of the recharge particles originated in the part of the Columbia aquifer that forms the freshwater subcrop area of the Ocean City aquifer (fig. 43A) and some of the particles originated in the Columbia aquifer offshore of Ocean City (fig. 43B). The endpoints of the pathlines denote the recharge area for the 44th Street well field.

Several of the pathlines from the freshwater recharge area followed flow lines in the freshwater-saltwater mixing zone before arriving at the pumping cell (figs. 43B–C). Also, some of the pathlines crossed the confining unit underlying the Ocean City aquifer into the brackish water-bearing parts of the Manokin aquifer and then returned to the Ocean City aquifer and entered a pumping cell. The flowlines of the recharge particles follow the general flow direction based on the head distribution and hydrology of the area. In the Salisbury-Whaleysville area, higher water levels in the upper aquifer caused a downward flow. In the Ocean City area, higher water levels in the lower aquifer caused an upward flow (Weigle and Achmad, 1982, p. 5).

The areal and cross-sectional views of the pathlines simulated using a pumpage of 1.6 Mgal/d in 1991 and 2.6 Mgal/d in 2010 show particle tracks similar to those generated in the 1972 simulation. The higher-pumpage simulations, however, produced more pathlines that followed the flow lines in the offshore portion of the freshwater-saltwater mixing zone. The endpoints of pathlines shown in figure 44 indicate the approximate recharge area for the 44th Street well field. Most of the points align in an irregularly shaped band that extends through northern Worcester County and adjacent parts of Delaware.

The 30-year capture zone for the 44th Street well field represents the portion of the Ocean City-Manokin aquifer system that contributed water to the well field during 30 years of constant pumping. The 30-year capture zone covered an area of about 7 square miles around the 44th Street well field. The 30-year pathlines extended about 1 mile offshore from the pumping cell in the Ocean City aquifer. Some of the pathlines originated from the Manokin aquifer, crossed the underlying confining unit and entered the pumping cell in the Ocean City aquifer.

The mass balance for the pumping cell using the 1972, 1990 and 2010 pumpages of 0.74, 1.2 and 2.6 Mgal/d respectively indicates that 65 to 62% of the flux entered the pumping cell from four cell faces in the Ocean City aquifer, namely 16 to 20% entered through the western face, 15 to 18% through the northern face, 14 to 16% through the seaward face, and about 9 to 20% through the southern face. About 33 to 36% of the flux entered the pumping cell from the underlying Manokin aquifer at a flow velocity of about 0.025 to 0.009 ft/d. A small amount, about 1 to 2% of the flux entered the pumping cell from the overlying Pocomoke aquifer.

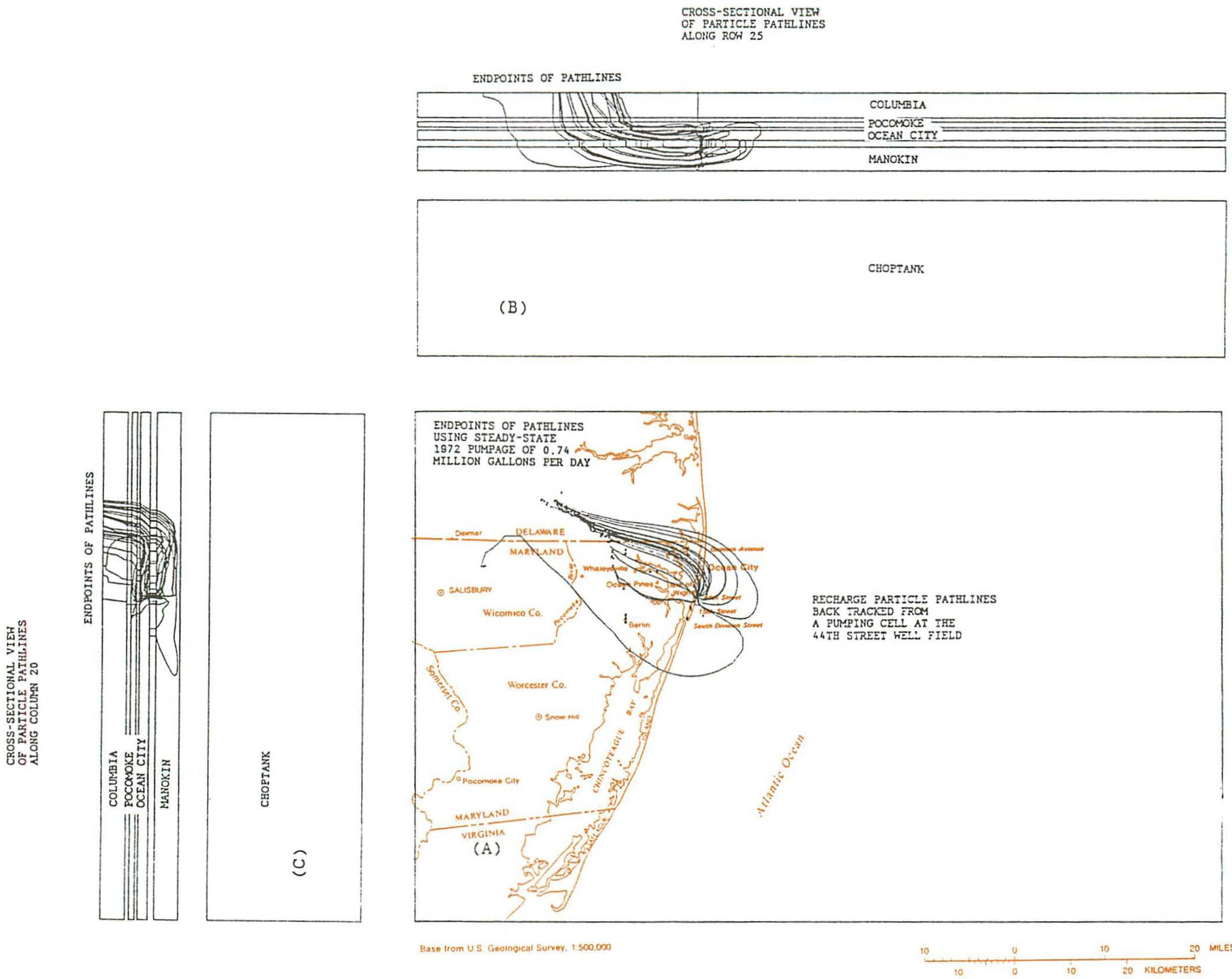

Figure 43.—Recharge particle pathlines and endpoints of pathlines backtracked from a pumping cell at the 44th Street well field simulating 1972 pumpage: (A). Areal view, (B). Cross-sectional view along row 25, and (C). Cross-sectional view along column 20.

The mass balance of the ground-water flux to the pumping cell indicates that brackish water in the Manokin aquifer at 44th Street is the primary source of the brackish water that enters the Ocean City aquifer. The amount of vertical leakage from the Manokin to the overlying Ocean City aquifer averaged more than 2.5 times the amount of lateral inflow to the pumping cell from the offshore portion of the freshwater-saltwater mixing zone. The rate of upward leakage from the Manokin aquifer to the Ocean City aquifer increases as the pumping rate increases.

Gorman Avenue Well Field

The production wells at the Gorman Avenue well field are screened in the Manokin aquifer. In 1973, when the first well was drilled, the annual average pumping rate was 0.02 Mgal/d. By 1990 the annual average pumping rate had increased to 3.7 Mgal/d. In 1990, pumpage was produced from five wells located between 130th and 141st Streets. The steady-state flow simulation for 1990 applied 3.7 Mgal/d pumpage to one cell covering the Gorman Avenue well field. Backtracking the recharge particles pathlines from the pumping cell to their endpoints indicates that the recharge areas for Gorman Avenue pumpage are located in the Columbia aquifer in the subcrop area of the Manokin aquifer located to the northwest of Ocean City, and also offshore of the Gorman Avenue well field. Several pathlines originating in the freshwater recharge areas followed flow lines in the freshwater-saltwater mixing zone before arriving at the pumping cell. Only a few of the pathlines crossed the St. Marys confining unit which indicates that very little leakage from the brackish Choptank aquifer enters the Manokin aquifer. The mass balance for the pumping cell also confirms that very lit-

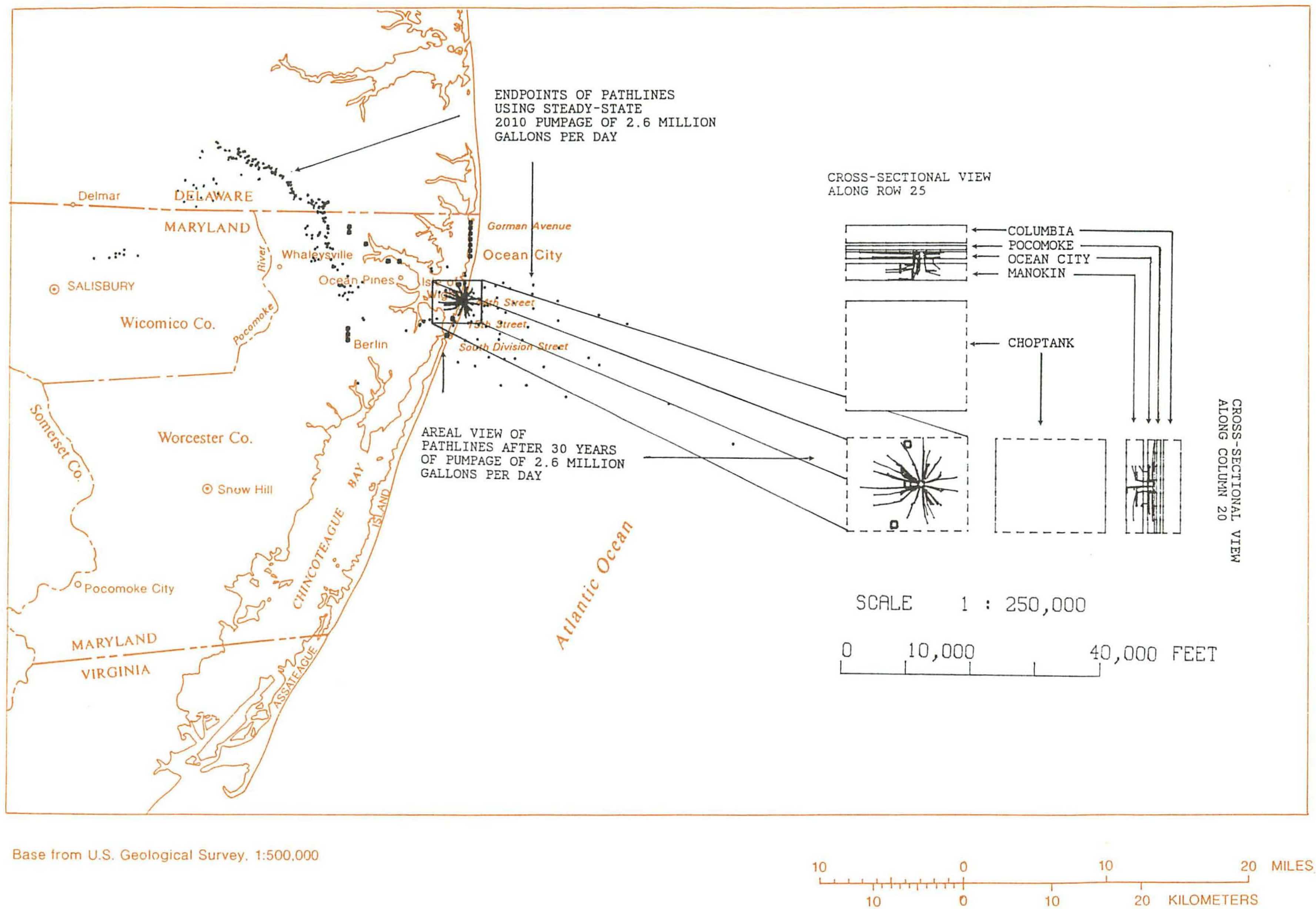

Figure 44.—Endpoints of recharge particle pathlines and a 30-year capture zone backtracked from a pumping cell at the 44th Street well field simulating the 2010 pumpage of 2.6 Mgal/d.

tle flux entered the pumping cell by upward leakage from the brackish Choptank aquifer.

Using the 1990 pumpage of 3.8 Mgal/d at the Gorman Avenue well field, the pumping cell mass balance indicates that 80% of the flux entered the pumping cell from the four cell faces in the Manokin aquifer, namely 23% entered through the western face, 22% through the northern face, 16% through the seaward face, and 19% through the southern face. About 20% of the flux entered from the overlying Ocean City aquifer. Less than 0.01% of the flux entered the pumping cell from the underlying St. Marys confining unit. This flux had a very low velocity (4×10^{-5} ft/d).

The 2010 simulation of the Gorman Avenue well field is based on a water-supply plan for Ocean City, which projects a 4.5 Mgal/d pumpage from an expanded well field (Whitman, Requardt and Associates, 1989). In the model the wells are represented by seven separate pumping cells that are located along the island between 141st and 95th Streets. Pumpage at each simulated well ranged from 0.33 Mgal/d to 0.74 Mgal/d, and equaled a total well field pumpage of 4.5 Mgal/d. Backtracking pathlines from the pumping cells indicated that the recharge areas are located in a band about 10 to 20 miles northwest of Gorman Avenue (fig. 45), and also offshore about 17 miles east of the shoreline. The 30-year capture zone using pumpage of 4.5 Mgal/d covered a rectangular shaped area of about 10 square miles in the Manokin aquifer extending from Gorman Avenue to 95th Street (fig. 45 inset). Very few pathlines crossed the St. Marys confining unit, and only a few pathlines crossed the overlying confining unit to the Ocean City aquifer (fig. 45 inset).

The mass balances for pumping cells simulating the 2010 projected pumpage of 4.5 Mgal/d indicate that about 74% of the flux entered from the four cell faces in the Manokin aquifer, namely 36% entered through the western face, 10% through the northern face, 26% through the seaward face, and 2% through the southern face. About 26% of the flux entered from the overlying Ocean City aquifer and less than 0.05% entered from the underlying St. Marys confining unit. Similar to the 1990 simulation, the pathlines and flux distributions of the 2010 simulation indicated that lateral encroachment from the offshore portion of the freshwater-saltwater mixing zone is the main source of brackish water to the Manokin aquifer at the Gorman Avenue well field. The rate of lateral encroachment increases as pumpage from the well field is increased.

The recharge area for all of the Ocean City well fields (figure 46) was obtained using a pumpage of 9.1 Mgal/d. The complete recharge area included the recharge area of the 44th Street and Gorman Avenue well fields (figs. 44 and 45), and the recharge areas of the 15th Street and South Division Street well fields. The recharge area of the 15th Street and South Division Street well fields is mostly located in areas near Whaleysville, Ocean Pines, Berlin, and Salisbury.

SIMULATION OF BRACKISH-WATER INTRUSION

A solute-transport model was applied to the Ocean City-Manokin aquifer system to quantify the relation between increased pumpage and chloride contamination from brackish-water encroachment. The transport model was also used to determine the chloride distribution in aquifers offshore of Ocean City. In solute-transport modeling the flow regime is viewed in terms of transport of solutes in the ground-water-flow system, which involves advective, dispersive and diffusive processes. The transport of solutes by the flow motion, the advective process, occurs at a rate equal to the average linear velocity of the ground water. During transport the solutes tend to disperse in the direction of flow (longitudinal dispersion), and perpendicular to the direction of flow (transverse dispersion). Diffusion of solutes from higher concentration to lower concentration occurs under the influence of the kinetic activities of the molecular constituents. The Saturated-Unsaturated Transport (SUTRA) model program, documented by the U.S. Geological Survey (Voss, 1984), mathematically simulates fluid movements and transport of dissolved substances in a subsurface environment. The SUTRA model program uses a two-dimensional hybrid finite-element and integrated finite-difference method to approximate the equations describing density dependent ground-water flow and transport of solutes in ground water and solve for pressure and solute distributions in the system.

A cross-sectional solute-transport model of the coastal ground-water system in the Ocean City area was developed using the SUTRA model program to study the potential intrusion of brackish water in the Ocean City-Manokin aquifer system. The algorithm in the model uses aquifer matrix and fluid properties to solve for chloride distribution in the system. In order to be consistent with the transport equations developed in the SUTRA program the units used for the aquifer and fluid properties are expressed in meter-kilogram-second units where pressure is expressed in kiloPascals.

Description of the Solute-Transport Model

The transport model was constructed along a line of section that parallels the regional direction of ground-water flow in the Ocean City area. The model extends from several miles west of Whaleysville in northwestern Worcester County to the upper part of the continental slope (fig. 1). A cross-sectional transport model was developed and applied to the 44th Street and Gorman Avenue well fields by using the hydrologic properties of the aquifer systems at each well field. In order to make the results of the solute-transport model comparable with results from the flow model, hydrologic properties and boundary conditions used in the transport model were derived from values used in the flow model. The boundary conditions and hydrologic properties used in the transport model were adjusted to account for the variable density of the fluids involved and the use of intrinsic permeability to describe the transmissive property of the aquifers independent of concentration, pressure, and temperature. These adjustments will be discussed in the Hydrologic Properties and Boundary Conditions sections of the report.

The 44th Street model was first developed and calibrated for the 1900 flow conditions assuming that the chloride distribution

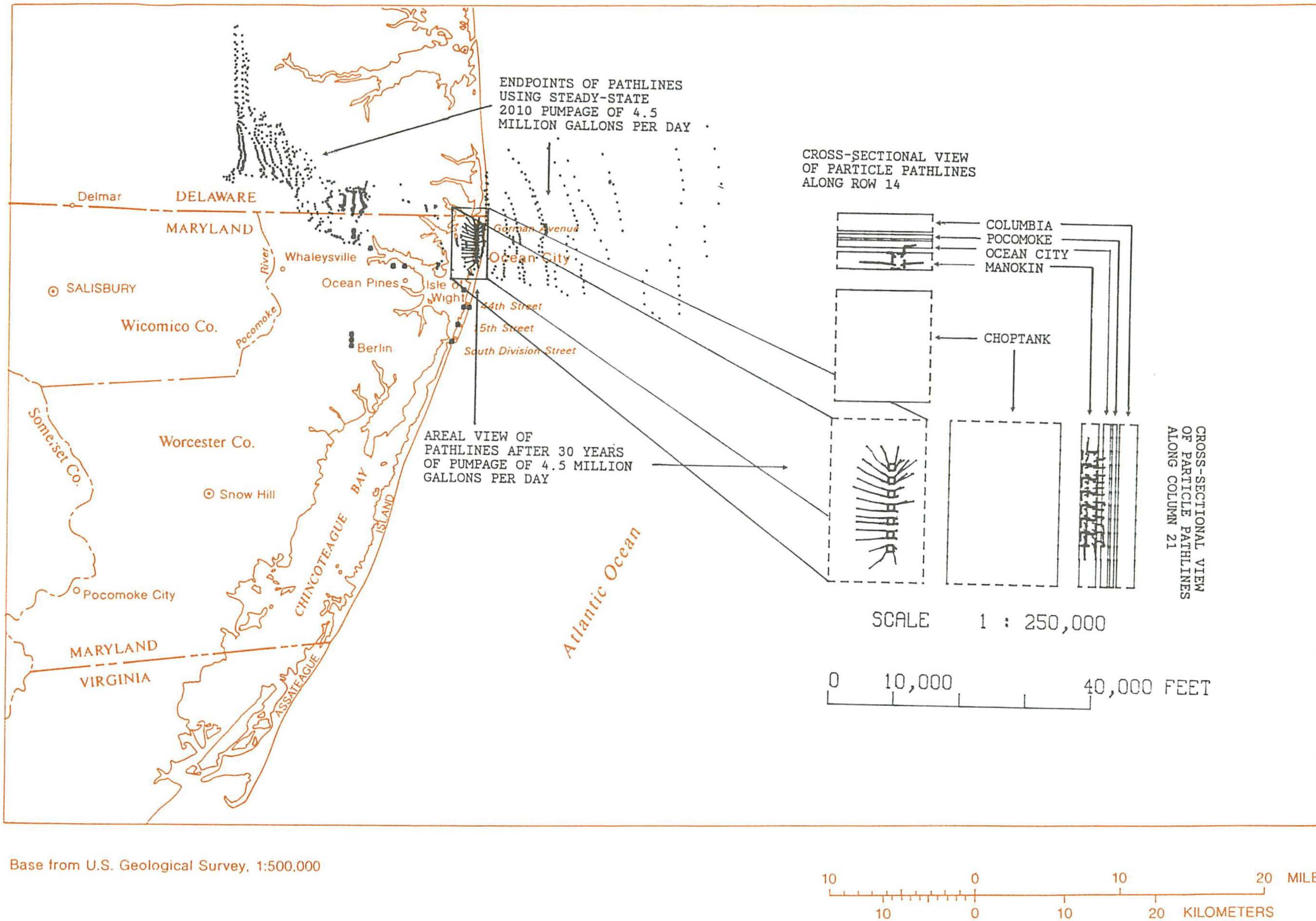

Figure 45.—Endpoints of recharge particle pathlines and a 30-year capture zone backtracked from pumping cells at the Gorman Avenue well field simulating the 2010 pumpage of 4.5 Mgal/d.

Base from U.S. Geological Survey, 1:500,000

10 0 10 20 MILES
10 0 10 20 KILOMETERS

Figure 46.—Endpoints of recharge particle pathlines backtracked from the Ocean City well fields simulating the 2010 pumpage of 9.1 Mgal/d.

was at equilibrium with present sea level. Calibration of the model for the 44th Street well field required several adjustments to the input data. The simulated pressure and chloride distributions calculated using the 1900–1990 pumpage were compared with measured values at the 44th Street well field in order to calibrate the model. The calibrated 44th Street model was modified to represent the Gorman Avenue well field by substituting the hydrologic properties of the aquifers at the Gorman Avenue well field. The Gorman Avenue model was calibrated by simulating the chloride and pressure distribution using the 1900–1990 pumpage and comparing the simulated values with measured values. The calibrated 44th Street and Gorman Avenue models were used to simulate the 2010 chloride and pressure distributions using the projected 1991 to 2010 pumpage at each well field.

Framework of Conceptual Model

The model encompasses the upper 1,900 feet of Coastal Plain sediments in the Ocean City area. The model includes the upper five aquifers and where applicable, their confining units (fig. 47). From stratigraphically highest to lowest, the five modeled aquifers are: the Columbia, Pocomoke, Ocean City, Manokin, and Choptank aquifers. The Choptank aquifer referred to in the model includes undifferentiated underlying aquifers (fig. 20).

The region represented by the cross-sectional model is about 80 miles long and 1,900 feet deep. It has a nominal thickness of 1 m (meter) and is discretized into a grid system consisting of 121 columns and 43 rows. The vertical grid spacing ranges from 33 to 100 feet and the lateral grid spacing ranges from 1,760 to 15,840 feet. In the vertical direction, each aquifer was divided into two or more grid spacings. The confining units occupy one grid spacing except for the confining unit formed by the St. Marys Formation. A finer grid spacing was used in the Ocean City area in order that a better resolution of the transport processes could be obtained near the well fields.

The transport model was initially constructed with abrupt and large conductivity contrasts of four to six orders of magnitude between the aquifers and confining units. In this first version of the model, the conductivity contrasts caused erratic flow patterns in the cross section beneath Ocean City. A second version of the model was constructed in which the four upper aquifers, the Columbia, Pocomoke, Ocean City, and Manokin, were assigned an exaggerated anisotropy. The substitution of an exaggerated anisotropy for the alternating aquifer-confining unit stratification works well in cases where the aquifers and confining units are relatively thin layers covering an extensive area (Bear, 1979, p. 33; Meisler, Leahy, and Knobel, 1984, p. 9). In order to arrive at an equivalent substitution, the vertical component of the permeability was made four orders of magnitude smaller than the lateral component. The anisotropic version of the transport model produced smooth flow lines in the Ocean City area, making the model more amenable to calibration. The anisotropic version of the model was used in this study.

Boundary Conditions

The transport model was designed to include natural boundaries where possible. At locations where the flow system was terminated by the model, boundary conditions were specified that would accurately simulate flow at those boundaries. The transport model is bounded at the bottom by a no-flow boundary. The basal no-flow boundary was placed sufficiently deep within the Calvert Formation to minimize the effects of this artificial boundary on the Ocean City-Manokin aquifer system. The other three sides of the cross section were bounded with specified-flux or specified-pressure boundary conditions. The solute concentrations of the boundary nodes were specified according to field conditions.

The upper boundary of layer 1 (the Columbia aquifer) was made a specified-pressure boundary. The onshore portion of the boundary was assigned pressures equivalent to the hydraulic head of the water table and chloride concentrations of zero milligrams per liter (mg/L). The offshore portion of the boundary was assigned zero pressure. The boundary nodes at the continental slope were assigned pressures equivalent to the hydraulic head of the simulated sea level. All offshore boundary nodes were assigned the chloride concentration of seawater (19,000 mg/L).

Pressure P in a column of a single density fluid, in terms of hydraulic head h and depth z, is defined as:

$$P = \rho g (h + z),$$

where P is pressure in kiloPascals,
ρ is density in kg/m^3,
g is gravitational acceleration in m/s^2,
h is hydraulic head in m, and
z is depth below sea level in m.

At sea level h=0, and z=0, therefore P=0. For locations where fluid columns consist of layers of fluids with variable densities ρ_i and incremental depth d_i, P may be calculated as:

$$P = g (\rho h + \sum_{i=1}^{i=n} \rho_i d_i), \qquad \text{equation (1)}$$

(Drummond, 1988, p. 70),

where the term ρgh is the pressure exerted by the freshwater hydraulic head and the term under the summation sign is the total pressure below sea-level datum exerted by a column of variable density fluid.

The onshore vertical boundary of the model was made a specified-flux boundary with a chloride concentration of zero mg/L. A specified-flux boundary onshore enables a freshwater flux to enter the model from the west. The magnitudes of the fluxes were estimated from the flow gradient in each aquifer.

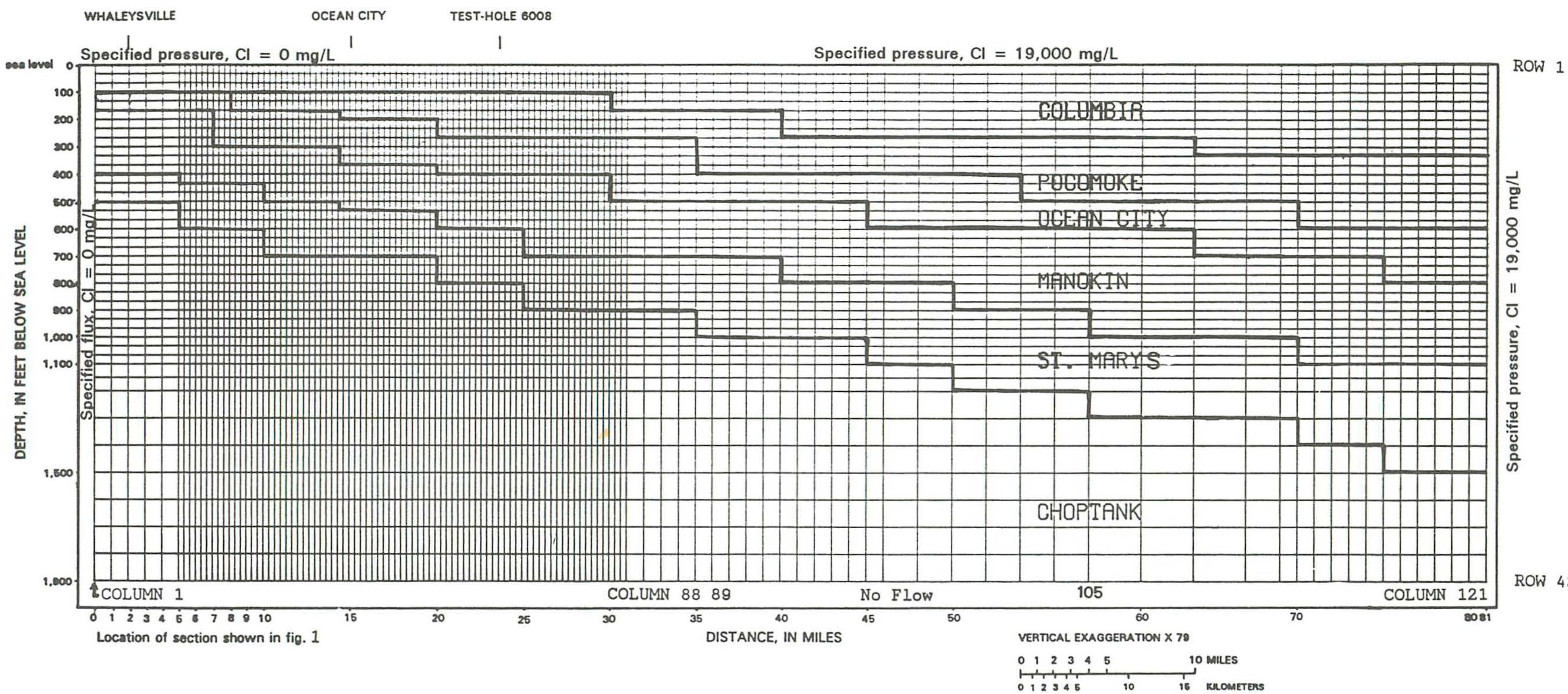

Figure 47.—Schematic diagram of the cross-sectional solute-transport model showing the finite-element grid and boundary conditions of model layers.

Aquifer Matrix and Fluid Properties

The aquifer matrix and fluid properties supplied to the model are not readily available from field measurements. These properties (tab. 12) were estimated from values obtained from published reports. Except for permeability, the fluid properties were applied uniformly throughout the model layers. The lateral and vertical permeabilities used for the model layers were derived from the hydraulic conductivities and transmissivities used in the flow model. The conversion of hydraulic conductivity into permeability assumed that the fluid saturation was 100% and the relative permeability is 1. In terms of hydraulic conductivity (K), the intrinsic permeability (k) = C K, where the conversion constant (C) is expressed as:

$$C = \frac{\mu}{\rho g}, \text{ (Voss, 1984, p. 27).}$$

The value of C is 1.02225×10^{-7} based on a water density (ρ) of 998.2 kg/m^3, a water viscosity (μ) of 10^{-3} kg/m.s (at 68°F), and a gravitational acceleration (g) of 9.8 m/s^2. When K (ft/d) is converted to k (m^2), the value of C becomes 0.3606×10^{-12}. Using the latter value of C, the lateral permeabilities used in the model range from 1.4×10^{-19} to 3.61×10^{-11} m^2.

The vertical component of permeability is calculated as a composite permeability of a confining unit and an underlying aquifer arranged in series. The composite permeability k can be calculated as

$$k = \frac{b_1 + b_2}{b_1/k_1 + b_2/k_2}$$

(Todd, 1980, p. 80; Freeze and Cherry, 1979, p. 34).

where b and k are thickness and permeability, and the indices (1 and 2) refer to the aquifer and confining unit. The composite vertical permeabilities for the Columbia, Pocomoke, Ocean City and Manokin range from about 3×10^{-15} to 7×10^{-17} m^2 and produce anisotropy of 10^{-3} to 10^{-5}. An average value of 10^{-4} was used in the model. A porosity of 0.30 and a matrix compressibility of 7.7×10^{-7} (kiloPascal)$^{-1}$ was assigned to all the layers.

The values used for the transport properties were estimated from published reports. Dispersivity is scale dependent (Wolff, 1982, p. 98; Voss, 1984, p. 232–233; Bush, 1988, p. 10). Reported field-scale longitudinal dispersivity values range from about 1 to 200 m and reported transverse dispersivity values range from about 0.0015 to 140 m. The value used in the model for the longitudinal dispersivity is 100 m and transverse dispersivity is 1.0 m. These dispersivity values were obtained from model calibration. The diffusivity coefficient (at 68°F) for major ions in ground water ranges from 1.0×10^{-9} to 2.0×10^{-9} m^2/s (Freeze and Cherry, 1979, p. 103). The diffusivity value used in the model is 1.0×10^{-9} m^2/s. This combination of transport properties produced a reasonable freshwater-saltwater transition zone in model simulations.

Fluid property values used in the model were based on values at a temperature of 68°F. The viscosity and fluid compressibility of freshwater are $1. \times 10^{-3}$kg/(m.s) and 4.4×10^{-7} (kilo-Pascal)$^{-1}$. The viscosity and compressibility of brackish water was assumed to be identical to freshwater for modeling purposes. The base chloride concentration of pure water is 0 mg/L and the maximum chloride concentration of seawater is 19,000 mg/L. The density of pure water is 998.2 kg/m^3 and the density of seawater is 1,025 kg/m^3. The coefficient describing the fluid density change with concentration is 1.4105×10^{-3} (kg/m^3) per (mg/L) or simply 1.4105.

Simulation of the Offshore Brackish-Water Plume

The presence of brackish ground water offshore of Maryland was demonstrated by the low chloride concentrations found in pore-water samples obtained from test hole 6008 drilled 8.8 miles east of Ocean City (Hathaway and others, 1976; 1979; app. C). The chloride concentrations are 15,352 mg/L at 100 feet below sea level, 231 mg/L at 260 feet below sea level and 896 mg/L at 367 feet below sea level (F. A. Kohout, written communication, 1976). Cooper (1964) has suggested that the high hydraulic head of discharging freshwater can keep saltwater at a distance from the shoreline and create a mixing zone instead of a sharp interface between the fresh and saltwater. Pressure changes caused by ocean tides and fluctuations of the water table caused by varying amounts of recharge produce a reciprocative motion of the saltwater front that in turn creates the freshwater-saltwater mixing zone. During high recharge or low tides, freshwater forces the saltwater front seaward. During low recharge or high tides, saltwater at the base of the mixing zone moves inland. Some of the diluted saltwater, however, rises and circulates seaward. The cyclic flow of saltwater tends to lessen the extent to which saltwater occupies the aquifer (Cooper, 1964, p. C1). Kohout (1964) determined that the mixing zone in a coastal aquifer in Florida is about 8 miles seaward of the interface location calculated using the Ghyben-Herzberg relationship.

The extent of the brackish ground-water plume offshore in coastal aquifers is related to the hydrologic and transport properties of the aquifer system, the areal seasonal recharge, and prior sea level positions (Meisler, 1981, p. 7; Meisler, Leahy, and Knobel, 1984, p. 26). According to Belknap and Kraft (1977, fig. 9) Holocene sea levels rose about 25 feet in the last 4,000 years relative to the coast of Delaware (fig. 48). Belknap and Kraft's sea-level curve is consistently lower than Bloom's (1970) eustatic sea-level curve because of tectonic subsidence in an offshore depositional basin, the Baltimore Canyon Trough. The sea-level curve for coastal Delaware was used as the reference curve for the rate of sea level rise used in the transport model. In the model simulations, sea level was elevated in stages until it reached the present shoreline.

The initial conditions under which the model was started assumed the entire cross section was saturated with freshwater. Each sea level rise was simulated by assigning appropriate pres-

Table 12.—Aquifer and fluid properties used in the transport model

Layer	Hydrologic unit	Permeability, in meter squared	Ansiotropy or $k_{vertical}/k_{lateral}$	Porosity, in percent
1	Columbia	$9.0 - 27.0\ 10^{-12}$	10^{-4}	0.30
2	Pocomoke	$7.2 - 28.8\ 10^{-12}$	10^{-4}	0.30
3	Ocean City	$9.0 - 27.0\ 10^{-12}$	10^{-4}	0.30
4	Manokin	$9.0 - 36.1\ 10^{-12}$	10^{-4}	0.30
5	St. Marys	$1.4\ 10^{-19}$	1.0	0.30
6	Choptank	$0.6 - 1.7\ 10^{-12}$	1.0	0.30

Thickness of cross section	=	1.0	m
Matrix compressibility	=	$7.7\ 10^{-7}$	$(\text{kiloPascal})^{-1}$
Longitudinal dispersivity	=	100.0	m
Transverse dispersivity	=	1.0	m
Diffusivity	=	$1.0\ 10^{-9}$	m^2/s
Fluid viscosity at 68°F	=	$1.0\ 10^{-3}$	kg/(m.s)
Fluid compressibility	=	$4.4\ 10^{-7}$	$(\text{kiloPascal})^{-1}$
Base chloride concentration	=	0	mg/L Cl^-
Base temperature	=	68°	F
Fresh-water density	=	998.2	kg/m^3
Maximum chloride concentration of ocean water	=	19,000	mg/L Cl^-
Ocean water density	=	1,025.0	kg/m^3
Coefficient of fluid density change with concentration	=	1.4105	unitless

sures and fluxes representative of the sea level position relative to the boundary nodes of the model. Changing sea level position changed the position of the shoreline, altered the pressures of the top onshore and offshore boundary nodes of layer 1 (the Columbia aquifer), required the assignment of a chloride concentration of 19,000 mg/L to the offshore boundary nodes, and also changed the hydrostatic pressures of the boundary nodes at the continental slope (column 121 of the model grid) (fig. 47). For the present-day sea level position, the pressures of the top onshore boundary nodes of layer 1 were calculated using the 1900 water levels simulated by the flow model. The offshore nodes were specific to each simulated shoreline position. The pressure of the offshore boundary nodes of layer 1 and also the hydrostatic pressure assigned to the top node of the continental slope boundary were kept at zero pressure during simulation. The pressures of the nodes along column 121 of the continental slope boundary, row 2 to 43 (fig. 47), were calculated using equation (1). At the present-day shoreline position, sea level is located at row 1 of column 121; therefore, the pressure at row 2 is the product of the grid spacing (33 feet) between rows 1 and 2, the gravitational acceleration of 9.8 m/s^2 and the ocean water density of 1,025 kg/m^3.

The shoreline was placed at column 105 of the model grid (fig. 47) to simulate the period when sea level was 25 feet below present-day sea level. The onshore boundary nodes (column 1 to 104) of layer 1 were assigned 0 mg/L chloride and the offshore boundary nodes (column 105 to 121) of layer 1 were assigned 19,000 mg/L chloride. These chloride adjustments were made every time the shoreline was moved westward. The pressures at the onshore boundary nodes were assigned values of the 1900 simulated heads plus 25 feet apportioned to land-surface gradient. The pressures at the offshore boundary nodes were assigned zero pressure. The continental slope boundary node of column 121 row 2 was then 8 feet (33–25 feet) below row 1. Therefore the pressure assigned was 8 feet times the product of gravitational acceleration and ocean water density.

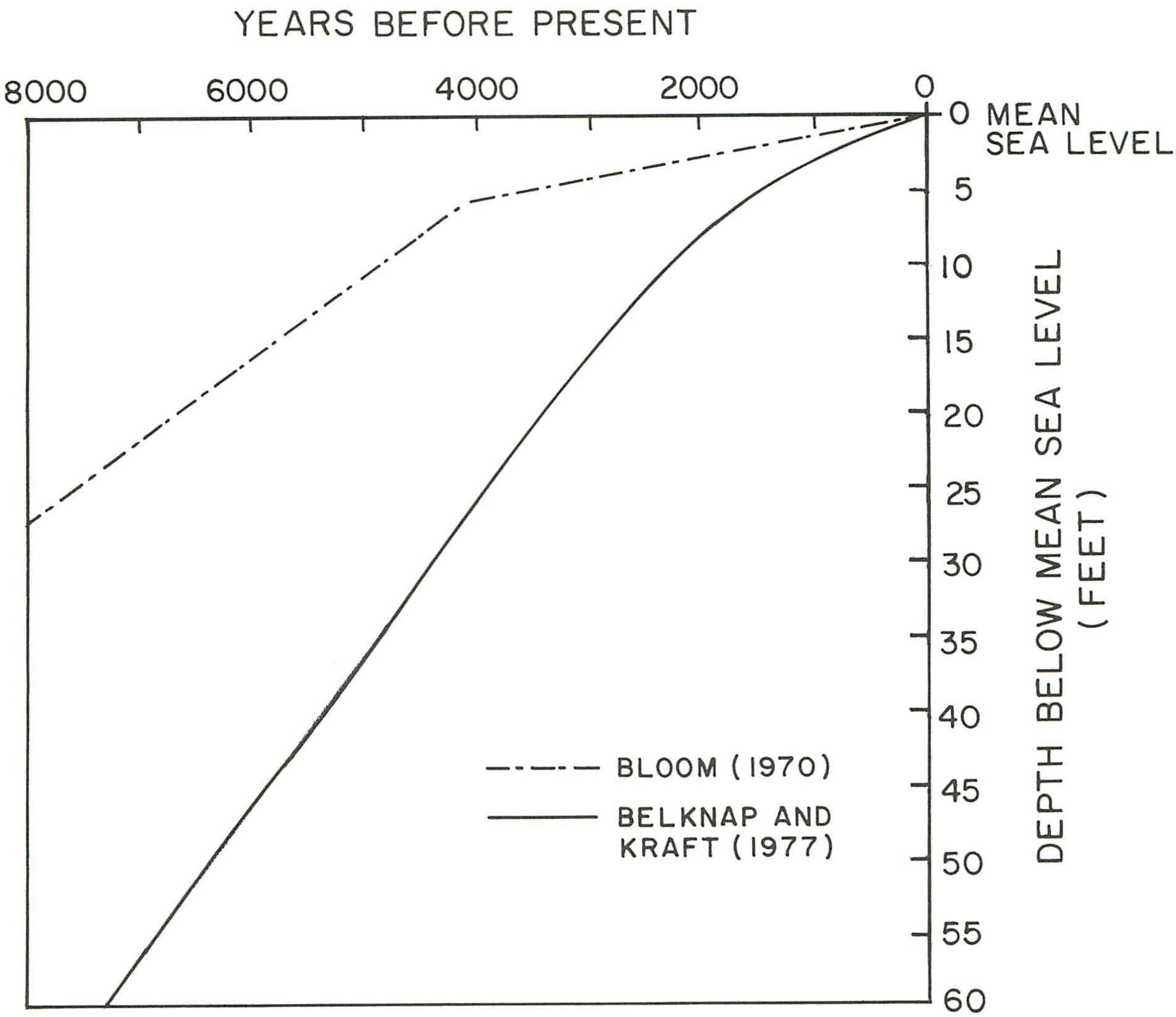

Figure 48.—Holocene sea-level curve.

When sea level was raised to a higher level, the pressure of the onshore boundary nodes were reduced in proportion to the amount of sea level rise, and the pressure at the continental slope boundary nodes was increased in proportion to the amount of sea level rise. When sea level reached the present-day shoreline position, the pressure of the top onshore boundary nodes of layer 1 were reduced back to the 1900 values and the pressure of the boundary nodes at the continental slope were increased to the 1900 values. The advantage of maintaining the different sea level positions at zero pressure is that negative pressures in the model simulation were avoided. The freshwater flux at the western vertical boundary of the model was calculated based on the 1900 flow gradient obtained from the flow model. The amount of freshwater flux assigned to each layer exposed at the western boundary was kept constant during the simulations.

Using the hydrologic and transport properties (tab. 12) described earlier and the boundary conditions for sea level at 25 feet below the present level, the model simulated steady-state conditions for the flow and the transport parts of the cross-sectional model. Initially the entire model was saturated with freshwater, but ocean water from the offshore boundary nodes moved westward as a result of its greater density, mixed with the freshwater, and occupied the eastern portion of the model. The flow part of the model reached steady-state readily, but the transport part of the model took about 2,000 years to stabilize. The chloride and pressure distributions of the steady-state simulation were used to define the initial conditions for the following transient simulation.

The 25-foot sea level rise was simulated in three increments of 10, 10, and 5 feet for simulation periods of 1,100 years, 1,500 years and 1,400 years respectively (fig. 48). Each simulated rise in sea level was identical except for the pressures assigned to the boundary nodes as described earlier. The pressures of the boundary nodes in the last stage of the simulation were equivalent to the head distributions of 1900 obtained from the flow model.

The first several model simulations were unsatisfactory because the simulated offshore brackish-water plume was not deep enough beneath the ocean floor and the saltwater wedge penetrated too far inland. Several adjustments to the model were made based on sensitivity analysis of the hydrologic and transport properties used in the model. The extent of the brackish-water plume offshore is more sensitive to changes in the landward freshwater fluxes and specified pressure of layer 1 than changes in the lateral permeabilities of the aquifer system. Lowering sea level position produced a freshwater plume extending farther offshore. Increasing the vertical permeability caused the plume to be thicker but shorter laterally. Varying the value of the transport properties used in the model indicates that a 25-percent change in the dispersivity values produced a minimal change in the width of the simulated transition zone. Altering the diffusivity value about one order of magnitude caused an instability in the numerical solution.

Other adjustments to the model were made to correct the high chloride concentrations simulated offshore of Ocean City in layer 1 and near Whaleysville at the contact between the Manokin aquifer and the St. Marys confining unit. In order to restrict the flow of saltwater from the ocean into layer 1, the permeability of the top elements of the offshore part of layer 1 was reduced. In order to decrease the simulated chloride concentrations near Whaleysville, the freshwater fluxes at the western vertical boundary were also adjusted. The final value for the Columbia aquifer was 3.5×10^{-7} m/s; for the Ocean City aquifer, 1.59×10^{-6} m/s; for the Manokin aquifer, 1.59×10^{-6} m/s; and for the Choptank aquifer, 1.2×10^{-8} m/s. The Pocomoke aquifer does not extend to the western boundary.

Adjustments were made to the model to force the simulated chloride concentrations, which initially were too high inland, farther seaward. First, the freshwater fluxes entering on the western vertical boundary were increased, but reasonable increases in fluxes from the western vertical boundary were not sufficient to move the salty water seaward. Adjustments were made to the specified-boundary pressures of layer 1. During the earlier simulations, the boundary nodes of layer 1 and the continental slope were assigned pressures equal to the pressure at the end of each simulated time segment. In subsequent simulations, average pressures for each time segment of the simulated sea level rise were assigned to boundary nodes of layer 1 and the continental slope boundary. This approach was considered reasonable because the sea level transgression probably occurred continuously and not in abrupt steps as first simulated in the model. An average pressure, therefore, better described the pressure distribution assigned to boundary nodes. Using average pressures the model simulated a reasonable brackish-water plume offshore of Ocean City (fig. 49).

Because there is no record of pressure and chloride concentration for 1900 flow conditions, model calibration was based on estimated values. The simulated pressures were converted to hydraulic heads and matched with the values obtained from the flow model steady-state simulation. The simulated chloride concentrations were matched with the earliest measured values from the Ocean City well fields. Table 13 shows that the water levels matched within 6 feet and the upper range of chloride concentrations matched within about 7% to 35%. The chloride concentrations obtained from water samples taken from test hole 6008 (F. A. Kohout, written communication, 1976) were also used for model calibration. There was good agreement between the simulated and measured chloride values in test hole 6008 (tab. 14), except for the 231 mg/L chloride at 260 feet below sea level.

The simulated 1900 chloride distribution is shown in figure 49. The 1,000 mg/L isochlor extends 10 miles offshore, the 5,000 mg/L isochlor extends 13 miles offshore, the 15,000 mg/L isochlor extends 25 miles offshore, and the 19,000 mg/L isochlor extends 60 miles offshore. The directions of ground-water flow are indicated by arrows and the size of the arrows indicate the relative magnitude of the rate of flow. These flow conditions were chosen as the starting conditions for the simulation of

Table 13.—Comparison of water levels and chloride concentrations in the vicinity of Ocean City using the 1900 flow model, 1900 transport model, and earliest measured values

	Aquifer				
	Beaverdam	Pocomoke	Ocean City	Manokin	Choptank
			Hydraulic head, in feet above sea level		
Flow model simulation	0-2	0-4	6-10	6-10	8-12
Transport model simulation	0-4	0-8	8-12	8-12	12-16
			Chloride concentration, in milligrams per liter		
Best estimate/ earliest measured	30 (Bg 38, 1951) 39 (Bh 84, 1973)	20 (Bh 1, 1951) 46 (Bh 85, 1973)	59 (Bh 81, 1971) 75 (Bh 28, 1974) 75 (Bh 41, 1977)	200 (Bh 93, 1989) 250 (Bh 91, 1989) 440 (Bh 89, 1986)	2,170 (Ah 6, 1969) 2,900 (Bh 90, 1990)
Transport model simulation	0-25	25-40	50-81	100-398	1,982-2,188

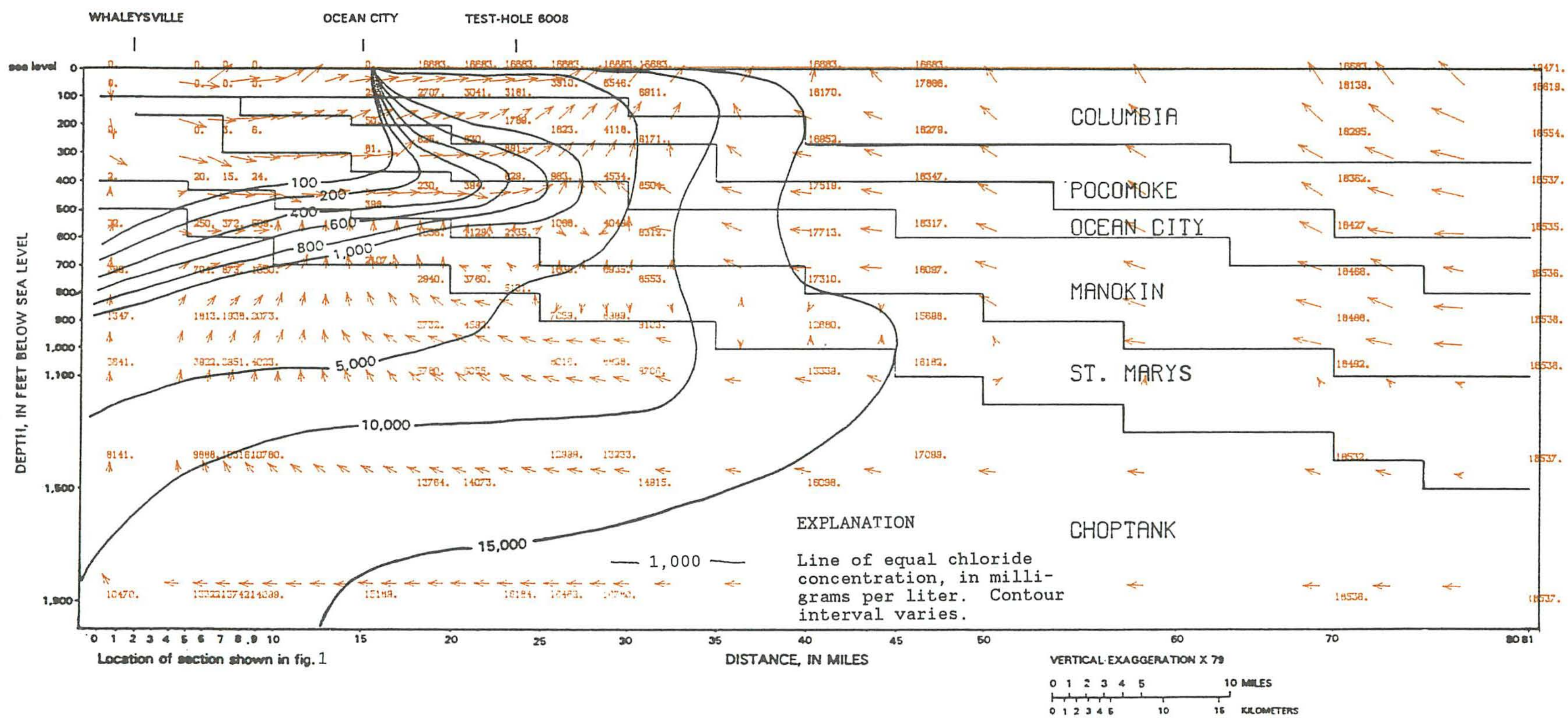

Figure 49.—Chloride distribution obtained by simulating Holocene sea level rise from approximately 4,000 years before present to 1900.

Table 14.—Comparison of simulated and measured chloride concentrations in test-hole 6008

Depth below sea level (feet)	Measured chlorides (mg/L)	Simulated chlorides (mg/L)	Percent difference
100	15,352	14,000	9
190	4,625	3,100	33
305	1,594	1,500	6
367	896	900	less than 1

pumpage at Ocean City. They are designated the pre-pumping conditions of 1900 for comparison with the initial conditions specified in the flow model. The simulated 1900 flow shows that fresh ground-water discharge beneath the Atlantic Ocean mixes with brackish water at a distance of about 8 miles offshore. In the shallow aquifer, the saltwater flux encroaching from the east changed direction toward the ocean floor and discharged to the ocean at about 25 miles offshore and beyond. In deeper aquifers, the saltwater flux changed direction upward at about Ocean City. At the base of the model the saltwater flux flowed to the western boundary and changed direction upward at this location.

Simulation of Pumpage from 1900 through 1990

The prime cause of the increase of chloride concentrations in the Ocean City well fields is the reversal of hydraulic gradient due to pumpage. Pumpage from the well fields in the Ocean City and surrounding areas alter the dynamic equilibrium of the freshwater-saltwater mixing zone and induce encroachment of saltwater. Using the calibrated pressure and chloride distributions for 1900 as initial conditions, simulations for 1900 to 1990 were used to calibrate the 44th Street and Gorman Avenue models for conditions when the aquifers were stressed by pumpage.

In applying the pumpage to the transport model the actual well field pumpage had to be reduced to account for the finite thickness of the cross section. Direct calculation of how much pumpage should be assigned to the transport model is difficult because the cross section is assigned an arbitrary thickness of 1 m. A reduction factor was estimated indirectly by comparing the drawdown obtained earlier from the flow model simulation with the drawdowns obtained from the transport model as pumpage was systematically reduced. The pumpage of the transport model that produced a drawdown matching the drawdown obtained from the flow model simulation was assumed to be the equivalent pumpage to use in the transport model. The assumption was reasonable because both models have the same hydrologic properties or their derivatives. The ratio between these two pumpages (0.35) was used to apportion the well field pumpage for the 1900 to 1990 period and for the future simulations. The effects of neighboring well fields on the 1900–1990 transport model simulations for the 44th Street and Gorman Avenue well fields were accounted for because the drawdowns obtained from the flow model include pumpage at the well head as well as the effects of neighboring well fields.

The simulation of the 1900–1990 pumpage from the 44th Street well field was divided into three stress periods of 1900–1959, 1960–1983, and 1984–1990. The 44th Street well field was not produced until 1960. The average pumpage for 1960–1983 was 1.0 Mgal/d and for 1984–1990 was 2.1 Mgal/d. The simulation of the 1900–1990 pumpage from the Gorman Avenue well field was divided into three stress periods of 1900–1972, 1973–1988, and 1989–1990. Production from the Gorman Avenue well field did not begin until 1973. The average pumpage for 1973–1988 was 1.0 Mgal/d and for 1989–1990 was 3.0 Mgal/d. An initial time step of 1 year and a maximum time step of 2.5 years was used for each stress period. The time step was capped at 2.5 years, because a time step of 5 years often causes instability and non-convergence in the computation. The 1-year time step and the 2.5 year ceiling were also applied to the 1991–2010 simulation. During simulations with no pumpage, 1900–1959 for the 44th Street and 1900–1972 for Gorman Avenue, the chloride concentration changed about 1–2 mg/L.

The transport model was calibrated by matching simulated water levels and chloride concentrations with measured data from wells at the 44th Street and Gorman Avenue well fields. The transport model was considered calibrated when the average differences between the simulated and measured annual average water levels were 5 feet or less and the average differences between the simulated and measured chloride concentrations was 10% or less. The altitude of many of the wells used to obtain measured water levels were from topographic maps with 5-foot contour intervals.

The results of simulating the 1900 to 1990 pumpage indicate that there is a general agreement between the simulated and measured annual average water levels and also between simulated and measured chloride concentrations at well locations at the 44th Street and Gorman Avenue well fields (tabs. 15, 16 and figs. 50–52). The average differences between the simulated and measured annual average water levels were less than 4 feet at both well fields. The maximum differences between the measured and simulated annual average water levels in the Poco-

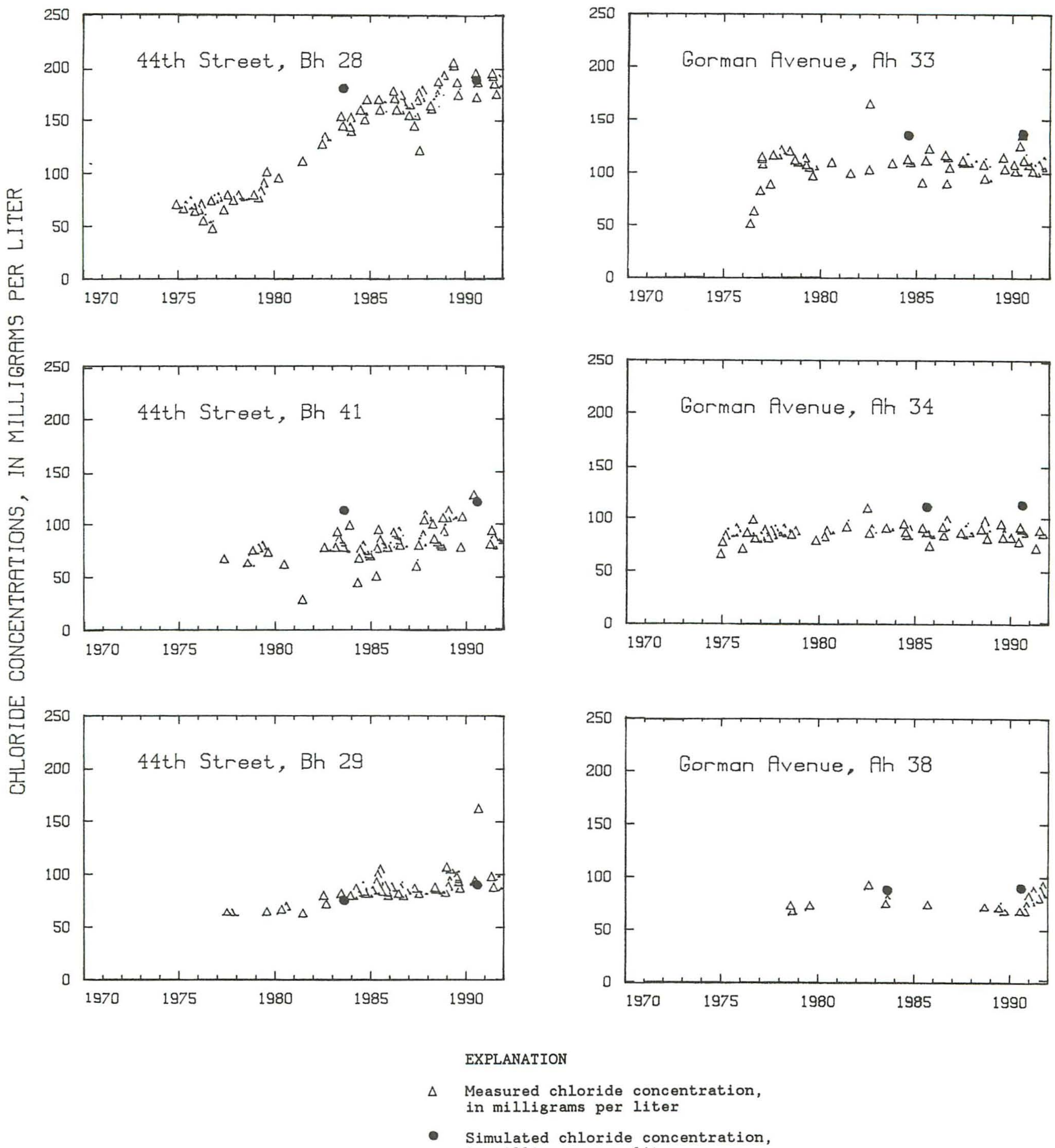

Figure 50.—Comparison of measured chloride concentrations in the Ocean City aquifer at the 44th Street well field and in the Manokin aquifer at the Gorman Avenue well field with corresponding simulated values obtained from the 1900–90 simulation.

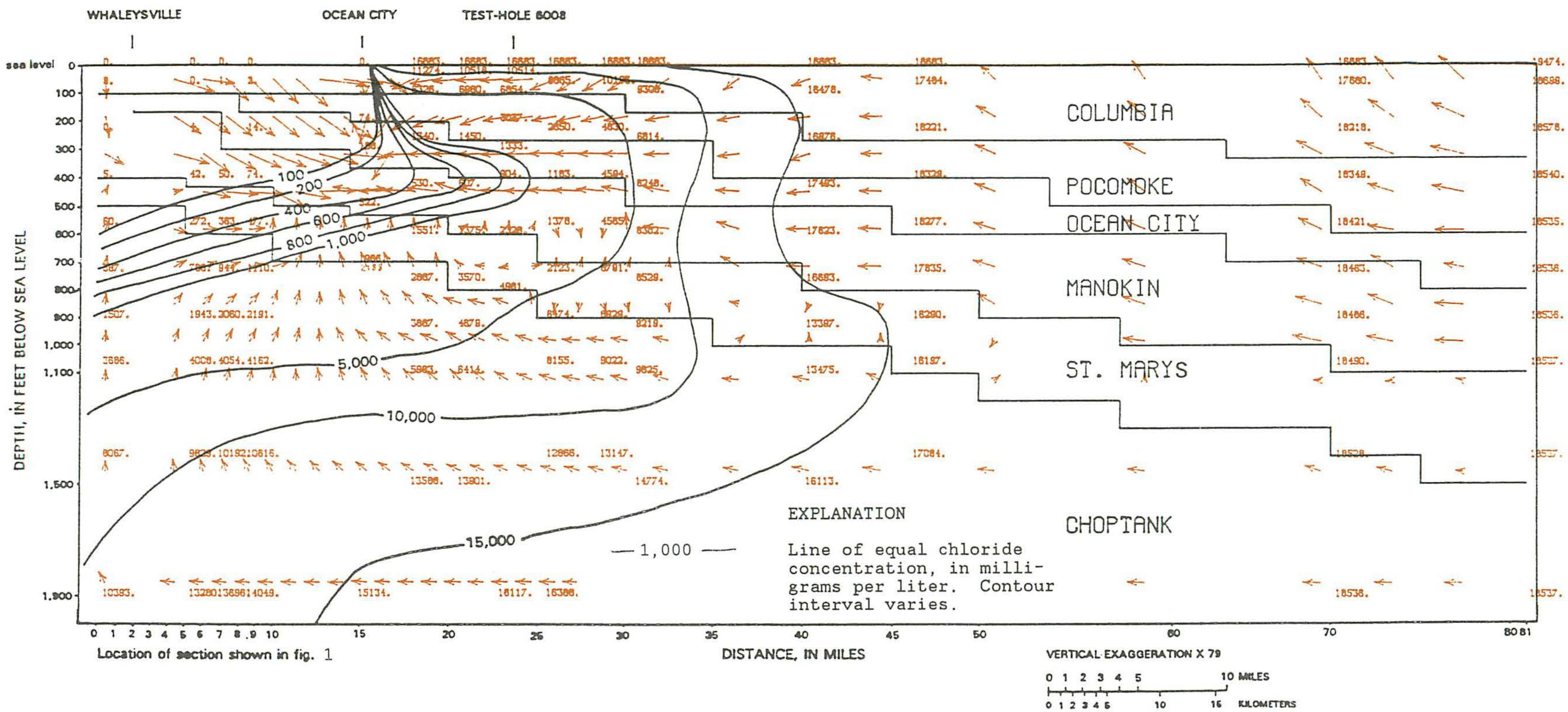

Figure 51.—Chloride distribution obtained simulating the 1984 to 1990 average pumpage of 2.1 Mgal/d at the 44th Street well field.

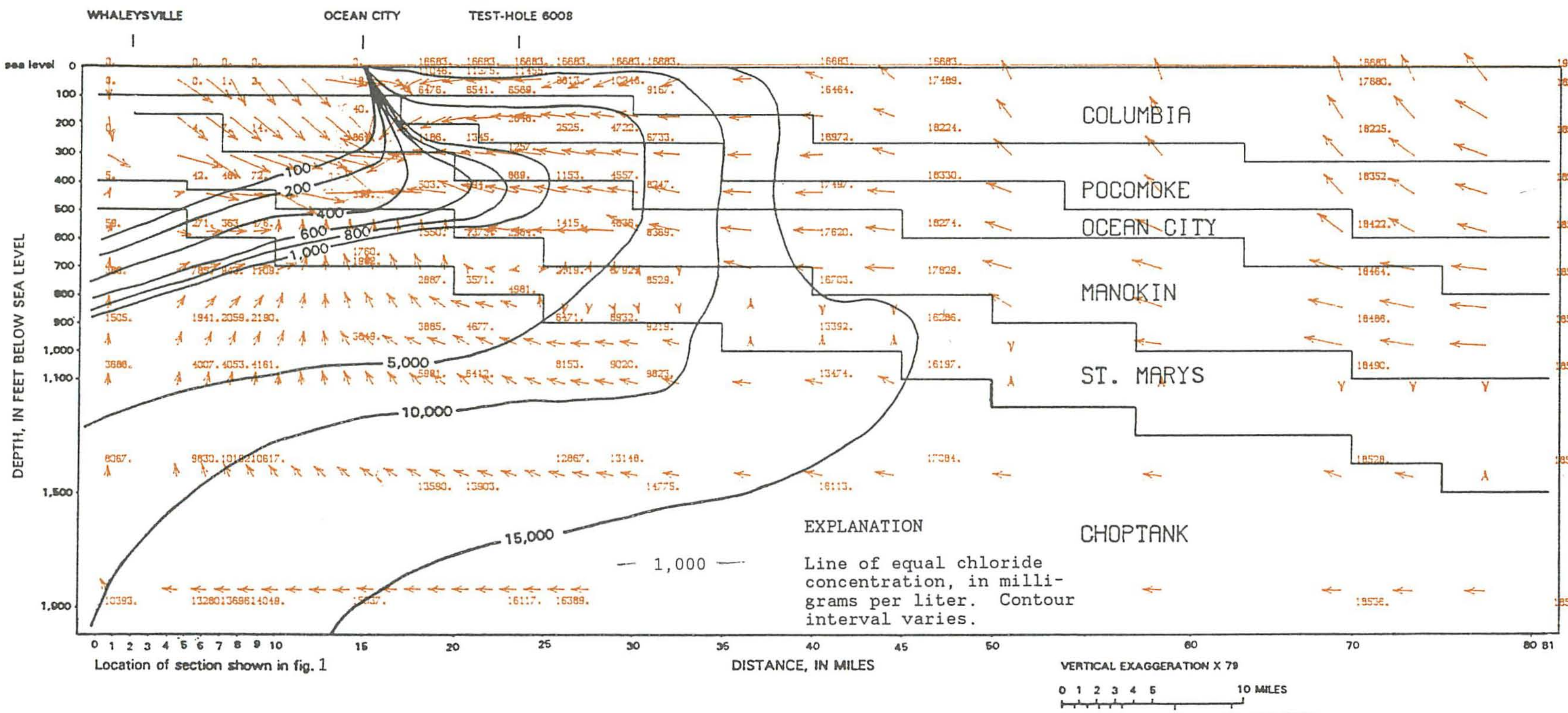

Figure 52.—Chloride distribution obtained simulating the 1989 to 1990 average pumpage of 3.0 Mgal/d at the Gorman Avenue well field.

Table 15.—**Comparison of measured and simulated annual average water levels and chloride concentrations in the aquifer system at the 44th Street well field used for the 1900–90 model calibration**

[-, no measurement recorded]

Well location	Annual average water levels (feet, sea-level datum)		Chloride concentrations (milligrams per liter)		Year
	Measured	Simulated	Measured	Simulated	
			Columbia aquifer		
Bh 84	2	4	39	35	1973
	1	4	40	37	1986
	-	4	36	37	1990
			Pocomoke aquifer		
Bh 85	2	7	46	55	1973
	-4	-11	46	56	1986
			Ocean City aquifer		
Bh 28	-	-14	160	180	1983
	-	-29	200	188	1990
Bh 41	-	-14	100	113	1983
	-	-29	135	121	1990
Bh 29	-	-14	80	75	1983
	-	-29	95	90	1990
Bh 31	-16	-14	-	-	1983
	-30	-29	-	-	1990
			Manokin aquifer		
Bh 89	-20	-23	520	522	1990
			Choptank aquifer		
Bh 90	-8	-13	2,900	2,188	1989

moke aquifer were 7 feet; in the Choptank aquifer, 5 feet; and in the Columbia, Ocean City, and Manokin aquifers, 4 feet.

The average differences between the simulated and measured chloride concentrations are less than 10%. The relatively large difference between measured and simulated values observed in wells Ah 2 and Ah 3 indicate that the model simulates the lower ranges of chloride concentrations less accurately than the higher chloride concentrations. The average percentage difference between the simulated and measured chloride concentrations in the Ocean City and Manokin aquifers at the 44th Street well field and in the Manokin aquifer at the Gorman Avenue well field are about 7%. This indicates that the chloride concentrations simulated in the producing aquifers are reasonably accurate. The differences between the simulated and measured chloride concentrations in the Choptank aquifer at the 44th Street and Gorman Avenue locations are 712 and 728 mg/L respectively or about 25%, which is probably indicative of the level of accuracy of the model for the Choptank aquifer.

The ground-water withdrawal during 1900–1990 moved the isochlors a maximum distance of 4 miles and changed the 1900 ground-water-flow direction. The 1984–1990 simulation using pumpage of 2.1 Mgal/d from the 44th Street well field shows that the freshwater was diverted from discharging across the ocean floor (fig. 52). The pumpage of 2.1 Mgal/d caused the encroachment of ocean water from the continental shelf toward Ocean City. Simulation using the 1989–1990 pumpage of 3.0 Mgal/d from the Gorman Avenue well field shows similar reversal of flow directions. The 3.0 Mgal/d pumpage diverted the freshwater from discharging across the ocean floor and caused the ocean water from the continental shelf to intrude toward Ocean City (fig. 52).

Evaluation of Fresh Ground-Water-Supply Potential

The calibrated solute-transport models were used to evaluate the potential of the Ocean City aquifer system to supply 1992–2010 freshwater demands from the 44th Street and Gorman Avenue well fields. The 2010 average annual well field pumpages used for simulation were increased to 2.6 Mgal/d at the 44th Street well field and 4.5 Mgal/d at the Gorman Avenue well field (tab. 10) based on the water-development plan for Ocean City (Whitman, Requardt and Associates, 1989).

Other pumpage scenarios were also used for simulation. In one scenario, the 2010 pumpage at 44th Street was increased to 3.3 Mgal/d and in a second scenario, to 4.4 Mgal/d. In a third scenario, the 2010 pumpage at Gorman Avenue was increased to 9.0 Mgal/d. The actual pumpage in the years to come from the well fields at Ocean City will probably differ from the pumpages simulated here; nevertheless, the scenarios simulated should provide useful insights into the relation between well field

Table 16.—Comparison of measured and simulated annual average water levels and chloride concentrations in the aquifer system at the Gorman Avenue well field used for the 1900–90 model calibration

[-, no measurement recorded]

Well location	Annual average water levels (feet, sea-level datum) Measured	Simulated	Chloride concentrations (milligrams per liter) Measured	Simulated	Year
			Columbia aquifer		
Ah 2	3	7	55	39	1952
Ah 3	-	7	66	39	1953
			Manokin aquifer		
Ah 33	5	2	125	135	1988
	-	-11	135	137	1990
Ah 34	5	2	102	111	1988
	-	-11	95	113	1990
Ah 38	3	2	80	88	1988
	-	-11	85	90	1990
Ah 39	-	2	69	80	1986
	-	-12	73	81	1990
Ah 6	2	2	296	313	1969
Ah 37	3	2	320	331	1975
	-15	-13	330	332	1990
			Choptank aquifer		
Ah 6	6	7	2,710	1,982	1969

pumpage and chloride distribution in the Ocean City-Manokin aquifer system.

44th Street Well Field

An annual average pumping rate of 2.6 Mgal/d in 1988 produced a maximum chloride concentration of 215 mg/L in well Bh 28 at the 44th Street well field. Because the chloride concentrations were approaching the recommended 250 mg/L limit in Bh 28, pumpage from the 44th Street well field was reduced to 1.6 Mgal/d in 1990. The water-development plan for Ocean City (Whitman, Requardt and Associates, 1991) suggested an average daily pumpage of 2.6 Mgal/d at the 44th Street site for the 1992–2010 period (tab. 10). In the first simulation, the well field pumpage was increased to 2.6 Mgal/d in 1992–2010. The simulated chloride distribution indicates that an 1.0 Mgal/d increase in pumpage for the simulation period 1992–2010 increased chloride concentrations by approximately 30 mg/L to about 230 mg/L.

Additional simulations at the 44th Street site were made to determine the highest pumping rate that could be sustained before simulated chloride concentrations exceeded 250 mg/L. Simulated 1992–2010 pumping rates of 3.3 and 4.4 Mgal/d produced chloride concentrations of 235 and 243 mg/L respectively. Well Bh 28 has chloride concentrations 90 to 100 mg/L higher than the other 44th Street production wells. Therefore additional pumpage from the 44th Street well field should come from the other production wells.

In order to show the effects of an average daily pumping rate of 4.4 Mgal/d at the 44th Street well field, the 2010 chloride concentrations obtained using a pumping rate of 4.4 Mgal/d were overlain on the 1990 chloride concentration obtained using the 1984–1990 pumping rate of 2.1 Mgal/d (fig. 53). The positions of 15,000, 10,000, 5,000, 1,000, and 100 mg/L isochlors using the 1984–1990 pumpage were compared to the corresponding isochlors using the 2010 pumpage. Significant shifts in the position of the isochlors occurred in the Ocean City and Manokin aquifers. The isochlors shifted a maximum of about 1 to 1.5 miles. For comparison, a velocity at the seaward face of about 1 ft/d or 1.4 miles in 20 years was calculated using the particle-tracking program with a pumpage of 4.4 Mgal/d.

The isochlor shift produced by the 4.4 Mgal/d simulation (fig. 54) suggests that ocean water is encroaching the Ocean City-Manokin aquifer system from the continental shelf rather than upward from deeper aquifers. Figure 51 indicates similar saltwater intrusion patterns. In the vicinity of the pumping wells shifts of the 100 mg/L and 1,000 mg/L isochlors were most pronounced in the Ocean City and Manokin aquifers. Chloride concentrations in the St. Marys confining unit and in the underlying Choptank aquifer are minimally effected.

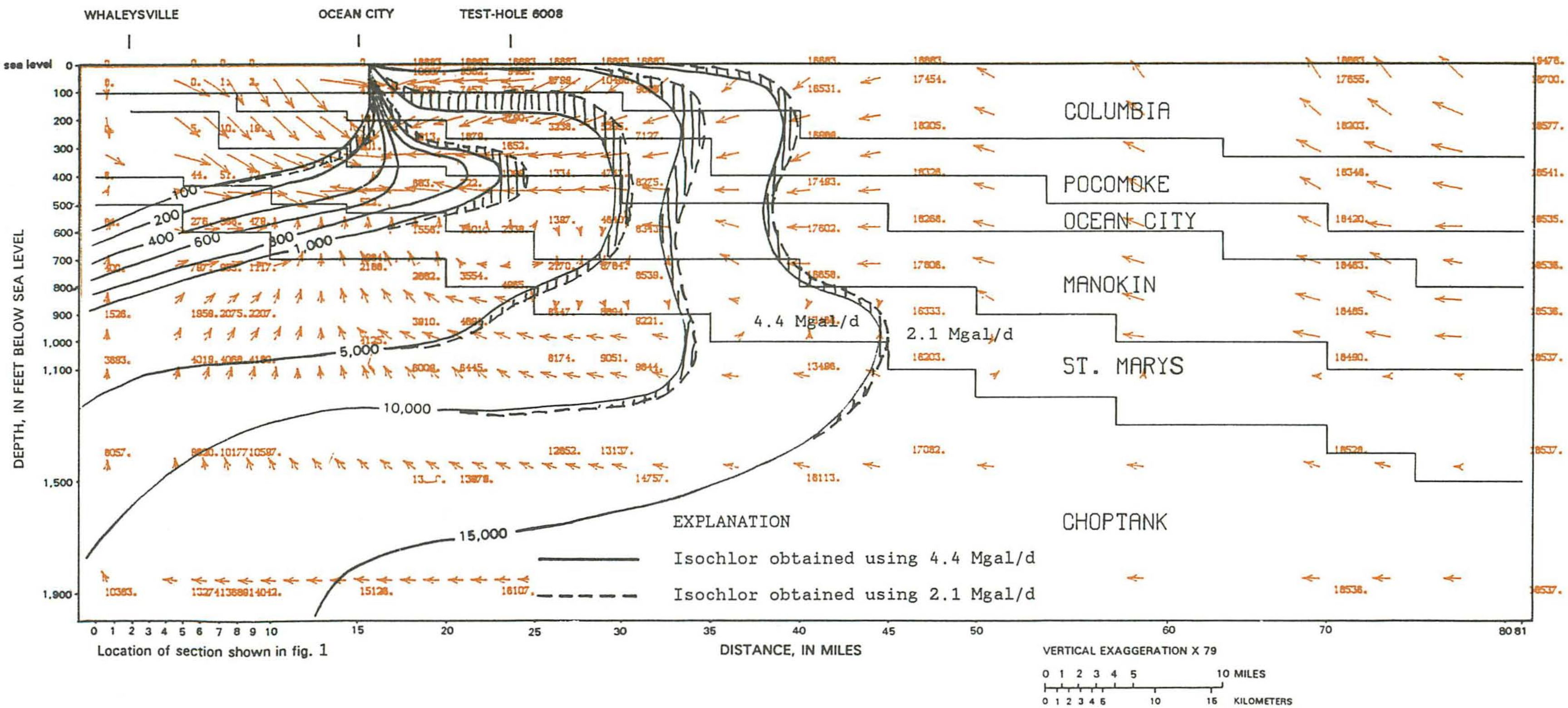

Figure 53.—Simulated chloride concentrations obtained using 2010 pumpage of 4.4 Mgal/d and 1984 to 1990 average pumpage of 2.1 Mgal/d at the 44th Street well field.

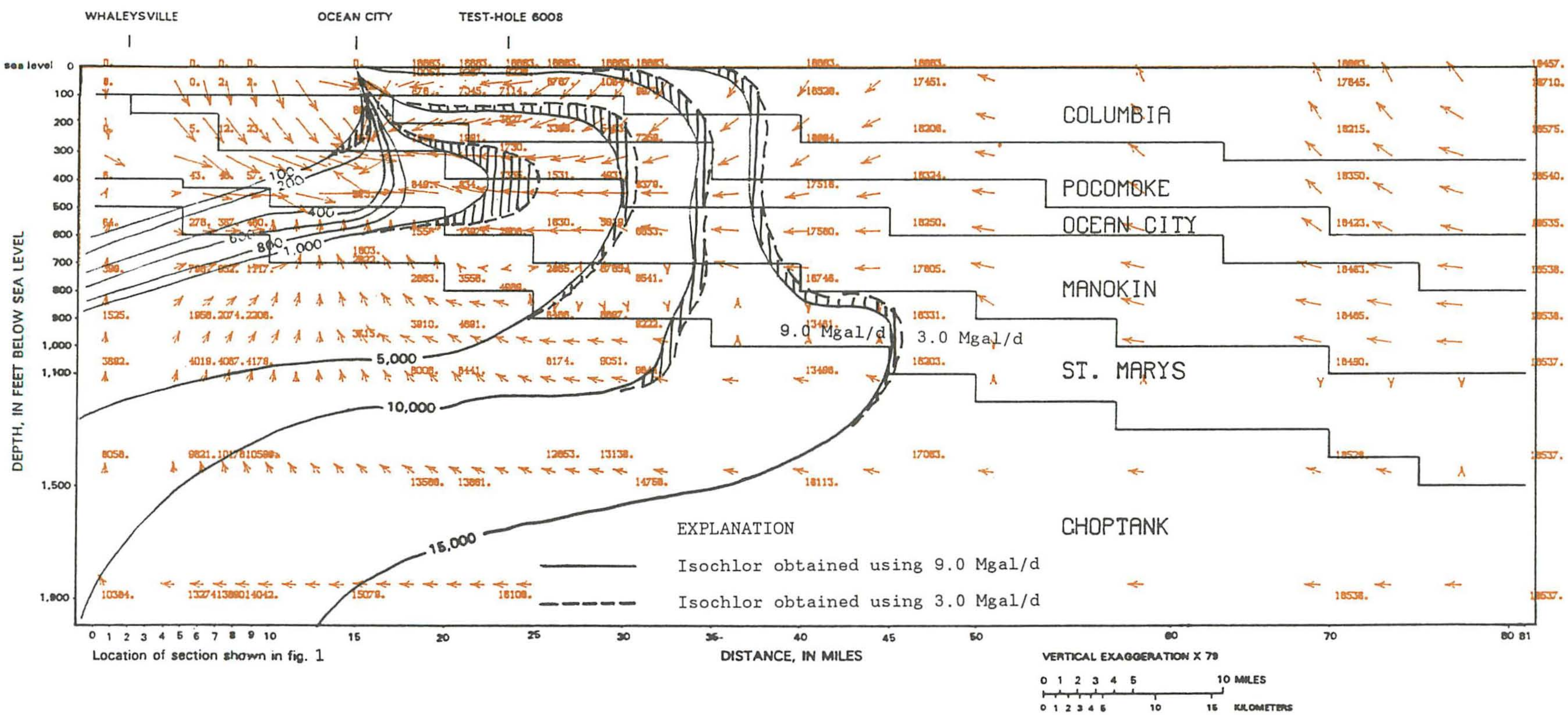

Figure 54.—Simulated chloride concentrations obtained using 2010 pumpage of 9.0 Mgal/d and 1989 to 1990 average pumpage of 3.0 Mgal/d at the Gorman Avenue well field.

Gorman Avenue Well Field

The planned expansion of the Gorman Avenue well field includes pumping wells located at 121st, 115th, 105th, and 95th Streets. The new well sites are in addition to the existing wells at 141st, 137th, 130th, and 125th Streets. The cross-sectional model, however, only simulates a combined pumpage from the well sites at 137th and 141st Streets because of the limited areal coverage of the cross section. The actual annual average 1990 and 1991 pumping rates of 3.8 and 3.9 Mgal/d from the wells at 137th and 141st Streets were simulated. The 3.9 Mgal/d pumping rate was continued through 2001 and was increased to 4.5 Mgal/d for 2002–2010 (tab. 10). Results of the 1992–2010 simulation indicate that an additional pumpage of 0.7 Mgal/d from the Manokin aquifer will produce an increase of 42 mg/L chloride. In 1990, chloride concentrations in Ah 33 were as high as 135 mg/L. The model simulation suggests, therefore, that a pumpage of 4.5 Mgal/d from the wells at 137th and 141st Streets would produce chloride concentrations up to about 175 mg/L in 2010.

The conditions that favor development of the Gorman Avenue well field over the 44th Street well field are lower chloride concentrations and greater available drawdown. The next scenario simulated the total projected water need of Ocean City in 2010 (9 Mgal/d annual average) entirely from the Manokin aquifer at Gorman Avenue well field. A model simulation pumping 9 Mgal/d from the Manokin aquifer at the 137th and 141st Street well sites resulted in a simulated chloride concentration up to 185 mg/L.

The effects of pumping 9 Mgal/d from the Manokin aquifer at the Gorman Avenue well field is shown by overlaying the 15,000, 10,000, 5,000, 1,000, and 100 mg/L isochlors obtained from the 2010 simulation (9 Mgal/d) on the isochlors obtained from the 1989–1990 simulation (3.8 Mgal/d) (fig. 54). The shift of the isochlors at Gorman Avenue resembles the pattern shown in figure 53 for the 44th Street well field. In the vicinity of the pumping wells at Gorman Avenue, the 100 and 1,000 mg/L isochlors in the Ocean City and Manokin aquifers are shifted the farthest inland. The 2010 simulation (9 Mgal/d) produced maximum isochlor shifts of 1 to 3 miles. For comparison, a velocity at the seaward face of 2 ft/d or 2.8 miles in 20 years was calculated using the particle-tracking program with a pumping rate of 9 Mgal/d. A pumping rate of 9 Mgal/d at the Gorman Avenue well field has a minimal effect on chloride concentrations in the St. Marys confining unit and underlying Choptank aquifer.

SUMMARY

From the stratigraphically highest to lowest aquifer, the hydrogeologic framework at Ocean City consists of the Columbia, Pocomoke, Ocean City, Manokin, and Choptank aquifers. The Ocean City and Manokin aquifers are hydraulically connected and comprise an aquifer system that provides the entire public water supply for Ocean City.

At Ocean City, the Manokin aquifer is essentially equivalent to the Manokin formation (an informal unit). The Manokin formation is the product of a fluvial dominated, high-constructive delta system that was subject to some marine reworking along the delta front. The Manokin is a gray to grayish and orange-tan, fine to coarse, in places silty sand. The Manokin generally coarsens upward in the section. At Ocean City, the Manokin formation ranges from 145 to 195 feet thick and the base of the formation ranges from 480 to 530 ft below sea level.

The Ocean City beds (an informal unit) overlie the Manokin formation at Ocean City and contain the Ocean City aquifer. In the central and southern parts of Ocean City, the Ocean City beds are predominantly a fine to coarse, grayish-tan and orange-tan sand that were probably deposited as coalescing distributary channel-sands or channel-mouth bars. In the northern part of Ocean City, the Ocean City beds are predominantly glauconite- and shell-bearing clayey silts and fine clayey sands that contain discontinuous, 10 to 25 foot thick beds of fine to medium sand. The lithology north of 61st Street is suggestive of offshore bars in a framework of marine reworked distal delta-front sediments.

Transmissivities of the Ocean City aquifer at Ocean City range from a high of about 5,300 ft^2/d at the 44th Street well field to less than 2,700 ft^2/d in the region from 61st to 100th Streets. Transmissivities in the Manokin aquifer range from 2,500 ft^2/d to 10,000 ft^2/d in Worcester County. Because the two aquifers are hydraulically connected, the potentiometric surfaces of the Ocean City and Manokin aquifer are similar; they range from about 25 feet above sea level in northeastern Worcester County to less than 5 feet above sea level at Ocean City. The general direction of ground-water flow is from northwest to southeast with a gradient of about 1 ft/mi.

Chloride concentrations in the Columbia aquifer ranged from a low of 36 mg/L to a reported high of 2,925 mg/L. Brackish water in the Columbia aquifer is not a threat to the Ocean City well fields because multiple confining units separate the Columbia aquifer from the Ocean City-Manokin aquifer system. Chloride concentrations in the Pocomoke aquifer are low, about 40 mg/L. Chloride concentrations in the Ocean City aquifer ranged from 26 mg/L to about 180 mg/L in 1990. At the 44th Street well field, chlorides rose from about 70 mg/L in 1976 to about 215 mg/L in 1988 because of upconing of brackish water from the underlying Manokin aquifer due to pumpage from the Ocean City aquifer. Reduction in pumpage has stabilized the chloride concentrations at about 180 mg/L in the Ocean City aquifer at 44th Street. Chloride concentrations in the Manokin aquifer ranged from a low of 14 mg/L to a high of 1,030 mg/L. The Manokin aquifer is brackish from 42nd Street north to between 51st and 61st Streets and contains brackish water near the base of the aquifer at other sites along the island. In the Choptank aquifer chloride concentrations ranged from 2,700 to 2,900 mg/L in the upper part of the aquifer. The Choptank is separated from the overlying Manokin aquifer by a thick and effective confining unit, the St. Marys Formation.

Aspects of the hydrogeologic framework that influence the distribution of chlorides in the Ocean City-Manokin aquifer system are: 1) the altitude of the basal silty sand facies of the Manokin aquifer, 2) the effectiveness of the confining units within the Manokin aquifer, 3) the occurrence of a thick confining unit (St. Marys Formation) that minimizes upward leakage from the brackish Choptank aquifer, and 4) multiple aquifers and confining beds that retard downward leakage of brackish water from the Columbia aquifer. Chloride distribution in the Ocean City aquifer is controlled by 1) the effectiveness of the confining unit between the Manokin aquifer and the Ocean City aquifer, 2) the chloride distribution in the sands of the Manokin aquifer that underlie the Ocean City aquifer, and 3) head differences between the Ocean City aquifer and the Manokin aquifer caused by pumpage from the Ocean City aquifer.

A ground-water flow model was constructed to determine the effects of increased pumpage at Ocean City on the ground-water flow system. The model was designed using boundary conditions that approximate the ground-water flow regime and hydrologic properties obtained from an earlier calibrated model (Weigle and Achmad, 1982). Model calibrations include a steady-state simulation for the 1900 pre-pumping conditions and transient simulations to approximate the annual average water levels from 1900 to 1990. The steady-state model was considered calibrated when it produced a reasonable 1900 pre-pumping water level distribution. Annual average water levels were simulated for the period 1900 to 1990 using documented pumpages from the Ocean City and Manokin aquifers at four well fields in Ocean City. The average difference between simulated and measured water levels for all aquifers was 0.9 feet, maximum difference was 5 feet, and 94th-percentile difference was 3 feet or less.

The calibrated model was used to determine the hydrologic effects of increased pumpage by simulating projected future pumpage based on proposed water-development plans for Ocean City through 2010. A pumpage of 9.1 Mgal/d was used to simulate annual average pumpage from the four well fields. The increased pumpage expanded and deepened the cones of depression at the 44th Street and Gorman Avenue well fields in the Manokin, Ocean City, and Pocomoke aquifers. These cones of depression are elongated in the seaward direction because the pressure gradient is less on the seaward side of the well fields than the landward side. The greater pressure gradient on the landward side indicates that there is a greater flow from the landward direction supplying recharge to the well fields than from the seaward direction.

Particle tracking was applied to steady-state flow model simulations at the 44th Street and Gorman Avenue well fields using the 1990 and 2010 pumpages. Most of the recharge particle pathlines back-tracked from pumping wells at the 44th Street well field originated from freshwater recharge areas of the Ocean City-Manokin aquifer system. Some pathline tracks followed flowlines in the offshore mixing zone before arriving at the well. The pumping cell mass balances calculated for the 1972, 1990, and 2010 pumpages of 0.74, 1.2, and 2.6 Mgal/d at the 44th Street well field indicated that about 65% to 62% of the volume contributing to the pumpage comes from the Ocean City aquifer of which about 14% to 16% comes from the offshore part of the freshwater-saltwater mixing zone. Downward leakage from the Pocomoke aquifer accounts for 2% to 1% of the mass balance. About 33% to 36% of the volume is upward leakage from the underlying Manokin aquifer, which contains brackish water at the 44th Street site. At higher pumping rates the upward leakage from the Manokin aquifer increases, causing higher chloride concentrations in the production wells at the 44th Street well field.

The pumping-cell mass balances calculated for the 1990 and 2010 pumpages of 3.7 and 4.5 Mgal/d at the Gorman Avenue well field indicated that about 80% and 74% of the volume contributing to pumpage come from the Manokin aquifer, of which 16% and 26% are from the offshore part of the freshwater-saltwater mixing zone; 20% and 26% come from the overlying Ocean City aquifer and less than 0.05% come from the underlying Choptank aquifer. This mass balance suggests that lateral encroachment through the Manokin aquifer is the major source of brackish water at the Gorman Avenue site.

A cross-sectional solute-transport model was developed and applied to the 44th Street and Gorman Avenue well fields to study chloride distributions in the coastal aquifers. Boundary conditions and hydrologic properties were derived from earlier flow models. A 1900 pre-pumping condition was simulated by modeling the progressive rise in sea level during the last 4,000 years from about 25 feet below sea level to the present shoreline. The 1900 simulation produced an offshore plume of relatively freshwater in the Ocean City-Manokin aquifer system. The 1,000 and 19,000 mg/L isochlors extend respectively, about 10 and 60 miles off the coast of Ocean City. The 1900 pressure and chloride distributions was used as the initial condition for the 1900–1990 simulations. The model was recalibrated by matching measured water levels and chloride concentrations with values obtained from simulating 1900 to 1990 pumpage at the 44th Street well field and also at the Gorman Avenue well field. The average difference between simulated and measured annual average water levels was less than 4 feet at both well field locations and the average difference between the simulated and measured chloride concentrations was within 10%. Simulations of 2.6, 3.3, and 4.4 Mgal/d at the 44th Street well field increased the chloride concentrations to about 230, 235, and 243 mg/L in 2010. Simulations of 4.5 and 9 Mgal/d pumpage at the Gorman Avenue well field increased the chloride concentration to about 170 and 185 mg/L in 2010.

The homogeneity and generalizations assumed by the model may not fully represent the heterogeneity and specific conditions existing in the field and the simulated pumpage may differ from the pumpage actually scheduled in future years. Nevertheless, the computed simulations provide useful insights into the temporal relationship between well field pumpage, water levels, and chloride distribution.

CONCLUSIONS

Conclusions of this study are:

1). In the Ocean City area two sandy facies comprise the Ocean City aquifer: a grayish-tan to orange-tan sand suggestive of coalescing distributary channel-sands or channel-mouth bars and a fine to medium, silty to clayey, glauconite- and shell-bearing sand. The abrupt change in lithology south of 61st Street strongly suggests that the Ocean City beds south of 61st Street represent a younger prograding delta sequence that has truncated the more muddy unit north of 61st Street.

2). The Manokin formation is the product of a prograding high-constructive lobate delta system. The Manokin aquifer is a series of stacked and truncated, coarsening upward sequences deposited as prograding delta front sands and coalescing distributary-channel sands. At 44th Street the confining unit that separates the Ocean City and Manokin aquifers is sandy, which facilitates the up-coning of brackish water. Also in the 44th Street area, the base of the Manokin aquifer is at its deepest; this allows saltwater to encroach farther inland and disperse stratigraphically higher.

3). The St. Marys Formation is a clayey, relatively thick confining unit that separates the Manokin aquifer from the underlying brackish water-bearing Choptank aquifer.

4). A plume of fresh to slightly brackish water extends offshore in the Ocean City-Manokin aquifer system. The solute-transport model was able to simulate the offshore part of the freshwater-saltwater mixing zone, which was used as an initial condition for calibration (1900–1990) and predictive runs (1990–2010).

5). At the 44th Street well field, brackish-water encroachment to the Ocean City aquifer occurs laterally and vertically. About 15 percent of the volume pumped from the Ocean City aquifer comes from the offshore part of the freshwater-saltwater mixing zone and about 35 percent of the pumpage originates as upward leakage from the underlying (brackish) Manokin aquifer. The remaining 50 percent comes from freshwater recharge areas. Simulated pumpage of 2.6, 3.3, and 4.4 Mgal/d for 20 years from the Ocean City aquifer at the 44th Street well field resulted in chloride concentrations of approximately 230, 235, and 243 mg/L in 2010; this simulation suggests the upper range of acceptable pumpage volume at the 44th Street well field.

6). At the Gorman Avenue well field, brackish-water intrusion to the Manokin aquifer occurs only as lateral encroachment. About 20 percent of the volume pumped from the Manokin aquifer comes from the offshore part of the freshwater-saltwater mixing zone and less than 0.05 percent is upward leakage from the underlying brackish Choptank aquifer. The remaining 80 percent comes from freshwater recharge areas. Simulating pumpage of 4.5 and 9.0 Mgal/d from the middle and upper parts of the Manokin aquifer at the Gorman Avenue well field resulted in chloride concentrations of approximately 170 and 185 mg/L.

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APPENDIXES

Appendix A.—Selected well and test-hole records, Worcester County, Maryland

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Ae 19	WO-72-0006	U.S.G.S.	Delmarva Drilling	06-25-75	40	503	--	--
WO Ae 23	WO-73-0513	U.S.G.S.	Delmarva Drilling	09-17-75	40	290	280	Manokin
WO Ae 24	WO-73-0512	U.S.G.S.	Delmarva Drilling	09-18-75	40	210	200	Ocean City
WO Ae 25	WO-73-0514	U.S.G.S.	Delmarva Drilling	09-19-75	40	120	110	Beaverdam
WO Af 5	--	Morris Hatchery	Shannahan Artesian	1943	27	642	379	Manokin
WO Af 30	WO-81-0293	U.S.G.S.	Burns Drilling	10-06-82	22	223	220	Pocomoke
WO Af 31	WO-81-0293	U.S.G.S.	Burns Drilling	10-04-82	22	223	145	Pocomoke
WO Af 32	WO-81-0293	U.S.G.S.	Burns Drilling	10-04-82	22	223	65	Beaverdam
WO Ah 5	WO-68-W-60	Ocean City	Sydnor Hydrodynamics	07-17-68	6	340	326	Ocean City Manokin
WO Ah 6	WO-70-0009	U.S.G.S.	Delmarva Drilling	01-01-69	6	1,210	357	Manokin
WO Ah 33	WO-72-0062	Ocean City	Shannahan Artesian	04-22-72	4	478	450	Manokin
WO Ah 34	WO-72-0059	Ocean City	Shannahan Artesian	02-10-72	5	488	450	Manokin
WO Ah 35	WO-73-0516	U.S.G.S.	Delmarva Drilling	10-24-75	10	728	726	St. Marys
WO Ah 36	WO-73-0518	U.S.G.S.	Delmarva Drilling	10-28-75	10	440	430	Manokin
WO Ah 37	WO-73-0517	U.S.G.S.	Delmarva Drilling	10-31-75	10	488	478	Manokin
WO Ah 38	WO-73-0689	Ocean City	C.Z. Enterprises	08-26-76	4	507	430	Manokin
WO Ah 39	WO-73-0690	Ocean City	C.Z. Enterprises	-- 1976	7	506	--	Manokin

Explanation

U.S.G.S.	U.S. Geological Survey
MD D.N.R.	Maryland Department of Natural Resources
+	indicates water level above land surface
NW	Northwest
SW	Southwest

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
--	--	--	--	--	--	--	--	WO Ae 19
	(Remarks: Test hole NW of Whaleysville)							
270 - 280	4	13	35	5	7	0.8	09-17-75	WO Ae 23
	(Remarks: Observation well NW of Whaleysville)							
190 - 200	2	18.5	35	7.5	4.7	0.5	09-19-75	WO Ae 24
	(Remarks: Observation well NW of Whaleysville)							
100 - 110	4	9	60	5	12	1	09-20-75	WO Ae 25
	(Remarks: Observation well NW of Whaleysville. Previously assigned to the Pocomoke aquifer by Weigle and Achmad [1982]).							
369 - 379	--	15	50	12	4.2		November, 1952	WO Af 5
218 - 220	2	6.3	--	--	--	--	12-07-82	WO Af 30
143 - 145	2	--	--	--	--	--	--	WO Af 31
63 - 65	2	--	--	--	--	--	--	WO Af 32
210 - 230 306 - 326	4	0	21	54	0.4	1.25	07-18-68	WO Ah 5
	(Test well; screened intervals tested separately; pump test data for the 210 to 230 ft screen; water chemistry data for the 306 to 326 ft screen)							
347 - 357	6	+2	40	24	1.7	8	08-20-69	WO Ah 6
	(Remarks: Observation well at the Gorman Ave. Water Plant; temporary screens set from 708 to 718 ft, 464 to 474 ft, and 363 to 373 ft; well plugged back and permanent screens emplaced from 347 to 357 ft.)							
346 - 450	12	4	810	19	43	24	04-21-72	WO Ah 33
	(Remarks: Production well B for the Gorman Ave. Water Plant)							
350 - 450	12	3	1,000	17	59	24	04-30-72	WO Ah 34
	(Remarks: Production well A for the Gorman Ave. Water Plant)							
716 - 726	2	7	1	107	0.01	11	10-24-75	WO Ah 35
	(Remarks: Observation well at 137th St. and the beach; screened in clay.)							
420 - 430	2	15	15	7	2.1	5	10-28-75	WO Ah 36
	(Remarks: Observation well at 137th St. and the beach)							
468 - 478	2	14	15	9	1.7	5	10-31-75	WO Ah 37
	(Remarks: Observation well at 137th St. and the beach)							
330 - 430	12	13	1,400	36	39	8	08-26-76	WO Ah 38
	(Remarks: Production well C for the Gorman Ave. Water Plant)							
-- --	--	--	--	--	--	--	--	WO Ah 39
	(Remarks: Production well D for the Gorman Ave. Water Plant)							

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Ah 42	WO-81-1753	Ocean City	Delmarva Drilling	03-02-87	6	560	410	Manokin
WO Ah 43	--	Ocean City	Delmarva Drilling	01-20-89	6	400	395	Manokin
WO Ah 44	WO-88-0316	Ocean City	Delmarva Drilling	08-01-90	6	480	454	Manokin
WO Ah 45	WO-88-0648	Ocean City	American Well Drilling	04-30-91	8	402.5	402.5	Manokin

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
300 - 410	4	6	95	16	5.9	4	03-02-87	**WO Ah 42**
	(Remarks: Observation well for WO Ah 43 at 130th St.)							
295 - 300 316 - 360 371 - 395	8	7.7	--	--	--	--	--	**WO Ah 43**
	(Remarks: Production well E for the Gorman Ave. Water Plant; located at 130th St.)							
332 - 342 373 - 398 413 - 418 429 - 434 444 - 449	4	26.6	93	16	5.8	8	08-01-90	**WO Ah 44**
	(Remarks: Observation well located at Northside Park, 125th St.)							
324.5 - 327.5 337.5 - 347.5 366.5 - 376.5 382.5 - 402.5	8	11.5	900	44.8	20.6	12	04-30-91	**WO Ah 45**
	(Remarks: Production well F at 125th St. and Northside Park)							

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet) below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Bf 63	WO-73-0192	U.S.G.S.	U.S.G.S.	12-06-73	30	520	--	--
WO Bg 10	--	Shore Lumber	Shannahan Artesian	1914	4	1,706	1,700	Calvert ?
WO Bg 15	WO-68-0066	Ocean Pines	Sydnor Hydrodynamics	11-20-68	6	500	318	Manokin
WO Bg 44	WO-68-0066	Ocean Pines	Sydnor Hydrodynamics	11-16-68	6	90	85	Beaverdam
WO Bg 45	WO-68-0066	Ocean Pines	Sydnor Hydrodynamics	11-13-68	10	80	77	Beaverdam
WO Bg 46	WO-68-0066	Ocean Pines	Sydnor Hydrodynamics	November, 1968	10	210	200	Pocomoke ?
WO Bg 47	WO-73-0522	U.S.G.S.	Delmarva Drilling	09-02-75	6	300	268	Ocean City
WO Bg 48	WO-73-0521	U.S.G.S.	Delmarva Drilling	09-02-75	6	441	420	Manokin
WO Bg 49	WO-73-0520	U.S.G.S.	Delmarva Drilling	10-16-75	10	261	243	Ocean City

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
--	--	--	--	--	--	--	--	**WO Bf 63**
	(Remarks: Test hole)							
Open Pipe	4	Flowed at 250 gpm in 1914; flowing on 3-11-70 - discharge not measured			--	--	--	**WO Bg 10**
	(Remarks: Drilled as an oil test well on the Isle of Wight;							
288 - 318	6	+0.7	110	--	--	10	09-10-70	**WO Bg 15**
	(Remarks: Observation well at Ocean Pines)							
50 - 80	6	5	110	7	16	10	11-16-68	**WO Bg 44**
	(Remarks: Observation well at Ocean Pines)							
56 - 77	3	9	--	--	--	--	11-13-68	**WO Bg 45**
	(Remarks: Observation well at Ocean Pines)							
164 - 194.5	4	4.1	110	13.9	7.9	10	11- -68	**WO Bg 46**
	(Remarks: Observation well at Ocean Pines)							
258 - 268	2	13	50	8	6.2	5	09-02-75	**WO Bg 47**
	(Remarks: Observation well on the Isle of Wight)							
410 - 420	2	13	40	4	10	2	09-02-75	**WO Bg 48**
	(Remarks: Observation well on the Isle of Wight)							
233 - 243	2	10	16	16	1	3	10-16-75	**WO Bg 49**
	(Remarks: Observation well on Keyser Point Rd.)							

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Bh 1	--	Ocean City	Shannahan Artesian	1939	6	285	285	Ocean City
WO Bh 8	WO-1489	Ocean City	Shannahan Artesian	06-28-47	6	190	176	Pocomoke
WO Bh 11	WO-847	Standard Oil of New Jersey	Noble Drilling Co.	1946	6	7,710	7,710	--
WO Bh 26	WO-27645	Ocean City	Sydnor Hydrodynamics	08-15-57	5	365	281	Ocean City
WO Bh 27	WO-37861	Ocean City	Sydnor Hydrodynamics	02-19-60	5	295	295	Ocean City
WO Bh 28	WO-50667	Ocean City	Sydnor Hydrodynamics	03-19-63	6	305	294	Ocean City
WO Bh 29	WO-50668	Ocean City	Sydnor Hydrodynamics	04-09-63	6	303	294	Ocean City
WO Bh 30	WO-67-W-56	Ocean City	Sydnor Hydrodynamics	03-24-67	6	325	298	Ocean City
WO Bh 31	WO-49586	Ocean City	Shannahan Artesian	11-14-62	6	311	278	Ocean City
WO Bh 34	WO-49588	Ocean City	Shannahan Artesian	11-20-62	4	365	353	Manokin
WO Bh 35	WO-69-0015 A	Ocean City	Delmarva Drilling	08-23-68	5	430	285	Ocean City
WO Bh 36	WO-69-0015 B	Ocean City	Delmarva Drilling	08-29-68	5	280	280	Ocean City
WO Bh 37	WO-69-0015 C	Ocean City	Delmarva Drilling	08-30-68	5	290	280	Ocean City

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
272 - 285	6	2	195	37	5.3	22	December, 1951	**WO Bh 1**
	(Remarks: Discontinued production well at 15th St.)							
151 - 176	8	7	100	9.7	10	6	06-28-47	**WO Bh 8**
	(Remarks: Discontinued production well at 15th St.)							
--	--	--	--	--	--	--	--	**WO Bh 11**
	(Remarks: Oil exploration hole, Maryland Esso No. 1)							
245 - 281	8	9	776	85.3	9.1	24	08-15-57	**WO Bh 26**
	(Remarks: Production well A for the 15th St. Water Plant)							
233 - 238 248 - 268 279 - 289	8	+0.7	715	80.7	8.8	24	02-19-60	**WO Bh 27**
	(Remarks: Production well B for the 15th St. Water Plant)							
248 - 294	9.6	1.7	703	20.3	35	24	03-19-63	**WO Bh 28**
	(Remarks: Production well A for the 44th St. Water Plant)							
248 - 294	9.6	0.5	503	34	15	24	04-19-63	**WO Bh 29**
	(Remarks: Production Well B for the 44th St. Water Plant)							
232 - 237 270 - 282 292 - 298	8	1	726	78	9.3	10	03-24-67	**WO Bh 30**
	(Remarks: Production well C for the 14th St. Water Plant)							
263 - 278	3	+3	60	10.8	5.6	2	11-14-62	**WO Bh 31**
	(Remarks: Observation well at the 44th St. Water Plant)							
337 - 353	3	+2	55	19.3	2.8	16	11-20-62	**WO Bh 34**
	(Remarks: Observation well at 100th St.)							
240 - 285	6	3.5	300	192	1.6	18	09-05-68	**WO Bh 35**
	(Remarks: Test well at the 66th St. water tower - destroyed)							
--	2	3	--	--	--	--	09-05-68	**WO Bh 36**
	(Remarks: Observation well 157 ft SW of WO Bh 35; screens not reported, but probably same as WO Bh 37)							
240 - 280	2	4	--	--	--	--	09-05-68	**WO Bh 37**
	(Remarks: Observation well 340 ft SW of WO Bh 35)							

Appendix A.—Continued

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Bh 39	WO-69-W-1	Ocean City	Shannahan Artesian	03-27-69	5	322	308	Ocean City
WO Bh 40	WO-69-W-2	Ocean City	Shannahan Artesian	06-30-69	5	352	298	Ocean City
WO Bh 41	WO-69-0080	Ocean City	Delmarva Drilling	07-13-69	5	343	318	Ocean City
WO Bh 81	WO-71-0080	Ocean City	Sydnor Hydrodynamics	06-16-71	5	528	297	Ocean City
WO Bh 84	WO-73-0095	U.S.G.S.	Ideal Well	05-15-73	5	89	85	Beaverdam
WO Bh 85	WO-73-0094	U.S.G.S.	Ideal Well	05-17-73	5	203	195	Pocomoke
WO Bh 87	none	Delmarva Power & Light	--	10-01-80	4	260	--	--
WO Bh 88	WO-81-0616	Ocean City	Delmarva Drilling	05-30-84	5	485	445	Manokin
WO Bh 89	WO-81-1497	Ocean City	Delmarva Drilling	09-15-86	5	530	510	Manokin
WO Bh 90	WO-81-1805	Ocean City	Layne-Atlantic	05-13-87	6	777	741	Choptank
WO Bh 91	WO-81-1830	Ocean City	Layne-Atlantic	06-12-87	10	780	385	Manokin
WO Bh 92	WO-81-1833	Ocean City	Layne-Atlantic	07-03-87	4	754	408	Manokin
WO Bh 93	WO-81-1832	Ocean City	Layne-Atlantic	07-15-87	4	750	435	Manokin

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
268 - 308	8	10	830	87	9.5	24	03-27-69	**WO Bh 39**
	(Remarks: Production well at 40th St. for the 44th St. Water Plant)							
258 - 268	8	10	830	87	9.5	24	06-30-69	**WO Bh 40**
	(Remarks: Production well at 41st St. for the 44th St. Water Plant)							
258 - 318	10	9	800	24	33.3	24	07-13-69	**WO Bh 41**
	(Remarks: Production well C at 42nd St. for the 44th St. well field)							
227 - 232 244 - 264 272 - 297	8	14	800	55	14.6	8	06-16-71	**WO Bh 81**
	(Remarks: Production well D for the 44th St. Water Plant)							
84 - 89	4	4.6	--	--	--	--	04-20-73	**WO Bh 84**
	(Remarks: Observation well at the 44th St. Water Plant)							
190 - 195	4	3.5	--	--	--	--	04-20-73	**WO Bh 85**
	(Remarks: Observation well at the 44th St. Water Plant)							
none	--	--	--	--	--	--	--	**WO Bh 87**
	(Remarks: Boring for electric grounding rod at 85th St.)							
365 - 445	8	7	1,016	60	16.9	34	05-30-84	**WO Bh 88**
	(Remarks: Production well D at 15th St. Water Plant)							
388 - 408 413 - 423 433 - 443 464 - 474 495 - 510	4	1	80	36	2.2	10	09-15-86	**WO Bh 89**
	(Remarks: Observation well at the 44th St. Water Plant)							
691 - 711 726 - 736	4	Flowed	50	>24	<2	2	05-27-87	**WO Bh 90**
	(Remarks: Observation well at 28th St.)							
340 - 380	4	23	80	--	--	2	06-12-87	**WO Bh 91**
	(Remarks: Observation well at 51st St.)							
347 - 372	4	15	70	45	1.6	12	07-03-87	**WO Bh 92**
	(Remarks: Observation well at 100th St.)							
335 - 345 367 - 377 387 - 397 420 - 430	4	18	80	14	5.7	8	07-15-87	**WO Bh 93**
	(Remarks: Observation well at 61st St.)							

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Bh 94	WO-81-1834	Ocean City	Layne-Atlantic	07-09-87	4	320	315	Ocean City
WO Bh 95	WO-81-1831	Ocean City	Layne-Atlantic	07-25-87	4	295	295	Ocean City
WO Bh 96	WO-81-1829	Ocean City	Layne-Atlantic	06-18-87	10	310	300	Ocean City
WO Bh 97	WO-81-1823	Ocean City	Layne-Atlantic	05-27-87	6	447	445	Manokin
WO Bh 98	WO-81-1822	Ocean City	Layne-Atlantic	05-17-87	6	330	310	Ocean City
WO Bh 99	WO-88-0350	Ocean City	Delmarva Drilling	08-15-90	6	340	322	Ocean City

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
285 - 310	4	12	18	30	0.6	4	07-09-87	WO Bh 94
	(Remarks: Observation well at 100th St.)							
275 - 295	4	13	30	79	0.3	8	07-25-87	WO Bh 95
	(Remarks: Observation well at 61st St.)							
255 - 275 285 - 295	4	30	120	--	--	2	06-18-87	WO Bh 96
	(Remarks: Observation well at 51st St.)							
370 - 380 390 - 400 410 - 420 430 - 440	4	14	100	15	6.7	2	05-27-87	WO Bh 97
	(Remarks: Observation well at 28th St.							
255 - 275 285 - 290 305 - 310	4	18	90	19	4.7	2	05-17-87	WO Bh 98
	(Remarks: Observation well at 28th St.)							
254 - 259 269 - 274 279 - 284 289 - 299 317 - 322	4	29.7	99	14.4	6.9	8	08-15-90	WO Bh 99
	(Test well located at 33rd St.)							

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Ce 12	--	Socony Vacuum Oil Co.	Big Chief Drilling Co.	1945	30	7,178	7,178	--
WO Ce 21	WO-53320	Dennis, W.	Daisey	08-19-63	30	155	155	Pocomoke
WO Ce 26	--	Molnar, D.	Ideal Well	1971	25	100	100	Pocomoke
WO Ce 31	--	U.S.G.S.	Delmarva Drilling	06-14-72	25	1,040	--	--
WO Cg 1	--	Ocean City	Shannahan Artesian	1900?	5	285	285	Ocean City
WO Cg 5	WO-1642-A	Ocean City	Shannahan Artesian	07-19-47	4	190	180	Pocomoke
WO Cg 32	WO-18528	Ocean City	Sydnor Hydrodynamics	01-01-55	4	300	280	Ocean City
WO Cg 33	WO-18529	Ocean City	Sydnor Hydrodynamics	05-21-55	5	300	290	Ocean City
WO Cg 34	WO-67-W-57	Ocean City	Sydnor Hydrodynamics	03-27-67	5	345	300	Ocean City
WO Cg 35	WO-9695	Taylor A.	A.V. Stoops	01-01-60	7	240	240	Manokin
WO Cg 68	WO-73-0191	U.S.G.S	Paul White	01-03-74	10	720	--	--
WO Cg 69	WO-73-0064	Mystic Harbour	Delmarva Drilling	03-24-73	10	245	235	Ocean City
WO Cg 72	WO-73-1304	Ocean City	Delmarva Drilling	03-30-78	6	560	450	Manokin
WO Cg 75	WO-81-0615	U.S.G.S.	Delmarva Drilling	04-09-84	6	460	433	Manokin

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
--	--	--	--	--	--	--	--	WO Ce 12
	(Remarks: Oil exploration hole, Bethards No. 1 well)							
147 - 155	2	12	40	12	3.3	2	08-19-63	WO Ce 21
	(Remarks: Inventoried domestic well near Ninepin, MD)							
80 - 100	4	--	--	--	--	--	--	WO Ce 26
	(Remarks: Inventoried domestic well near Ninepin. MD)							
--	--	--	--	--	--	--	--	WO Ce 31
	(Remarks: Exploratory test hole)							
255? - 285	6	+5	--	--	--	--	1925	WO Cg 1
	(Remarks: Discontinued production well at Dorchester St.)							
160.5 - 180.5	8	8	120	8	15	6	07-19-47	WO Cg 5
	(Remarks: Discontinued production well at Philadelphia Ave. and Somerset St.)							
245 - 280	8	Flowed	663	>40.5	<16	24	05-10-55	WO Cg 32
	(Remarks: Production well A at the South Well Field)							
253 - 290	8	Flowed	663	>48.5	<14	24	05-21-55	WO Cg 33
	(Remarks: Production well B at the South Well Field)							
226 - 231 240 - 260 270 - 280 284 - 294	8	1.5	869	37.3	23	24	03-27-67	WO Cg 34
	(Remarks: Production well C for the South Well Field)							
232 - 240	2	7	20	2	10	2	07-28-60	WO Cg 35
	(Remarks: Inventoried domestic well near Berlin, MD).							
none	--	--	--	--	--	--	--	WO Cg 68
	(Remarks: Test hole at the Ocean City Airport)							
215 - 235	6	7	167	--	--	8	03-24-73	WO Cg 69
	(Remarks: Observation well near Berlin, MD)							
384 - 394 404 - 424 445 - 450	4	2.5	100	17.5	5.7	24	04-08-78	WO Cg 72
	(Remarks: Observation well at the South Well Field.)							
367 - 433	8	7	1,000	56	18	33	04-09-84	WO Cg 75
	(Remarks: Production well D at the South Well Field)							

Appendix A.—Continued

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (feet)	Depth drilled (feet below lsd)	Depth of well (feet below lsd)	Aquifer screened
WO Dd 10	WO-2648	Snow Hill	Shannahan Artesian	06-08-48	20	405	366.5	Manokin
WO Dd 60	WO-73-1512	Gruy Federal	Energy Services	11-07-78	18	1,043	1,043	--
WO De 36	WO-73-0515	U.S.G.S.	Delmarva Drilling	09-11-75	30	341	330	Manokin
WO Df 3	WO-67-W-19	Ocean City Yacht Club	Shannahan Artesian	01-01-66	5	145	144	Pocomoke
WO Dg 10	WO-69-0034	MD D.N.R.	Ideal Well	05-20-69	5	340	313	Manokin
WO Dg 20	WO-73-0560	MD D.N.R.	Delmarva Drilling	10-03-75	6	640	--	--
WO Dg 21	WO-73-0519	MD D.N.R.	Delmarva Drilling	10-08-75	6	380	310	Manokin
WO Ed 8	WO-46	Selby, M.	Ennis Bros	10-02-45	36	181	181	Pocomoke
WO Ed 46	WO-81-0445	Baptist Church	Somerset Well Drilling	07-25-83	35	210	210	Pocomoke
WO Ef 3	WO-12729	McConville	R.C. Scott	06-24-53	4	169	169	Pocomoke
WO Fb 2	WO-1633	Pocomoke City	Rulon	1947	20	130	130	Pocomoke
WO Fb 19	--	Pocomoke City	Shannahan Artesian	1906-1907	4	1,540	--	??
WO Fb 96	WO-71-0007	Campbell Soup Co.	Sam Shannahan	05-03-70	5	212	130	Manokin?
WO Fc 46	WO-81-2289	U.S.G.S.	U.S.G.S.	01-06-88	33	60	43	Beaverdam
WO Fd 33	--	U.S.G.S.	U.S.G.S.	10-20-88	22	650	--	--

Screened intervals (feet below lsd)	Screen diameter (in.)	Static water level (feet below lsd)	Discharge (gal/min)	Drawdown (feet)	Specific capacity (gal/min/ft)	Pumping period (hours)	Date water level and discharge measured	Well number
306.5 - 366.5	10	17	500	85	5.9	24	06-08-48	**WO Dd 10**
	(Remarks: Production well in Snow Hill, MD)							
	--	--	--	--	--	--	--	**WO Dd 60**
	(Remarks: Geothermal gradient test well							
320 - 330	2	15	6	16	0.3	6	09-11-75	**WO De 36**
	(Remarks: Observation well near Newark, MD)							
119 - 124	--	6	43	6	7.2	6	November, 1966	**WO Df 3**
	(Remarks: Inventoried irrigation well on Sinepuxent Neck)							
278 - 308	6	5	175	171	1.0	24	05-20-69	**WO Dg 10**
	(Remarks: Observation well at Assateague St. Park)							
--	--	--	--	--	--	--	--	**WO Dg 20**
	(Remarks: Test hole at Assateague St. Park)							
300 - 310	2	3	30	27	1.1	2	10-08-75	**WO Dg 21**
	(Remarks: Observation well at Assateague St. Park)							
171 - 181	2.5	28	40	13.5	3	16	10-02-45	**WO Ed 8**
	(Remarks: Inventoried domestic well near Girdletree, MD)							
180 - 210	2	15	15	4	3	1	07-25-83	**WO Ed 46**
	(Remarks: Supply well for church near Girdletree, MD)							
159 - 169	2	0	20	5	1.4	4	September, 1953	**WO Ef 3**
	(Remarks: Domestic well at Ocean Beach, MD; abandoned in 1968)							
100 - 130	--	18	--	--	--	--	1947	**Wo Fb 2**
--	--	Flowed	--	--	--	--	08-13-52	**WO Fb 19**
70 - 80 92 - 97 110 - 130	--	26	700	35	20	24	05-31-70	**WO Fb 96**
	(Remarks: Commercial production well in Pocomoke City)							
40 - 43	2	--	--	--	--	--	--	**WO Fc 46**
--	--	--	--	--	--	--	--	**WO Fd 33**
	(Remarks: Continuous stratigraphic core-hole)							

Appendix B: Chemical analyses of ground-water samples from Ocean City and northeastern Worcester County, Maryland.

This table presents chemical analyses for production and observation wells in Ocean City and adjacent areas of Worcester County, Maryland. The majority of analyses were made by the National Water-Quality Laboratory of the U.S. Geological Survey. Analyses made by other laboratories are noted in the table.

<u>Note regarding sulfate determinations for the years 1982-1988.</u>

In March 1989 the National Water-Quality Laboratory discovered a bias in the turbidimetric method it used to determine sulfate concentrations during the period 1982 to 1988. For all samples analyzed by the laboratory from 1982 to 1988, there is a median positive bias of 2 mg/L over the correct value for sulfate determinations of less than 75 mg/L.

The actual positive bias for some of the sulfate determinations listed in this table that were analyzed between 1982 and 1988 may equal an order of magnitude or more over the true concentration of sulfate. The values in this table are listed as reported by the National Water-Quality Laboratory. No attempt has been made to correct possibly incorrect sulfate determinations; the amount of error in a given sulfate analysis cannot be calculated because of the type of analytical error.

<u>Explanation of certain codes used in table.</u>

T	Total dissolved ions and suspended solids
F	Field determined value
C	Calculated value
mg/L	milligrams per liter
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25° Celsius

Well number (Locality)	Aquifer	Date sampled	Sodium, dis- solved (mg/L)	Potas- sium, dis- solved (mg/L)	Calcium, dis- solved (mg/L)	Magne- sium, dis- solved (mg/L)	Chlo- ride, dis- solved (mg/L)	Fluo- ride, dis- solved (mg/L)	Bromide, dis- solved (mg/L)	Sulfate, dis- solved (mg/L)	Alkalinity, total lab or field (F) value (mg/L as $CaCO_3$)
WO Ae 23	Manokin	09-17-75	9.4	2.9	12	2.6	7.5	0.1	--	1.7	56 F
		09-11-85	9.4	3.4	9.1	3.6	7.1	<0.1	--	1.8	55
(Near Whaleysville)		04-11-86	9.4	3.1	9.2	3.7	6.9	<0.1	--	12	56
		08-22-86	9.6	2.9	9.1	3.6	6.5	<0.1	--	12	55
		08-26-87	9.6	3.2	8.8	3.6	2.1	0.1	--	7.2	68 F
		09-09-88	9.7	2.6	9.3	3.9	6.7	0.1	--	9.6	53
		09-20-89	9.2	2.9	9.1	3.4	5.9	0.1	--	<1.0	54
		01-17-90	9.2	3.5	8.7	3.5	7.4	0.1	0.32	<1.0	54
WO Ae 24	Ocean City	09-17-75	7.4	1.3	76	2.6	10	0.2	--	2.3	221 F
		09-11-85	7.7	1.4	77	3.2	11	<0.1	--	1.2	219
(Near Whaleysville)		04-11-86	7.9	1.2	83	3.1	8.2	<0.1	--	7.2	222
		08-22-86	7.5	1.5	70	2.6	9.4	0.1	--	3.8	219
		08-26-87	8.0	1.7	79	3.1	8.9	0.1	--	5.7	232 F
		09-09-88	7.8	1.2	80	3.3	9.3	0.1	--	3.1	240 F
		09-20-89	7.8	1.5	81	3.0	9.9	0.1	--	<1.0	207
		01-17-90	7.7	1.1	80	3.1	10.0	0.1	0.07	<1.0	217
WO Ae 25	Beaverdam	09-19-75	8.3	0.7	86	1.8	12	0.1	--	3.0	238 F
		09-11-85	8.3	0.7	85	2.3	11	0.1	--	11	231
(Near Whaleysville)		04-11-86	8.6	0.6	90	2.2	10	<0.1	--	8.6	234
		08-22-86	8.7	0.8	90	2.2	12	0.1	--	8.7	231
		08-26-87	8.7	0.9	86	2.2	2.1	0.1	--	5.6	245 F
		09-09-88	8.7	0.6	87	2.5	11	0.1	--	3.4	247 F
		09-20-89	8.8	0.6	88	2.3	10	0.1	--	1.0	222
WO Af 30	Pocomoke	12-07-82	7.5	1.1	2.8	0.91	8.8	--	--	3.0	14
(In Bishopville)		12-06-89	6.5	1.3	2.5	0.77	9.3	<0.1	0.04	<1.0	12
WO Af 31	Pocomoke	12-07-82	7.0	1.0	3.1	0.89	7.8	--	--	2.0	17
(In Bishopville)											
WO Ah 5	Manokin	07-18-68	22.0	--	17.5	5.2	22.0	0.05	--	2.9	77
		Sample from 306 to 326 ft screen; Analysis by Froehling & Robertson, Inc.									
WO Ah 6	Choptank	07-14-69	1700	65	100	98	2700	0.8	--	150	512 F
(137th St., O.C.)		Sample on 07-14-69 from screens set from 708 to 718 feet below land surface.									
WO Ah 6	Manokin	07-24-69	230	13	42	15	300	0.3	--	7.2	253 F
(137th St., O.C.)		Sample on 07-24-69 from screens set from 464 to 474 feet below land surface.									
WO Ah 6	Manokin	07-25-69	23	4.0	28	5.9	30	0.1	--	--	105 F
(137th St., O.C.)		Sample on 07-25-69 from screens set from 363 to 373.									
WO Ah 6	Manokin	07-29-69	24	3.8	24	5.8	35	0.1	--	--	90 F
(137th St., O.C.)		12-21-76	21	3.6	26	6.0	30	0.1	--	1.7	92 F
		Samples from screens set from 347 to 357 feet below land surface; lower screens plugged.									
WO Ah 33	Manokin	09-12-73	52	4.7	22	6.2	68	0.2	--	<1.0	91 F
(Gorman Ave., O.C.)		03-08-76	60	4.7	22	7.0	91	<0.1	--	5.9	100 F
		08-03-76	65	4.9	23	6.0	99	0.1	--	0.1	95 F
WO Ah 34	Manokin	04-27-72	38	4.7	23	5.6	53	0.1	--	--	89 F
		09-03-85	57	5.1	21	4.9	87	<0.1	--	16	85
(137th St., O.C.)		04-08-86	54	3.8	21	4.7	81	<0.1	--	19	83
		08-27-86	57	4.4	21	5.1	84	<0.1	--	14	85
		08-24-87	57	4.7	21	5.2	84	0.1	--	5.3	85
		09-07-88	59	4.0	22	5.9	90	0.1	--	3.8	85
		05-23-89	57	4.4	22	5.6	75	<0.1	0.66	<1.0	93
WO Ah 36	Manokin	10-03-75	110	6.1	34	6.8	170	0.2	--	2.3	107 F
(137th St., O.C.)		05-24-89	110	5.8	24	6.7	140	0.1	0.63	<1.0	118
WO Ah 37	Manokin	10-30-75	220	11	21	15	320	0.2	--	6.5	172 F
(137th St., O.C.)		05-24-89	230	11	20	17	320	0.2	1.0	7.0	190
		01-18-90	230	11	19	17	320	0.2	1.0	8.0	177
		07-26-90	240	11	20	18	350	0.2	1.3	9.4	195 F
WO Ah 38	Manokin	08-03-76	39	4.0	24	4.1	54	0.1	--	0.2	88 F
(Gorman Ave., O.C.)		05-23-89	48	3.7	20	4.3	59	0.1	0.84	<1.0	84

Phosphorus dissolved (mg/L as P)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Silica, dissolved (mg/L as SiO_2)	pH whole water field	Hardness (total) (mg/L) as $CaCO_3$)	Specific conductance (µS/cm)	Solids, residue measured (mg/L)	Color Pt-Co units	Density (g/cm^3 at 20°C)	Temperature, degrees Celsius	Well number
--	5200 T	110 T	28	--	41	--	--	85	--	13.7	WO Ae 23
<0.01	4800	97	27	6.6	38	151	98	--	--	14.0	
0.07	5400	97	28	6.3	38	135	93	--	--	14.0	
0.01	6600	82	28	6.8	31	140	--	--	--	15.0	
0.06	7100	110	28	5.6	37	143	86	--	--	14.6	
0.09	5500	110	28	6.8	38	140	94	--	--	14.6	
0.09	5300	110	28	6.7	37	139	74	--	--	14.5	
0.11	6900	140	29	5.8	36	141	--	--	--	14.0	
--	12000 T	90 T	28	--	200	--	261	20	--	13.7	WO Ae 24
0.01	14000	82	29	6.9	210	485	286	--	--	14.0	
0.12	14000	91	30	6.8	220	475	289	--	--	14.0	
0.07	12000	84	29	7.1	190	470	290	--	--	14.5	
<0.01	12000	87	30	6.4	210	464	279	--	--	14.5	
0.06	14000	89	30	7.2	210	467	299	--	--	14.5	
0.08	14000	89	30	7.1	210	459	255	--	--	14.5	
0.04	15000	150	30	6.4	210	448	--	--	--	14.0	
--	13000 T	110 T	31	--	220	--	--	230	--	13.5	WO Ae 25
<0.01	13000	120	34	6.7	220	530	307	--	--	14.0	
0.02	14000	130	34	6.7	230	492	309	--	--	14.0	
0.03	14000	130	36	7.1	230	490	324	--	--	14.5	
<0.01	13000	130	34	6.4	220	488	296	--	--	14.5	
0.05	14000	130	35	7.1	230	489	325	--	--	14.5	
0.09	15000	140	36	7.1	230	481	298	--	--	14.5	
--	7100	--	23	5.9	11	80	--	--	--	14.5	WO Af 30
0.07	7000	41	22	5.7	9	79	--	--	--	15.5	
--	8600	--	21	6.3	11	85	--	--	--	15.0	WO Af 31
--	8500 T	--	5.0	6.9	65	--	237	-	--	--	WO Ah 5
--	2100	40	51	8.4	650	8900	5,240	3	--	--	WO Ah 6
--	810 T	50 T	58	8.4	170	1430	801	5	--	22.0	WO Ah 6
--	13000 T	120 T	32	7.0	94	298	203	15	--	17.0	WO Ah 6
--	12000 T	180 T	33	6.4	84	297	191	--	--	21.0	WO Ah 6
0.46 T	83000 T	260	35	--	90	--	286	50	--	15.5	
--	7000 T	210 T	32	6.5	80	420	--	--	--	--	WO Ah 33
--	14000 T	170 T	32	7.1	84	550	--	360	--	15.0	
--	14000	160	33	6.7	82	--	327	100	--	19.0	
--	12000 T	180 T	33	7.5	81	341	216	20	--	16.0	WO Ah 34
<0.01	12000	130	34	5.9	73	505	278	--	--	16.0	
0.04	13000	140	34	6.1	72	475	258	--	--	16.5	
0.02	12000	130	36	6.5	73	485	264	--	--	18.0	
0.04	12000	130	34	6.6	74	370	276	--	--	17.0	
0.09	12000	130	35	5.2	79	492	280	--	--	17.0	
0.10	13000	130	34	6.5	78	505	249	75	0.997	18.0	
--	13000 T	150 T	31	--	110	--	--	140	--	15.5	WO Ah 36
0.09	14000	130	33	6.6	88	836	446	54	0.997	16.0	
--	--	--	29	--	110	--	--	41	--	15.5	WO Ah 37
0.18	2900	77	27	7.0	120	1480	755	20	<0.990	16.5	
0.07	5300	110	29	6.8	120	1320	--	--	--	19.0	
0.02	3000	86	29	7.0	120	1470	744	42	0.999	16.3	
--	17000	180	33	6.7	77	400	268	120	--	19.0	WO Ah 38
0.12	12000	120	35	6.4	68	421	244	120	0.996	16.0	

Well number (Locality)	Aquifer	Date sampled	Sodium, dis- solved (mg/L)	Potas- sium, dis- solved (mg/L)	Calcium, dis- solved (mg/L)	Magne- sium, dis- solved (mg/L)	Chlo- ride, dis- solved (mg/L)	Fluo- ride, dis- solved (mg/L)	Bromide, dis- solved (mg/L)	Sulfate, dis- solved (mg/L)	Alkalinity, total lab or field (F) value (mg/L as $CaCO_3$)
WO Ah 39	**Manokin**	08-03-76	39	4.0	27	5.0	63	0.1	--	0.1	85 F
(141st. St., O.C.)		05-24-89	33	3.6	22	5.4	52	0.1	0.47	<1.0	81
WO Ah 42	**Manokin**	05-25-89	29	5.2	23	8.2	51	<0.1	0.15	<1.0	92
(130th St., O.C.)											
WO Bg 15	**Manokin**	09-10-85	24	3.5	17	5.0	26	0.1	--	12	90
		04-10-86	24	3.2	16	4.9	20	<0.1	--	18	90
(Ocean Pines)		08-26-86	24	3.4	20	5.2	26	0.1	--	20	88
		08-26-87	24	3.4	16	4.9	34	0.1	--	7.2	80
		09-08-88	20	2.7	17	5.0	24	0.1	--	16	87
		07-25-89	25	3.1	17	5.0	24	0.1	0.33	<1.0	90
		09-20-89	24	3.2	17	4.6	22	0.1	--	<1.0	87
WO Bg 45	**Beaverdam**	08-26-87	9.7	1.4	2.6	1.0	12	0.1	--	1.0	14
		09-08-88	9.7	1.4	2.6	0.86	12	<0.1	--	1.1	14
(Ocean Pines)		09-20-89	9.2	1.6	2.4	0.89	12	<0.1	--	<1.0	13 F
WO Bg 46	**Pocomoke**	08-26-87	13	6.0	15	7.0	9.9	0.1	--	5.3	88
		09-08-88	13	5.3	16	7.5	9.9	0.1	--	0.8	90
(Ocean Pines)		09-20-89	13	5.6	15	6.8	9.4	0.1	--	<1.0	86
WO Bg 47	**Ocean City**	10-28-76	56	5.8	15	7.3	68	0.1	--	0.7	95 F
		08-29-85	49	4.9	13	6.4	52	0.1	--	12	100
(Isle of Wight)		04-09-86	50	5.3	14	6.5	47	<0.1	--	27	102
		08-26-86	23	5.1	45	5.9	51	0.1	--	13	101
		08-25-87	45	4.8	12	6.2	46	0.2	--	5.4	95
		09-08-88	47	4.5	13	6.6	45	0.1	--	11	100
		06-21-89	46	4.9	13	6.0	43	0.1	0.42	<1.0	95
		09-21-89	44	4.9	12	5.7	41	0.1	--	<1.0	100
WO Bg 48	**Manokin**	10-28-76	65	7.1	15	8.0	87	0.2	--	1.2	107 F
		08-29-85	51	9.1	15	7.9	68	0.1	--	1.2	105
(Isle of Wight)		04-09-86	53	7.6	16	8.3	62	0.2	--	9.2	106
		08-25-87	50	7.2	15	8.2	66	0.2	--	5.7	98
		09-08-88	48	6.7	16	8.7	67	0.1	--	1.8	97
		06-22-89	51	7.0	16	8.1	65	0.1	0.31	<1.0	104
		09-21-89	49	7.1	15	8.0	61	0.2	--	<1.0	103
WO Bg 49	**Ocean City**	10-16-75	37	10	33	10	17	0.2	--	2.9	201 F
		09-10-85	48	11	27	8.0	15	<0.1	--	<0.2	198
(Keyser Point Rd.)		04-10-86	42	9.9	31	9.5	12	<0.1	--	18	201
		04-27-88	42	9.5	31	9.8	15	0.2	--	1.9	202
		04-21-89	44	9.5	31	9.9	14	0.1	--	<1.0	202
		09-20-89	46	8.5	29	8.0	14	0.1	--	<1.0	198
WO Bh 1	**Ocean City**	12-12-51	27	12	37	16	30	0.1	--	2.0	--
(14th St., O.C.											
WO Bh 8	**Pocomoke**	12-17-51	36	10	29	14	20	0.1	--	0.1	--
(14th St., O.C.)											
WO Bh 28	**Ocean City**	09-03-85	94	13	19	16	160	0.1	--	2.0	115
		04-08-86	110	10	19	16	160	0.2	--	38	117
(44th St., O.C.)		08-27-86	96	1.3	18	16	160	0.2	--	1.4	118
		08-24-87	110	11	18	16	160	0.2	--	5.1	115 F
		09-07-88	120	11	18	17	180	0.2	--	1.4	124
		05-23-89	110	11	18	16	190	0.2	0.74	<1.0	131
		09-12-89	120	9.7	18	16	170	0.2	--	<1.0	137
WO Bh 29	**Ocean City**	05-29-89	57	8.5	12	10	71	0.2	0.49	<1.0	116
(45th St., O.C.)											
WO Bh 31	**Ocean City**	04-24-86	160	12	23	17	260	0.2	--	0.9	127
(44th St., O.C.)		04-19-89	110	10	18	15	170	0.2	0.50	<1.0	124
WO Bh 34	**Manokin**	09-06-85	11	5.4	14	5.7	18	<0.1	--	27	73
		04-09-86	12	5.0	15	5.7	14	0.1	--	26	73
(100th St., O.C.)		08-27-86	11	4.7	14	5.6	15	0.1	--	2.5	72
		08-25-87	12	4.9	14	5.6	14	0.1	--	5.2	72
		09-08-88	12	4.4	15	6.2	14	0.1	--	3.6	71
		07-27-89	12	4.7	15	5.8	13	0.1	0.05	<1.0	74
		09-25-89	11	4.7	14	5.5	14	0.1	--	<1.0	72

Phosphorus dissolved (mg/L as P)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Silica, dissolved (mg/L as SiO_2)	pH whole water field	Hardness (total) (mg/L) as $CaCO_3$	Specific conductance (µS/cm)	Solids, residue measured (mg/L)	Color Pt-Co units	Density (g/cm^3 at 20°C)	Temperature, degrees Celsius	Well number
--	15000	190	34	6.8	88	450	273	45	--	19.0	WO Ah 39
0.11	9300	100	37	6.4	77	356	210	140	0.998	18.0	
0.01	29000	240	37	6.5	91	417	243	5	0.997	18.0	WO Ah 42
0.20	8700	130	36	6.6	63	310	168	--	--	14.5	WO Bg 15
0.27	8900	110	36	6.4	60	269	173	--	--	15.0	
0.30	9600	98	37	6.8	71	266	179	--	--	15.5	
0.32	9000	120	36	6.1	60	275	167	--	--	15.5	
0.23	9200	130	36	7.0	63	276	163	--	--	15.5	
0.34	8900	120	38	6.6	63	256	184	210	0.997	14.5	
0.38	8900	120	38	6.8	61	271	137	--	--	15.5	
0.01	71	4	17	5.4	11	78	61	--	--	14.0	WO Bg 45
0.01	49	2	19	6.5	10	74	47	--	--	14.0	
0.02	40	2	18	6.0	10	75	50	--	--	14.0	
0.01	22000	290	29	6.1	66	267	125	--	--	14.5	WO Bg 46
0.05	23000	310	30	7.2	71	270	159	--	--	14.5	
0.01	20000	290	29	6.8	65	261	122	--	--	14.5	
--	100	120	36	--	68	--	224	35	--	16.5	WO Bg 47
0.03	8300	97	35	6.7	59	412	226	--	--	15.0	
0.33	8200	94	37	6.5	62	370	202	--	--	16.0	
0.37	7000	85	35	6.8	140	380	220	--	--	16.5	
0.33	7500	89	35	--	56	353	208	--	--	16.5	
0.37	7300	92	35	6.7	60	359	216	--	--	16.5	
0.41	8100	96	36	6.6	57	300	226	150	0.997	--	
0.41	7500	89	36	6.8	53	349	203	--	--	16.5	
--	400	100	37	--	70	485	267	60	--	17.0	WO Bg 48
0.19	4700	94	37	6.6	70	454	250	--	--	16.0	
0.31	4800	91	37	6.5	74	432	253	--	--	16.5	
0.08	4700	96	36	--	71	408	233	--	--	17.0	
0.21	4800	100	37	6.6	76	421	248	--	--	17.0	
0.36	5200	98	38	6.7	73	410	267	110	0.998	19.0	
0.33	4500	96	36	6.8	70	412	230	--	--	17.0	
--	2200 T	50 T	23	--	120	--	--	6	--	14.5	WO Bg 49
0.07	990	24	23	7.4	100	448	243	--	--	15.0	
0.06	1500	29	23	7.3	120	400	252	--	--	15.0	
0.18	1400	23	24	7.7	120	428	245	--	--	15.0	
0.12	1300	30	24	7.1	120	411	249	--	--	15.0	
0.12	1300	27	24	7.4	110	405	252	--	--	15.5	
--	2900 T	--	24	7.2	160	434	260	5	--	--	WO Bh 1
--	1300 T	--	28	7.8	130	413	260	10	--	--	WO Bh 8
<0.01	7400	140	34	6.7	110	820	411	--	--	16.0	WO Bh 28
0.02	7200	130	33	6.4	110	837	431	--	--	17.0	
0.07	7100	130	33	6.7	110	740	430	--	--	17.0	
<0.01	6700	130	33	6.5	110	615	418	--	--	17.0	
0.05	6800	130	34	6.9	110	827	449	--	--	17.0	
0.08	6200	130	33	6.6	110	840	529	25	0.997	16.5	
0.16	3500	180	33	6.8	110	815	452	--	--	17.5	
0.27	4700	100	33	6.7	71	445	263	45	0.996	19.0	WO Bh 29
0.03	9200	180	33	6.6	130	1080	588	--	--	16.5	WO Bh 31
0.11	6900	140	36	6.7	110	774	432	--	0.997	16.5	
<0.01	12000	100	35	6.6	58	241	138	--	--	15.0	WO Bh 34
0.02	12000	91	35	6.3	61	219	161	--	--	16.5	
0.11	5300	100	36	6.7	58	207	152	--	--	17.0	
<0.01	13000	110	35	6.4	58	216	114	--	--	17.0	
0.03	13000	110	35	6.6	63	225	149	--	--	16.5	
0.01	16000	120	35	6.3	61	220	129	23	0.997	17.0	
0.05	13000	110	35	6.7	58	225	126	--	--	16.5	

Well number (Locality)	Aquifer	Date sampled	Sodium, dis- solved (mg/L)	Potas- sium, dis- solved (mg/L)	Calcium, dis- solved (mg/L)	Magne- sium, dis- solved (mg/L)	Chlo- ride, dis- solved (mg/L)	Fluo- ride, dis- solved (mg/L)	Bromide, dis- solved (mg/L)	Sulfate, dis- solved (mg/L)	Alkalinity, total lab or field (F) value (mg/L as $CaCO_3$)
WO Bh 35	**Ocean City**	09-05-68	--	--	--	--	82	--	--	0.1	78
(66th St., O.C.)			(Analysis by Booth, Garret, & Blair Inc.)								
WO Bh 41	**Ocean City**	06-20-69	36	--	11	12	28	--	--	<1.0	138
(42nd St., O.C.)			(Analysis by Hungerford & Terry Inc.)								
WO Bh 81	**Ocean City**	06-16-71	44	11	15	13	59	0.2	--	8.0	112 F
(42nd St., O.C.)		05-24-89	52	7.7	12	11	96	0.2	0.44	<1.0	109
WO Bh 84	**Beaverdam**	04-18-73	30	8.1	17	11	39	0.3	--	6.0	108 F
		04-08-86	29	9.1	18	11	36	<0.1	--	12	83
(44th St., O.C.)		08-27-86	29	8.7	17	11	40	0.1	--	13	110
		08-24-87	35	8.5	17	10	38	0.1	--	5.5	119 F
		09-07-88	32	9.1	17	11	38	0.1	--	9.5	113
		09-21-89	30	11	17	10	36	0.1	--	<1.0	104
WO Bh 85	**Pocomoke**	04-20-73	41	14	16	13	46	0.5	--	5.0	136
		04-08-86	38	11	17	14	43	<0.1	--	5.4	137
(44th St., O.C.)		08-27-86	39	14	17	14	46	0.1	--	3.4	137
		08-24-87	39	12	15	14	45	0.2	--	5.1	130 F
		09-07-88	40	9.0	15	15	45	0.1	--	4.6	132
		09-21-89	38	11	15	13	41	0.2	--	<1.0	130
WO Bh 89	**Manokin**	09-15-86	230	16	25	37	440	0.2	--	3.6	172 F
(44th St., O.C.)		04-19-89	320	14	25	40	520	0.2	1.7	15	209
		04-16-90	260	16	26	37	460	0.2	--	1.2	204 F
WO Bh 90 28th St., O.C.)	**Choptank**	05-25-89	1900	52	62	90	2900	0.3	10	210	475
WO Bh 91 (51st St., O.C.)	**Manokin**	07-26-89	170	14	14	17	250	0.2	0.93	<1.0	176
WO Bh 92 (100th St., O.C.)	**Manokin**	07-27-89	30	22	30	9.1	24	0.1	0.06	<1.0	171
WO Bh 93 (61st St., O.C.)	**Manokin**	07-26-89	130	9.4	24	9.8	200	0.2	0.92	<1.0	128
WO Bh 94 (100th St., O.C.)	**Ocean City**	07-27-89	43	11	33	3.6	76	0.1	0.28	1.0	102
WO Bh 95 (61st St., O.C.)	**Ocean City**	07-26-89	61	7.7	16	9.2	88	0.1	0.29	<1.0	99
WO Bh 96 (51st St., O.C.)	**Ocean City**	07-26-89	69	8.5	12	11	83	0.2	0.40	<1.0	137
WO Bh 97 (28th St., O.C.)	**Manokin**	07-26-90	40	10	17	10	66	0.2	0.23	<1.0	108 F
WO Bh 98 (28th St., O.C.)	**Ocean City**	07-25-90	22	12	39	15	29	0.2	0.09	<1.0	185 F
WO Ce 21 (Near Libertytown)	**Pocomoke**	12-20-71	22	5.6	--	--	14	0.2	--	--	105 F
WO Ce 26 (Near Libertytown)	**Pocomoke**	12-20-71	18	2.1	--	--	21	0.2	--	--	67 F
WO Cg 5 (Philadelphia and Somerset Aves., O.C.)	**Pocomoke**	01-04-52	39	9.2	18	8.3	16	0.2	--	0.8	--
WO Cg 32	**Ocean City**	09-03-85	36	11	33	11	40	0.2	--	0.5	168
(S. Division St.,		04-08-86	36	9.5	33	11	37	0.2	--	6.2	172
O.C.)		08-24-87	36	8.6	34	12	34	0.2	--	1.3	169
		09-07-88	36	8.8	33	12	34	0.2	--	0.9	169
		09-21-89	36	8.2	33	11	38	0.2	--	<1.0	166
WO Cg 35 (Near Lewis Corner)	**Manokin**	12-20-71	23	8.7	--	--	7.5	0.2	--	--	164 F

Phos- phorus dissolved (mg/L as P)	Iron, dis- solved (µg/L)	Manga- nese, dis- solved (µg/L)	Silica, dis- solved (mg/L as SiO_2)	pH whole water field	Hard- ness (total) (mg/L) as $CaCO_3$)	Spe- cific conduct- ance (µS/cm)	Solids, residue measured (mg/L)	Color Pt-Co units	Density (g/cm^3 at 20°C)	Tem- pera- ture, degrees Celsius	Well number
--	12000 T	350	--	6.3	72	--	203	--	--	--	WO Bh 35
--	4300 T	30	29	6.7	76	240		5	--	--	WO Bh 41
--	1000 T	120 T	30	--	91	407	248	35	--	--	WO Bh 81
0.29	4600	91	29	6.7	75	535	291	45	<0.990	18.0	
--	11000 T	120 T	33	7.9	88	338	--	--	--	--	WO Bh 84
0.26	6400	75	36	6.6	90	350	228	--	--	15.5	
0.21	6300	78	35	6.9	88	365	212	--	--	16.0	
0.19	6100	80	37	6.7	84	332	214	--	--	16.0	
0.20	6100	80	36	7.0	88	356	210	--	--	16.0	
0.23	5900	78	35	6.9	84	351	198	--	--	16.0	
--	19000 T	270 T	6.6	8.0	94	412	--	--	--	--	WO Bh 85
0.16	4200	74	33	6.5	100	430	235	--	--	16.0	
0.16	4500	87	33	6.8	100	410	222	--	--	16.5	
0.08	4400	85	33	6.6	95	363	230	--	--	16.5	
0.23	4500	92	33	6.5	99	401	235	--	--	17.5	
0.21	4600	88	32	6.8	91	396	212	--	--	16.5	
0.01	7800	120	35	6.7	210	1500	1140	--	--	17.5	WO Bh 89
0.16	7000	130	27	6.8	230	1950	1100	--	0.999	17.0	
<0.01	8700	130	29	7.0	220	1680	972	--	--	17.0	
0.03	60	20	37	7.7	530	10000	5480	15	1.000	16.5	WO Bh 90
0.13	7600	75	28	6.8	100	1080	602	100	0.997	17.0	WO Bh 91
0.18	1500	33	24	7.2	110	378	258	20	0.998	16.5	WO Bh 92
0.01	13000	130	25	6.6	100	897	490	25	0.998	17.5	WO Bh 93
0.15	6300	67	29	6.7	97	404	277	22	0.998	17.0	WO Bh 94
<0.01	17000	280	29	6.5	78	485	267	25	0.997	17.0	WO Bh 95
0.31	7100	78	32	6.6	75	491	297	110	0.998	16.5	WO Bh 96
0.01	7200	160	30	6.9	84	426	225	68	0.998	17.2	WO Bh 97
0.09	1900	43	28	7.4	160	402	238	27	0.999	16.8	WO Bh 98
--	13000	70 T	34	7.0	76	262	166	--	--	15.0	WO Ce 21
--	12000	90 T	45	7.2	57	212	148	--	--	14.0	WO Ce 26
--	13000 T	--	32	7.3	79	325	214	28	--	15.5	WO Cg 5
0.07	550	82	26	7.4	130	468	260	--	--	16.0	WO Cg 32
0.09	1400	82	25	6.6	130	450	253	--	--	16.5	
0.08	1600	87	26	7.1	130	336	242	--	--	17.0	
0.29	2400	94	27	7.1	130	425	254	--	--	16.5	
0.16	1900	88	26	7.3	130	434	241	--	--	17.0	
--	2000	50	29	7.9	120	353	215	--	--	14.5	WO Cg 35

Well number (Locality)	Aquifer	Date sampled	Sodium, dis- solved (mg/L)	Potas- sium, dis- solved (mg/L)	Calcium, dis- solved (mg/L)	Magne- sium, dis- solved (mg/L)	Chlo- ride, dis- solved (mg/L)	Fluo- ride, dis- solved (mg/L)	Bromide, dis- solved (mg/L)	Sulfate, dis- solved (mg/L)	Alkalinity, total lab or field (F) value (mg/L as $CaCO_3$)
WO Cg 69	**Ocean City**	09-09-85	34	15	32	12	19	<0.1	--	0.4	195
(West Ocean City)		04-10-86	36	11	32	12	17	<0.1	--	3.8	200
		08-26-86	34	12	33	13	18	0.1	--	1.1	195
WO Cg 75	**Manokin**	09-03-85	65	9.0	9.5	8.5	78	0.2	--	2.5	106
		04-08-86	64	7.8	10	8.6	69	0.2	--	5.9	109
(S. Division St., O.C.)		08-27-86	64	7.2	9.5	8.6	78	0.2	--	8.4	106
WO Dd 10	**Manokin**	05-27-52	110	6.4	16	5.6	52	0.1	--	2.5	242 F
(Snow Hill)											
WO De 36	**Manokin**	09-11-75	29	3.7	36	5.1	9.3	0.3	--	1.8	172 F
(Newark)		09-12-85	29	4.3	39	5.8	8.2	0.1	--	0.4	181
WO Df 3	**Pocomoke**	10-05-67	25	3.8	32	9.5	12	0.2	--	0.2	159 F
(Sinepuxent Neck)											
WO Dg 10	**Manokin**	12-20-71	49	10	--	--	21	0.1	--	0.4	212 F
(Assateague Is.)											
WO Dg 21	**Manokin**	10-09-75	44	8.9	39	13	26	0.1	--	2.0	223 F
		09-06-85	44	12	33	13	25	<0.1	--	0.5	214
(Assateague Is.)		04-11-86	45	9.6	37	13	24	0.1	--	2.7	225
		08-25-86	42	9.0	37	13	24	0.1	--	0.7	225
		08-27-87	45	8.5	38	13	23	0.1	--	1.1	210 F
		09-07-88	49	8.9	38	14	25	0.1	--	0.6	221
		09-25-89	44	9.1	37	13	22	0.1	--	<1.0	220
WO Ed 8	**Pocomoke**	11-05-52	26	12	19	13	10	--	--	5.2	--
(Near Girdletree)											
WO Ed 46	**Pocomoke**	12-06-89	47	9.7	16	9.8	23	0.1	0.05	<1.0	162
(Near Girdletree)											
WO Ef 3	**Pocomoke**	09-10-53	160	8.0	12	4.7	47	0.4	--	0.1	--
(Assateague Is.)											
WO Fb 96	**Manokin?**	07-12-70	950	32	96	86	1,520	0.2	--	310	269
(Pocomoke City)											

Phosphorus dissolved (mg/L as P)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Silica, dissolved (mg/L as SiO_2)	pH whole water field	Hardness (total) (mg/L) as $CaCO_3$	Specific conductance (µS/cm)	Solids, residue measured (mg/L)	Color Pt-Co units	Density (g/cm^3 at 20°C)	Temperature, degrees Celsius	Well number
0.05	1000	47	21	7.1	130	445	257	--	--	15.0	WO Cg 69
0.06	1400	49	20	7.4	130	400	264	--	--	15.0	
--	1100	46	24	7.6	140	420	246	--	--	15.5	
0.30	6300	180	29	6.9	59	500	270	--	--	17.0	WO Cg 75
0.31	5500	150	29	6.4	60	460	260	--	--	17.0	
0.39	7000	170	29	6.8	59	470	260	--	--	18.0	
--	70 T	20 T	17	7.9	63	612	381	2	--	--	WO Dd 10
0.25	2600 T	110 T	30	--	110	340	219 C	14	--	15.5	WO De 36
0.12	730	91	27	7.6	120	390	227	--	--	15.0	
--	2900 T	80 T	29	7.7	120	323	205	3	--	14.0	WO Df 3
--	20	20	16	8.2	130	472	260	--	--	15.5	WO Dg 10
--	1000 T	50 T	21	--	150 T	365	--	2	--	16.0	WO Dg 21
0.14	33	41	19	8.0	140	499	285	--	--	16.0	
0.17	300	42	19	7.4	150	475	276	--	--	16.5	
0.14	30	42	20	7.9	150	480	278	--	--	17.0	
0.18	300	43	20	7.2	150	480	270	--	--	17.0	
0.17	290	48	20	7.3	150	481	282	--	--	16.5	
0.16	330	45	20	7.8	150	474	274	--	--	16.5	
--	90 T	80 T	34	7.8	100	330	220	10	--	--	WO Ed 8
0.35	200	60	27	8.0	80	370	--	--	--	14.5	WO Ed 46
--	360 T	20 T	15	8.1	49	776	491	21	--	15.5	WO Ef 3
--	--	--	11	8.0	593	5580	3300	5	--	--	WO Fb 96

Appendix C.—Chemical analyses of pore water from cores from offshore test hole 6008

[mg/L = milligrams per liter; ppt = parts per thousand; cc = core catcher sample; −1 = sample section]

Core number	Cored interval feet below sea level	Sodium mg/L	Potassium mg/L	Calcium mg/L	Magnesium mg/L	Ammonia mg/L
1-cc	68- 98	8,463	283	624	963	19
2-cc	98-128	7,793	237	543	977	15
3-1	128-158	4,608	175	525	545	12
4-cc	158-188	2,110	205	478	312	19
6-1	228-259	164	37	58	44	1
8-cc	273-304	586	40	295	142	8
9-cc	304-335	--	--	162	--	--
10-cc	335-366	353	60	527	106	3

Core number	Cored interval (feet below sea level)	Chloride mg/L	Sulfate mg/L	Alkalinity* mg/L as $CaCO_3$	pH*	Salinity* ppt
1-cc	68- 98	15,352	1,847	205	7.1	27.6
2-cc	98-128	13,927	1,913	240	7.5	25.5
3-1	128-158	8,871	709	210	7.5	15.9
4-cc	158-188	4,625	251	145	7.8	9.7
6-1	228-259	231	230	180	8.4	1.6
8-cc	273-304	1,594	100	--	7.5+	4.7
9-cc	304-335	--	--	150	8.0	1.3
10-cc	335-366	896	1,098	--	8.1	2.3

* Alkalinity, pH, and salinity values were analyzed onboard the <u>D/V Glomar Conception</u>; All other determinations were made by the U.S. Geological Survey Water Quality Laboratory, Denver, Colorado.

+ Punch in pH

(Data from F. A. Kohout, written communication, 1980)

Appendix D.—Descriptions of drill cuttings from selected test holes

Description of drill cuttings for WO Bh 91 (Ocean City at 51st St.)
(Altitude of land surface = 10 ft)

Lithology	Thickness (ft)	Depth (ft)
No sample.	20	20
Sand, medium, quartz mostly clear, some iron-stained to pale orange; trace shell light gray (N 7).	20	40
Sand, fine, some medium, silty; quartz is subrounded and clear; trace shell; trace muscovite; very light olive gray (5Y 6/1).	20	60
Sand, fine to medium, ranges up to coarse; quartz is subangular to subrounded, moderately equidimensional, feldspar bearing, trace shell; opaques present; some micas (biotite/ chlorite) very light olive gray (5Y 6/1).	20	80
Sand, fine and silty; feldspar bearing, quartz subangular to subrounded and moderately equidimensional; feldspars are blocky and subrounded; trace medium flakes of muscovite, trace shell fragments, trace opaques (probably magnetite and ilmenite); very light olive gray (5Y 6/1).	20	100
Sand, fine to medium, some silt, sample ranges up to coarse, quartz is subangular to subrounded, moderately equidimensional; feldspar bearing, subrounded, blocky relatively fresh grains; 80 percent of quartz grains are iron-stained to a pale orange; trace opaques; grayish orange (10YR 7/4) to yellowish orange (10YR 7/6).	20	120
Sand and pebbles, very coarse to very small pebble, some quartz and chert fragments from small pebble size material; quartz is iron-stained to pale orange; very coarse sand and pebbles are mixed with fine to medium, silty sand; quartz grains are subangular to subrounded; about 40 percent of quartz grains show some iron stain; overall color of sample is yellowish orange (10YR 7/6).	20	140
Sand, fine to coarse, some silt; quartz is subangular to subrounded, some quartz is well rounded; sample appears more mature than above; some bright rust-red iron-oxide cement; trace worn feldspars (pitted, chalky, easily fractured) overall color is yellowish brown (10YR 5/6).	20	160
Sand, fine to coarse, some silt; quartz is mostly subrounded to subangular, some grains moderately well rounded; all generally moderately equidimensional; yellowish brown (10YR 5/6).	20	180
Sand, fine to coarse and very coarse, quartz is mostly subrounded, some subangular and some moderately well rounded grains; feldspar bearing (chalky, pitted, easily fractured grains); some quartz grains covered with iron-oxide cement, also iron-oxide cemented aggregates of fine quartz; about 60 percent of quartz show some degree of iron stain; color of sample is moderate grayish orange (10YR 6/4).	20	200
Sand, fine to medium, silty, ranges up to coarse, quartz is subangular to subrounded, quartz is not as heavily iron-stained as above; trace of chalky weathered feldspars; yellowish brown (10YR 5/2) to grayish brown.	20	220
Sand, fine to coarse and very coarse, silty matrix, quartz is subangular to subrounded, some iron-oxide cemented grains; moderate brown (10YR 5/4).	20	240
Sand, medium to granular, some small pebble fragments; quartz grains iron-stained to pale orange; some bright orange, iron-oxide cemented aggregates of fine quartz; quartz is mostly subangular to subrounded, with some well rounded grains; yellowish orange (10YR 6/6).	10	250
Sand, medium to granular and very small pebble; quartz is iron-stained to pale orange; subangular to subrounded grains, some moderately well rounded granules; trace opaques, moderate yellowish brown (10YR 5/4).	20	270
Sand, fine to medium, silty, ranges to coarse; glauconite bearing; mica bearing; quartz is clear angular to subangular with less subrounded grains than above; some quartz grains in sample are iron-stained, pale yellowish gray.	10	280
Sand, fine to medium, silty; generally same as above; color is pale yellowish gray.	10	290
Sand and very small pebbles; some chert and quartz pebble fragments were from small pebbles; quartz is iron-stained to pale orange; trace of glauconite (probably from higher in hole); quartz is subangular to subrounded; some well rounded; yellowish orange to yellowish brown (10YR 6/4 to 5/4).	10	300
Sand, fine to medium, ranges up to coarse; quartz is iron-stained to pale yellowish orange; quartz is subangular to subrounded; some moderately well rounded grains; trace opaques; grayish orange (10YR 7/4) to moderate grayish orange (10YR 7/5).	10	310
Sand, fine and silty, ranges up to medium, quartz is subangular to subrounded; about 50 percent of quartz grains show some iron staining; trace glauconite; trace feldspar; opaques about 0.5 percent of sample (probably mostly magnetite and ilmenite); moderate grayish orange (10YR 6/4).	10	320
Sand, fine and very fine, silty; quartz is subangular to subrounded, some moderately well rounded grains; about 50 percent of quartz grains are iron-stained, the remainder are clear, gray; overall color of sample is moderate grayish orange (10YR 6/4).	20	340

Appendix D.—Continued

WO Bh 91 - Continued

Lithology	Thickness (ft)	Depth (ft)
Sand, fine, silty, ranges up to medium; quartz grains mostly subangular to subrounded, some moderately well rounded; trace glauconite; trace muscovite; about 50 percent of quartz grains iron-stained; opaques (probably magnetite and ilmenite) relatively common; moderate grayish orange (10YR 6/4).	20	360
Sand, very fine to fine and silty; quartz is subangular to subrounded, mica bearing; about 30 percent of quartz grains show some iron staining (less than above); medium grayish brown (10YR 6/3).	10	370
Sand, fine, silty, quartz is subangular to subrounded; about 20 percent of quartz shows iron staining; remainder is clear; mica bearing; trace glauconite; medium grayish brown (10YR 6/3).	10	380
Sand, fine, very silty, mica bearing; glauconite bearing; minor amounts of shell fragments; quartz is subangular to subrounded; about 20 percent of quartz shows iron staining; remainder is clear; medium grayish brown (10YR 6/3).	10	390
Sand, fine, silty, micaceous; glauconite bearing; about 40 percent of quartz shows slight iron staining; moderate grayish brown (10YR 6/3).	10	400
Sand, very fine, silty, micaceous; glauconite bearing; slight amount of iron stain on about 20 percent of quartz grains; trace carbonized wood fragments; medium olive brownish gray (5Y 5/1).	20	420
Sand, as above, color medium olive brownish gray (5Y 5/1) to medium light gray (N 6).	10	430
Sand, very fine, silty, micaceous; glauconite bearing; slight amount of iron stain on about 20 percent of quartz grains; medium olive brownish gray (5Y 5/1) to medium light gray (N 6).	20	450
Sand, fine to medium, ranges up to coarse, silty matrix; quartz is subangular to subrounded, some moderately well rounded; about 50 percent of quartz shows some iron stain; trace of carbonized wood fragments; trace of muscovite and feldspars; trace of glauconite in fine sand fraction; moderate yellowish brown (10YR 5/4).	10	460
Sand, fine to medium, silty, ranges up to coarse; quartz is subangular to subrounded, some moderately well rounded; about 40 percent of quartz is iron-stained to a pale orange; trace glauconite; medium grayish orange (10YR 6/4).	10	470
Sand, fine, silty, ranges up to medium; trace muscovite and glauconite; medium yellowish brown (10YR 5/2).	10	480
Sand, fine, silty; quartz is mostly subangular, some subrounded; about 80 percent of quartz is iron-stained to a pale orange, remainder is light medium gray; trace of glauconite and gypsum?; medium yellowish gray brown.	10	490
Sand, fine, silty; quartz is subangular to subrounded, some moderately well rounded; about 30 percent of quartz is iron-stained to a pale orange; trace of glauconite and minor gypsum (?), mica bearing, medium grayish orange (10YR 6/4) and light brownish gray (5YR 6/1).	20	510
Sand, fine, silty, angular to subangular; some subrounded grains; about 25 percent of quartz is iron-stained; mica bearing; glauconite bearing; trace gypsum(?); moderate yellowish brown (10YR 5/4).	30	540
Silt, clayey, some fine sand, micaceous, glauconite bearing, medium olive gray (5Y 5/1).	20	560
Silt, clayey, some fine sand, trace shell, trace mica, medium olive gray (5Y 5/1).	20	580
Silt, very clayey, trace shell, light olive gray (5Y 6/1).	40	620
Silt, very clayey, trace shell, light brownish gray (5YR 6/1) to light gray (N 7).	20	640
Silt, very clayey, glauconitic, light olive gray (5Y 6/1).	60	700
Silt, fine sand, clayey, glauconitic, small shell fragments common, light olive gray (5Y 6/1).	12	712
Sand, fine to medium, quartz is mostly subrounded, glauconite bearing, shell fragments common, dark yellowish brown (10YR 4/2).	8	720
Sand, fine, silty, trace shell, quartz is subrounded to subangular; glauconitic; dark yellowish brown (10YR 4/2) to olive gray (5Y 4/1).	10	730
Sand, fine, silty, glauconite bearing, shell fragments common, olive gray (5Y 4/1).	5	735
Silt, fine sand, very clayey, glauconitic, medium light gray (N 5).	10	745
Sand, fine, silty, clayey, glauconite bearing, shell fragments common, medium light gray (N 5).	15	760
Sand, fine to medium, silty and clayey, glauconite bearing, shell fragments, light olive gray (5Y 6/1).	20	780

Total depth drilled = 780 feet.

Appendix D.—Continued

Description of drill cuttings for WO Bh 92 (Ocean City at 100th St.)
(Altitude of land surface = 4 ft)

Lithology	Thickness (ft)	Depth (ft)
Sand, fine to medium, minor shell fragments; traces of glauconite; opaques (magnetite?) common; quartz grains subangular to subrounded, generally iron-stained to an orange-tan; very light gray (N 7).	20	20
Sand, fine to medium, glauconite bearing; shell fragments; quartz grains subangular, subrounded, and clear; very light gray (N 7).	20	40
Sand, fine, silty, mica bearing; feldspar bearing; traces of glauconite; about 20 percent of silt size quartz grains iron-stained; yellowish gray (5Y 7/2).	20	60
Pebbles, very small to medium; and granular sand; feldspar bearing; trace shell; pebbles are light gray and white to grayish orange (10 YR 7/4); mixed with olive gray, micaceous clayey silt.	20	80
Silt, very clayey, with very fine sand; micaceous, about 50 percent of fine sand iron-stained to a pale orange; overall sample color is light olive gray (5Y 6/1); and about 5 percent small quartz pebbles and granular sand as above.	20	100
Sand, fine to medium, silty, traces of glauconite; quartz is subangular to subrounded, most of quartz is iron-stained; mixed with coarse to granular, feldspar bearing sand; sample color is yellowish gray (5Y 7/2).	20	120
Silt, very fine sand, clayey, mica bearing, rust red, iron-oxide cemented aggregates of silt and fine sand; most quartz grains show some degree of iron stain; traces of gypsum(?); minor amounts of granules and very-small-pebble size quartz; light olive brown (5Y 5/6) to medium yellowish brown (10YR 6/4).	20	140
Sand, fine, silty, clayey matrix; quartz is subangular to subrounded; most quartz shows some degree of iron stain; moderate yellowish brown (10YR 5/4).	20	160
Sand, fine to medium, silty with a clayey matrix; quartz is generally subangular to subrounded with some well rounded grains; about 60 percent of quartz shows some degree of iron staining; traces of shell; mixed with chips of light olive gray clay (5Y 5/2).	20	180
Sand, fine, silty, some medium, micaceous, about 50 percent of quartz is iron-stained; trace opaques; minor amounts of granular to small pebble size quartz sand and pebbles; medium yellowish brown (10YR 6/4).	20	200
Sand, fine to medium, some silt; mica bearing; glauconite bearing; minor gypsum; about 50 percent of quartz is iron stained; dark yellowish orange (10 YR 6/6).	10	210
Sand, fine, silty, subangular to subrounded; glauconitic, mica bearing; about 15 percent of quartz is iron-stained; light olive gray-brown (5YR 6/6).	10	220
Sand, fine, silty; glauconitic, mica bearing; about 10 percent of quartz is iron-stained; light olive gray-brown (5YR 6/6).	10	230
Sand, fine, silty; glauconitic, mica bearing; about 10 percent of quartz is iron-stained; traces of shell, mixed with and light olive gray clayey silt.	10	240
Sand, fine, silty, glauconitic, quartz is mostly clear, subrounded; about 10 percent of quartz is iron-stained; shell fragments common; light olive gray (5Y 5/2).	20	260
Sand, fine, silty, mica bearing, shell fragments common, trace carbonized wood fragments; light olive brown (5Y 5/6).	10	270
Sand, fine, silty, glauconitic; shell fragments common; medium light gray (N 6).	10	280
Sand, as above, slightly more clayey matrix than above.	20	300
Sand, fine, silty, about 40 percent of quartz is iron-stained; glauconitic; shell fragments common, dominantly light olive gray (5Y 6/1) to medium yellowish brown (10 YR 5/4).	20	320
Sand, fine, silty, glauconitic, about 50 percent of quartz shows some iron stain; traces of carbonized wood fragments; shell fragments common; medium yellowish brown (10 YR 6/4).	10	330
Sand, fine to medium, silty, about 40 to 50 percent of quartz is iron stained; traces of glauconite; traces of carbonized wood fragments; mica bearing; traces shell fragments dark yellowish orange (10 YR 6/6).	20	350
Sand as above, glauconite bearing.	10	360
Sand, fine to medium, about 20 percent of quartz is iron-stained; glauconite bearing; traces of shell; pale yellowish brown (10 YR 6/2).	10	370
Sand, fine, silty, some medium; glauconite bearing; pale yellowish brown (10 YR 6/2).	10	380
Silt, clayey, some fine sand; glauconite bearing; shell fragments; light olive gray to pale yellowish brown.	10	390
Sand, fine to medium, silty, with some small gravel; quartz generally clear; minor amounts of shell; pale yellowish brown to medium light gray.	10	400
Sand, fine to very coarse; ranges up to granular; medium yellowish brown (10 YR 6/4).	10	410
Sand, fine, silty, some medium to coarse; mica bearing; glauconite bearing; medium yellowish brown (10 YR 6/4).	10	420

WO Bh 92 - Continued

Lithology	Thickness (ft)	Depth (ft)
Sand, fine to coarse, silty, mostly clear; trace shell material; medium yellowish brown (10 YR 6/4).	10	430
Sand, fine to coarse, trace shell fragments; medium light gray (N 6) to very pale yellowish brown (10 YR 7/2).	10	440
Sand as above; with traces of glauconite.	10	450
Sand, fine to medium; silty; ranges up to granular; mica bearing; medium yellowish brown (10 YR 6/4).	10	460
Sand, fine silty and very coarse; some granular sand; medium yellowish brown.	10	470
Sand, fine to medium, some silt, ranges up to coarse; some quartz heavily iron-stained; traces glauconite; grayish orange (10 YR 7/4) to dark yellowish orange (10 YR 6/6), trace shell.	10	480
Sand, fine to silty; mica bearing; trace glauconite; trace shell fragments; very pale yellowish brown (10 YR 6/2).	10	490
Sand, fine, silty mica bearing, trace shell; very pale yellowish brown (10 YR 6/2).	10	500
Silt, fine sand, clayey; trace shell, trace opaques; light olive gray (5Y 5/2).	10	510
Sand, fine, silty; trace of glauconite and shell; very pale yellowish brown (10 YR 6/2).	20	530
Silt, clayey, light brownish gray; mixed with sand as above.	10	540
Silt, clayey, fine sand, mica bearing; glauconitic; traces of shell; very light olive brown (5Y 5/1).	10	550
Silt, clayey, with fine sand; glauconitic, medium olive gray (5Y 5/1).	10	560
Sand, fine to medium; silty; about 40 percent of quartz is iron stained mixed with very light olive brown, glauconitic, clayey silt.	10	570
Silt, clayey, glauconitic, light olive brown.	10	580
Silt, very clayey; fine sand, glauconitic, shelly, mica bearing; light olive brown (5Y 5/2).	20	600
Sand, fine, silty, shell fragments, mica bearing; glauconitic; light olive brown.	10	610
Sand, fine to medium; silty, shell fragments; glauconitic; light olive brown.	10	620
Silt, very clayey, very glauconitic, mica bearing; shell fragments; light olive gray (5Y 5/2).	10	630
Sand, fine to medium, silty, glauconitic, shelly, mica bearing; medium olive gray (5Y 4/2).	10	640
Sand, as above, slightly more silty.	10	650
Silt, fine sand, clayey, as above.	10	660
Silt, clayey, as above.	30	690
Sand, fine, silty, clear subangular quartz sand; glauconitic; light olive gray (5Y 5/2).	10	700
No samples	54	754

Total depth drilled = 754 feet

Appendix D.—Continued

Description of drill cuttings for WO Bh 93 (Ocean City at 61st St.)
(Altitude of land surface = 4 ft)

Lithology	Thickness (ft)	Depth (ft)
Sand, fine, opaques common (probably magnetite and ilmenite), quartz is generally clear, subangular to subrounded; light gray.	20	20
Sand, fine to medium, silty, ranges up to very coarse; feldspar bearing, quartz is generally subangular to subrounded; medium light gray.	20	40
Sand, fine to medium, ranges up to coarse; majority of quartz grains show some degree of iron staining; quartz is subrounded to moderately well rounded; traces shell fragments; opaques common; medium yellowish gray (5Y 7/2).	20	60
Sand, coarse to medium; feldspar bearing; quartz is generally clear, subangular to subrounded; traces of shell fragments; yellowish gray (5Y 8/1).	20	80
Sand, as above, mixed with very coarse to granular sand and very small quartz pebbles; about 10 percent of quartz is iron-stained to grayish orange; yellowish gray (5Y 8/1).	20	100
Sand, medium to very coarse, some fine, feldspar bearing; quartz grains are mostly subangular to subrounded; about 10 percent of quartz shows iron staining; yellowish gray with a yellowish orange cast (10 YR 7/4).	20	120
Sand, fine to very coarse; silty, feldspar bearing; about 60 percent of quartz is iron-stained; pale yellowish brown (10YR 6/2) to dark yellowish orange (10YR 6/6).	20	140
Sand, fine to medium, feldspathic, quartz is generally clear, subangular; about 20 percent of quartz shows a slight degree of iron stain; light yellowish brown (10 YR 7/2).	20	160
Sand, medium to granular with some small pebbles; feldspar bearing; heavily iron-stained quartz; minor trace of glauconite; dark yellowish orange (10 YR 6/6) to moderate yellowish brown (10 YR 5/4).	20	180
Sand, fine to medium; feldspar bearing; moderate yellowish brown (10 YR 5/4) mixed with silty, clayey, glauconite bearing, pale yellowish brown (10 YR 6/2).	20	200
Sand, medium to coarse, minor feldspar; quartz generally subangular to subrounded; majority of quartz is iron-stained, pale yellowish brown (10YR 6/2) to grayish orange (10 YR 7/4).	20	220
Sand, as above, but more silty.	20	240
Sand, fine to coarse, silty, minor feldspar; heavily iron-stained; medium yellowish brown (10 YR 5/4).	10	250
Sand, fine to coarse, quartz is heavily iron-stained; feldspar bearing; trace lignitic wood fragments; medium yellowish brown (10 Yr 6/4).	10	260
Sand, fine to coarse, silty, as above; mixed with moderate yellowish brown clayey silt (10 YR 5/4) to dark yellowish brown (10 Yr 4/2).	10	270
Sand, fine, silty, some medium; quartz is subangular to subrounded; generally iron-stained; mica bearing, medium yellowish brown (10 YR 5/4).	10	280
Sand, fine, silty, quartz is subrounded to moderately well rounded; minor shell fragments; medium olive gray (5Y 5/1).	10	290
Sand, fine to medium; silty, quartz is subangular to subrounded; about 60 percent of quartz is heavily iron-stained; minor shell fragments; dark yellowish orange (10 Yr 6/6) to moderate yellowish brown (10 YR 5/4).	10	300
Sand, fine, silty, trace shell, trace glauconite(?); medium olive gray (5Y 5/1).	10	310
Sand, fine, silty, clayey matrix; trace shell; medium yellowish orange (10 YR 5/2).	10	320
Silt, very fine to fine sand; trace shell, mica bearing, trace glauconite(?); light olive gray (5Y 6/1).	10	330
Sand, fine to medium; silty, minor feldspar; quartz is heavily iron-stained; dark yellowish orange (10YR 6/6).	10	340
Sand, as above, with chips of pale grayish orange (10 YR 5/4) clayey silt, quartz is subangular to subrounded, heavily iron-stained; dark yellowish orange.	10	350
Sand, fine, silty; about 50 percent of quartz is iron-stained; trace opaques; dark yellowish orange (10 YR 6/6).	10	360
Sand, fine to coarse; silty; feldspar bearing; about 50 percent of quartz grains show iron staining; quartz ranges from subangular to moderately well rounded; dark yellowish orange (10YR 6/6) to grayish orange (10YR 7/4).	20	380
Sand, fine to coarse; quartz ranges from subangular to moderately well rounded; about 50 percent of quartz is iron-stained; dark yellowish orange (10YR 6/6) to grayish orange (10YR 7/4).	10	390
Sand, fine to very coarse; coarser sand fraction is dominantly moderate to well rounded; finer fraction is dominantly subangular to subrounded; trace of weathered feldspars; metamorphic rock fragments, and opaques; dark yellowish orange (10YR 6/6).	10	400
Silt, clayey, and fine sandy, mica bearing; traces of carbonized wood fragments; dark yellowish orange to very pale yellowish orange brown (10YR 7/2).	10	410
Sand, fine to coarse, silty, coarse fraction dominantly subrounded to moderately well rounded; finer fraction subangular to subrounded grains; about 50 percent of quartz is iron-stained; dark yellowish orange (10YR 6/6).	10	420

Appendix D.—Continued

WO Bh 93

Lithology	Thickness (ft)	Depth (ft)
Sand, fine to coarse; quartz generally subangular to subrounded; with some well rounded grains; about 30 percent of quartz shows some iron stain with some grains heavily coated with dark-orange limonite cement.	10	430
Sand, fine to coarse and very coarse; minor feldspar; about 50 percent of grains iron-stained; quartz is subangular to subrounded with some moderately well rounded grains; grayish orange (10YR 7/4).	10	440
Sand, fine to coarse; quartz generally subangular to subrounded; about 20 percent of quartz shows some iron stain; trace opaques; mica bearing; grayish-orange (10YR 7/4).	10	450
Sand, as above.	10	460
Sand, fine to coarse, subangular to subrounded, about 50 percent of quartz shows some iron stain; grayish orange (10YR 7/4).	20	480
Sand, fine, silty; quartz is mostly subangular; about 50 percent of quartz shows some iron stain, grayish-orange (10YR 7/4).	20	500
Silt, fine to medium sand, silty and clayey; mica bearing; minor gypsum(?); quartz mostly clear; yellowish gray (5Y 7/2).	20	520
Silt, fine sand; about 40 percent of quartz is iron-stained; angular to subangular grains; minor gypsum(?); yellowish gray (5Y 7/2).	20	540
Silt, clayey, some fine sand, glauconite bearing; light olive gray (5Y 5/2).	20	560
Silt, clayey, with fine to medium sand, glauconite bearing; olive gray (5Y 3/2).	20	580
Silt, very clayey, mixed with some fine to coarse sand; minor shell; medium gray (N5).	20	600
Silt, very clayey; glauconitic; trace shell; medium light gray.	40	640
Silt, very clayey, glauconitic, minor shell; medium gray (N5) to light olive gray.	20	660
Sand, fine, silty, shell fragments common; glauconite bearing; light gray (N6).	20	680
Silt, very clayey; shell fragments; glauconite bearing; olive gray (5Y 4/1).	30	710
No recovery.	20	730
Sand, fine, silty and clayey, shell fragments common; glauconitic; medium light gray (N6).	10	740

Total depth drilled 740 feet.

Appendix D.—Continued

Description of drill cuttings for WO-Dg 20 (Assateague Island)
(Altitude of land surface = 6 ft)

Field description modified from J. M. Weigle
(written communication, 1975)

Lithology	Thickness (ft)	Depth (ft)
Sand, fine, medium gray; clayey zone (less than 1 ft thick), near bottom of interval.	20	20
Sand, fine.	1	21
Silt, medium to dark gray.	13	34
Peat, chocolate brown.	1	35
Silt and clay; minor shell.	5	40
Silt, medium to dark gray, some tannish brown; shell fragments.	20	60
Silt, similar to above but stiffer; interbedded with fine to medium, gritty sand, and shells.	21	81
Sand, very coarse to fine gravel, gray, shell fragments common.	19	100
Sand, fine to coarse, interbedded with dark gray silt.	27	127
Sand, coarse, some small pebble.	13	140
Sand, coarse to very coarse, greenish gray to brownish gray, shell fragments.	20	160
Sand, shell, as above, but with some fine to coarse sand.	17	177
Sand, very fine, silt matrix, medium to light greenish gray.	3	180
Silt, soft plastic, tannish gray and light gray.	30	210
Silt, medium to dark gray, some fine sand; many shell fragments.	10	220
Silt, medium to dark greenish gray; and sand, fine to gritty, many shell fragments.	20	240
Silt, as above.	60	300
Sand, shell fragments.	20	320
Sand, fine to medium, gray; shell fragments.	20	340
Silt, clayey, light greenish gray to greenish brown; interbedded with fine sand and shells.	20	360
Silt, as above; shells more common; some gritty fine sand.	20	380
Sand, fine to coarse.	20	400
Sand, as above, shell fragments common.	30	430
Clay; silty, medium gray, a little sandy.	10	440
(Clay thickened drilling mud and brought up very coarse, granular sand; driller thinks sand came from 380-420).		
Sand, coarse, with some fine sand; a few very fine pebbles; shell fragments.	20	460
Sand, medium to coarse; a little clay, soft; medium gray.	20	480
Sand, fine to medium; a little medium gray, clayey silt. Cemented layers every foot or so from 485 to 500 ft.	20	500
Sand, fine to very fine, gray; some cemented layers.	20	520
Sand, fine to very fine, and clayey silt, medium dark gray.	30	550
Silt, clayey, with some sand; medium to dark gray; some shells.	45	595
Slow drilling; hard layer (1 3/4 hr for 1 ft).	1	596
Sand, from "feel" of rig; no cuttings recovered	4	600
No cuttings recovered; drilled easy.	40	640

Description of cores from offshore test hole 6008.

Latitude 38°24'21" N 74°53'83" W. Water depth 68 ft. (20.7 m)

Core number	Field description* (core catcher sample (-cc) or section (-1))	Cored interval (feet below mean sea level)	Cored interval recovered (feet)
1-cc	Clay, sandy, dark gray.	68-98	17.2
2-cc	Clay, silty, dark gray siderite.	98-128	3
3-1	Clay, silty, dark gray.	128-158	8.7
4-cc	Clay, silty, blue-green.	158-188	8.6
	Drilled interval	188-197	
5-cc	Clay, shelly, sticky, gray; with loose sand.	197-228	10.5
6-1	Sand, shelly and clayey, blue-gray; mixed with drilling mud.	228-259	4
7	No recovery	259-273	0
8-cc	Clay, sticky, gray with loose sand.	273-304	0.7
9-cc	Clay, silty, gray-green, with loose sand above.	304-335	8
10-cc	Sand, clayey, shelly, gray.	335-366	3
	(Cores below 366 feet were loose washed sand that had been invaded by drilling fluid)		
11	Shell hash, coarse, clayey, gray.	366-397	10
12	Sand, coarse, clayey, gray-brown.	397-428	6
13	Sand, coarse and pebble gravel.	428-460	11

*Complete core descriptions unavailable
Data from Hathaway and others (1976) and F. A. Kohout (written commun., 1976)

Appendix E.—List of sources of data for wells and test holes not included in Appendix A

[M.G.S. = Maryland Geological Survey]

Dorchester County:

Well number	
DO Af 3	M.G.S. files
DO Bg 59	M.G.S. files
DO Dg 1	Rasmussen and Slaughter (1957) and M.G.S. files
DO Dh 8	Rasmussen and Slaughter (1957)
DO Dh 9	Rasmussen and Slaughter (1957)
DO Dh 11	Hansen (1981) and M.G.S. files

Somerset County:

Well number	
SO Ae 20	Werkheiser (1990) and M.G.S. files
SO Bb 1	Rasmussen and Slaughter (1955) and M.G.S. files
SO Bd 39	Werkheiser (1990) and M.G.S. files
SO Bd 42	Werkheiser (1990) and M.G.S. files
SO Be 46	Rasmussen and Slaughter (1955) and M.G.S. files
SO Be 48	Rasmussen and Slaughter (1955) and M.G.S. files
SO Bg 3	Hansen (1981), Werkheiser (1990) and M.G.S. files
SO Cd 41	Werkheiser (1990) and M.G.S. files
SO Ce 57	Werkheiser (1990) and M.G.S. files
SO Ce 95	Hansen and Wilson (1990) and M.G.S. files
SO Dd 46	Werkheiser (1990) and M.G.S. files
SO De 27	Werkheiser (1990) and M.G.S. files
SO De 28	Hansen (1981), Werkheiser (1990) and M.G.S. files
SO Ec 49	Werkheiser (1990) and M.G.S. files

Wicomico County:

Well number	
WI Bd 45	Rasmussen and Slaughter (1955) and M.G.S. files
WI Cc 33	M.G.S. files
WI Cd 63	M.G.S. files
WI Cd 69	M.G.S. files
WI Cd 65	Hansen (1981) and M.G.S. files
WI Ce 231	M.G.S. files
WI Cf 61	Rasmussen and Slaughter (1955)
WI Cf 185	Hansen (1981) and M.G.S. files
WI Cg 35	Rasmussen and Slaughter (1955)
WI Cg 37	Anderson (1948), Rasmussen and Slaughter (1955), Hansen and Doyle (1982)
WI Cg 52	M.G.S. files
WI Cg 53	Hansen (1981) and M.G.S. files
WI Ch 36	Hansen (1981) and M.G.S. files
WI Dd 23	M.G.S. files

Delaware:

Well number	
Nc 43-2	Gamma logs and map locations for the wells and testholes located in Delaware are published in Andres (1986). The Delaware Geological Survey may be contacted for more information regarding these wells and test holes.
Ni 31-7	
Of 13-1	
Of 34-2	
Oi 24-6	
Oi 35-27	
Pc 35-14	
Pc 45-3	
Pf 24-3	
Pg 53-14	
Ph 41-19	
Pj 11-1	
Qd 52-2	
Qh 54-4	
Qj 32-14	
Qj 41-4	
Rh 32-7	
Ri 15-1	
Rj 22-5	

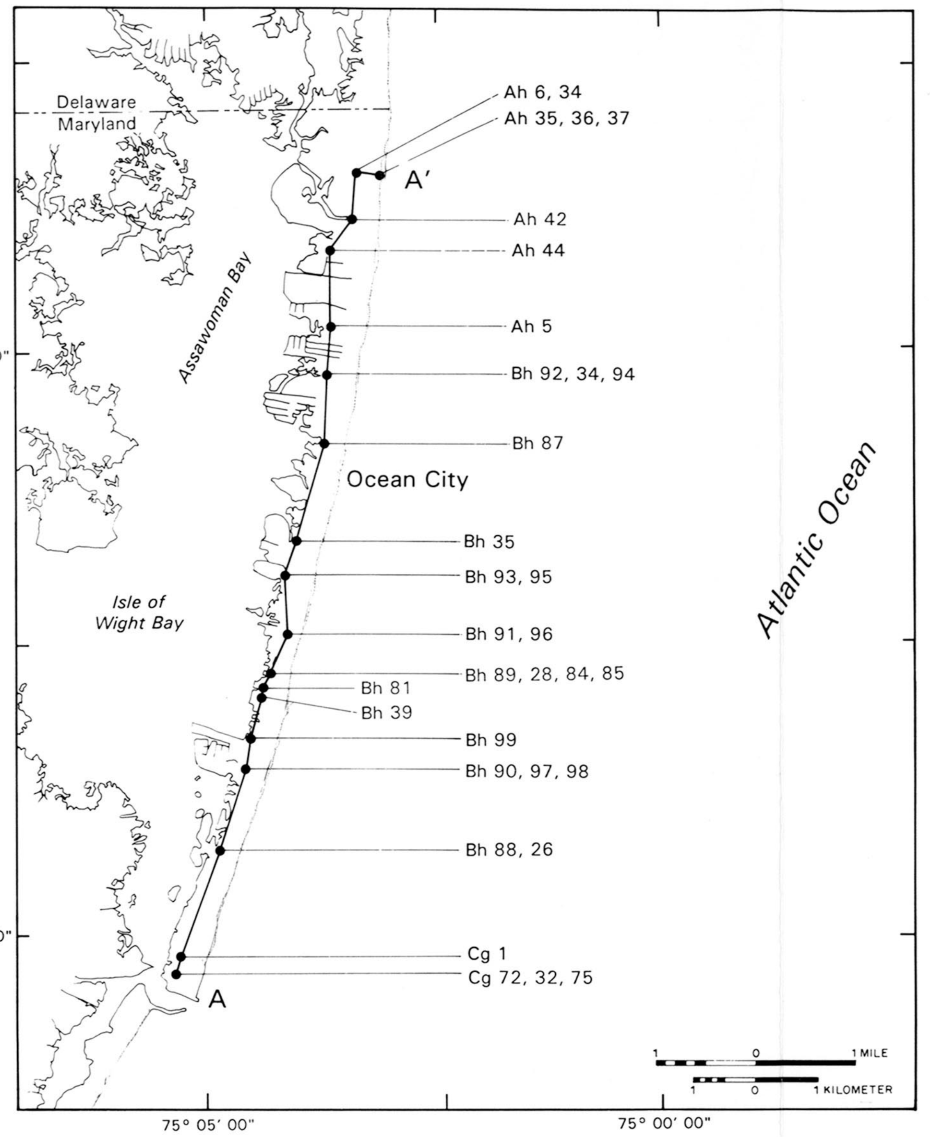
Virginia:

Well number	
66 M-23	M.G.S. files
66 M-2	M.G.S. files

Formation (or informal unit)	Series	System
Sinepuxent	Pleistocene	Quaternary
Beaverdam Sand	? Pliocene	Tertiary
Pocomoke beds	?	
Ocean City beds	Upper Miocene	
Manokin		
St. Marys	? Upper to Middle Miocene	
Choptank and Calvert undifferentiated	? Middle to Lower Miocene	

(Holocene units not differentiated)

Hydrogeology by John M. Wilson (1993)



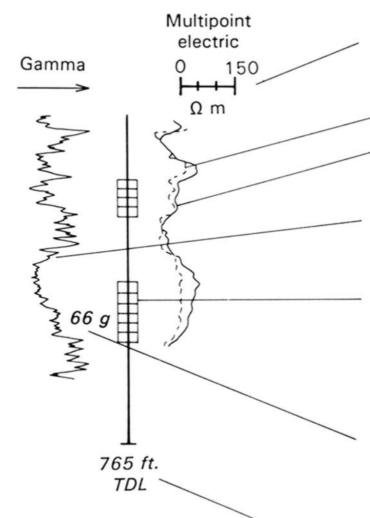
EXPLANATION

——?—— Line of correlation, queried where uncertain.

〰?〰 Line of correlation showing major unconformity, queried where uncertain.

WO Bh 90
28th Street
Alt. = 6 ft.

Well number of logged bore hole, location, and altitude in feet.



Multipoint electric log scale in ohm-meters.

16-inch normal curve, dashed.
64-inch normal curve, solid.

Gamma log, radiation increases to right.

Screened zone in well at or near site.

Chloride concentration in milligrams per liter. All values from 1989 unless noted otherwise. Letter designates well in adjacent list in which chloride concentration was measured.

Total depth logged in feet below land surface.

Note: In the northern part of Ocean City, the Ocean City aquifer is comprised of discontinuous, fine to medium grained sands in a predominantly clayey silt section.

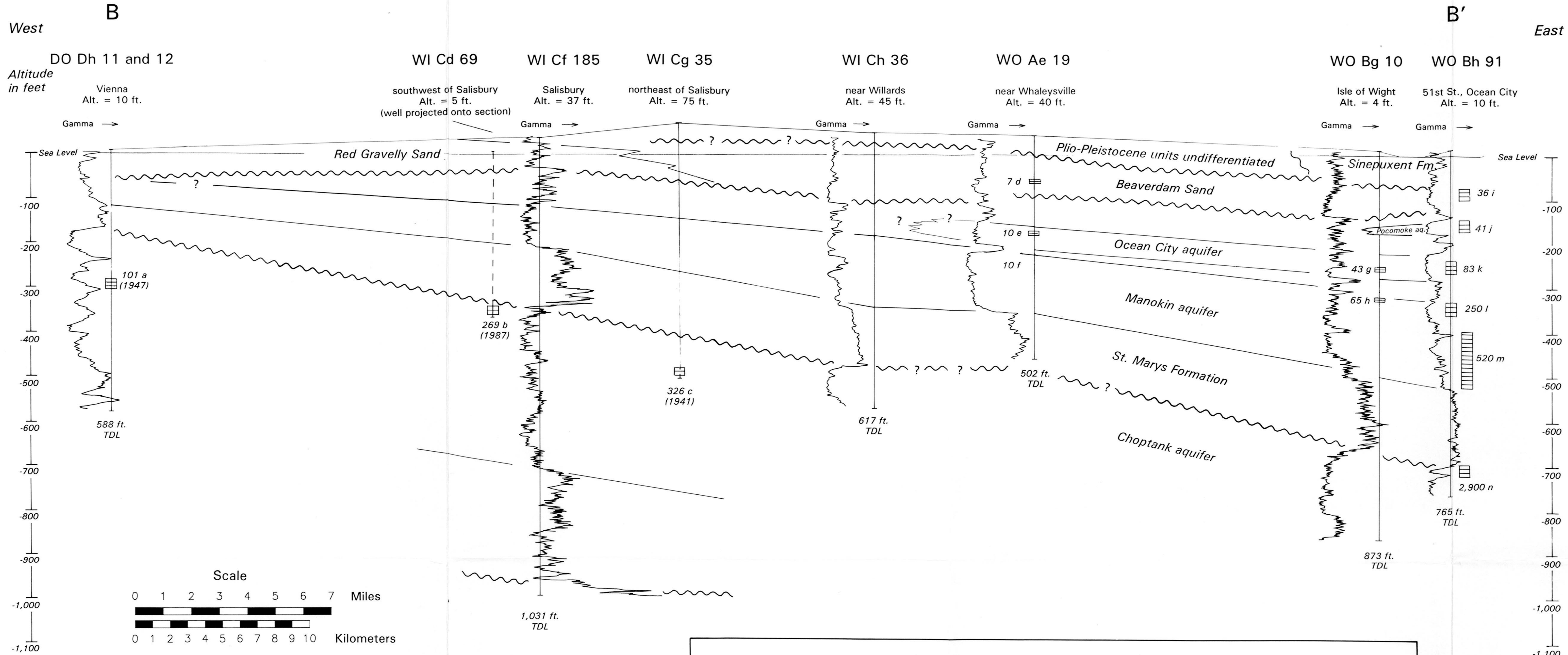
List of wells with chloride determinations

a WO Cg 32
b WO Cg 75
c WO Cg 1
d WO Bh 26
e WO Bh 88
f WO Bh 98
g WO Bh 97
h WO Bh 90
i WO Bh 99
j WO Bh 39
k WO Bh 81
m WO Bh 84
n WO Bh 85
p WO Bh 28
q WO Bh 89 (all screens)
r WO Bh 89 (basal screen)
s WO Bh 96
t WO Bh 91
u WO Bh 95
v WO Bh 95
w WO Bh 35
x WO Bh 94
y WO Bh 34
z WO Bh 92
A WO Ah 5
B WO Ah 42
C WO Ah 6 (temporary screen)
D WO Ah 6 (temporary screen)
E WO Ah 34
F WO Ah 6 (temporary screen)
G WO Ah 36
H WO Ah 37
J WO Ah 35
K WO Ah 35

Scale

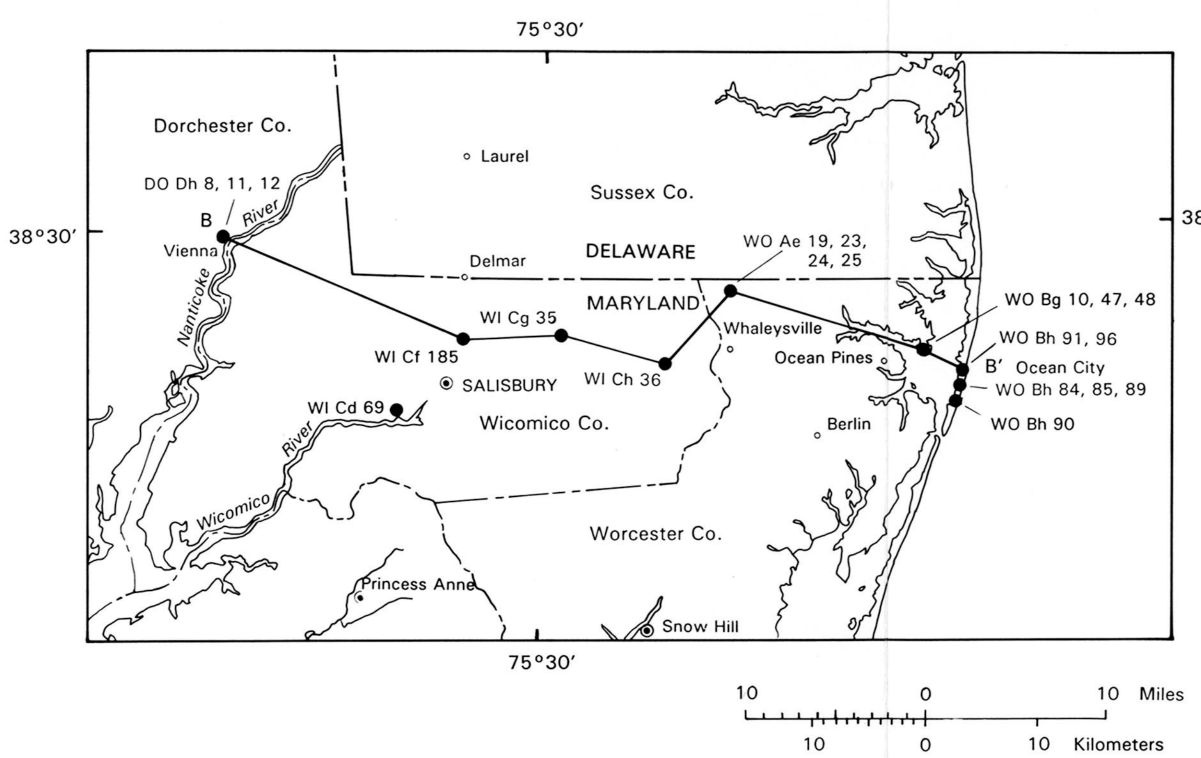
0 1/4 1/2 3/4 1 Mile

0 1/4 1/2 3/4 1 Kilometer



Formation (or informal unit)	Series	System
Sinepuxent	Pleistocene	Quaternary
Beaverdam Sand	Pliocene	Tertiary
Pocomoke beds	Pliocene	
Ocean City beds	Upper Miocene	
Manokin	Upper Miocene	
St. Marys	Upper to Middle Miocene	
Choptank and Calvert undifferentiated	Middle to Lower Miocene	

(Holocene units not differentiated)
Hydrogeology by John M. Wilson (1993)
Modified from Hansen (1981, pl. 1)



EXPLANATION

— ? — Line of correlation, queried where uncertain.

Line of correlation showing major unconformity, queried where uncertain.

Facies change.

WO Bh 91
51st St., Ocean City
Alt. = 10 ft. — Well number of logged bore hole, location, and altitude in feet.

Screened zone in well at or near site.

83 k — Chloride concentration in milligrams per liter. All values from 1989 unless noted otherwise.

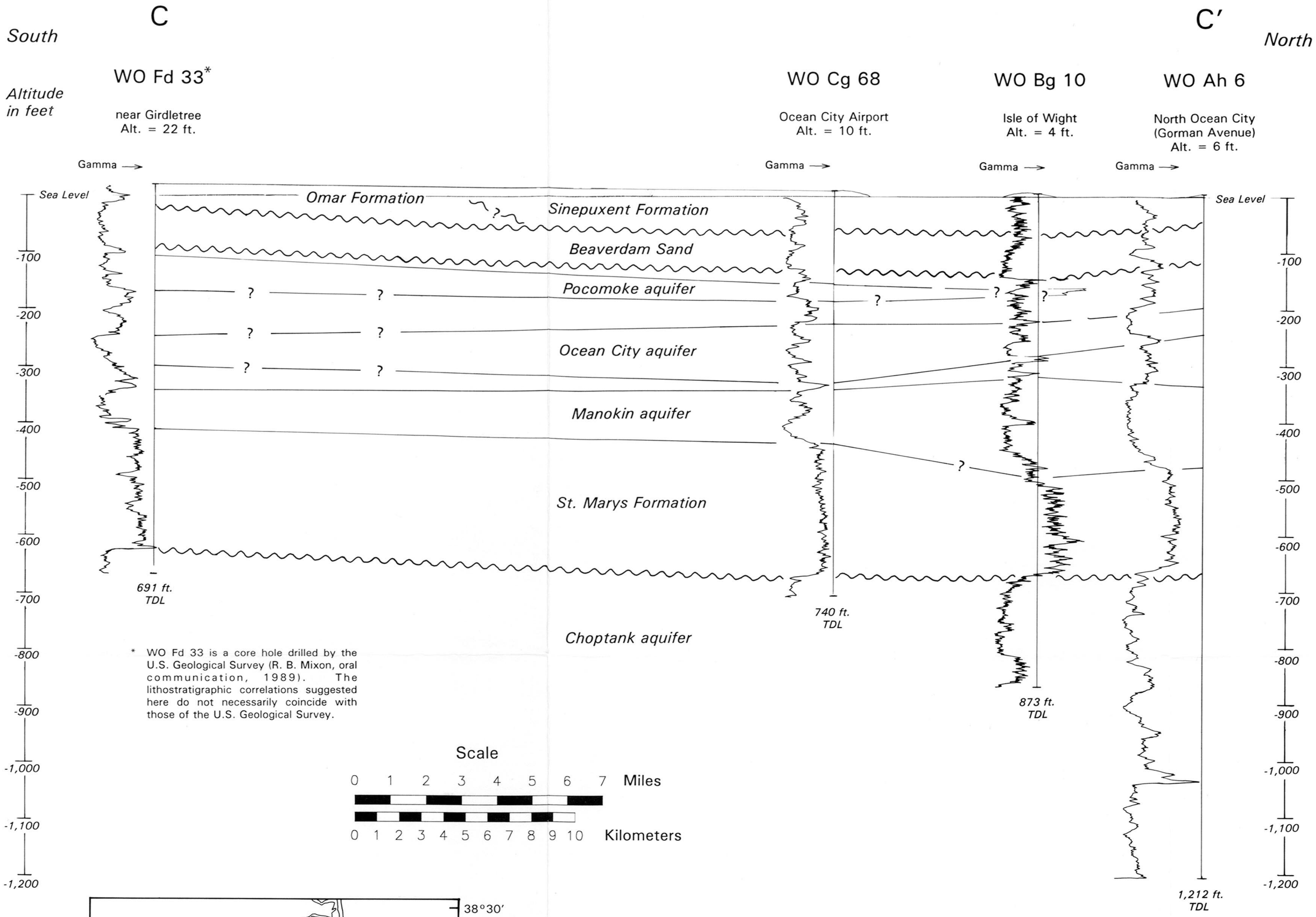
Letter designates well in following list in which chloride concentration was measured: *a* DO Dh 8; *b* WI Cd 69; *c* WI Cg 35; *d* WO Ae 25; *e* WO Ae 24; *f* WO Ae 23; *g* WO Bg 47; *h* WO Bg 48; *i* WO Bh 84; *j* WO Bh 85; *k* WO Bh 96; *l* WO Bh 91; *m* WO Bh 89; *n* WO Bh 90.

765 ft. TDL — Total depth logged in feet below land surface.

Well site projected onto section.

Fm. Formation

aq. aquifer

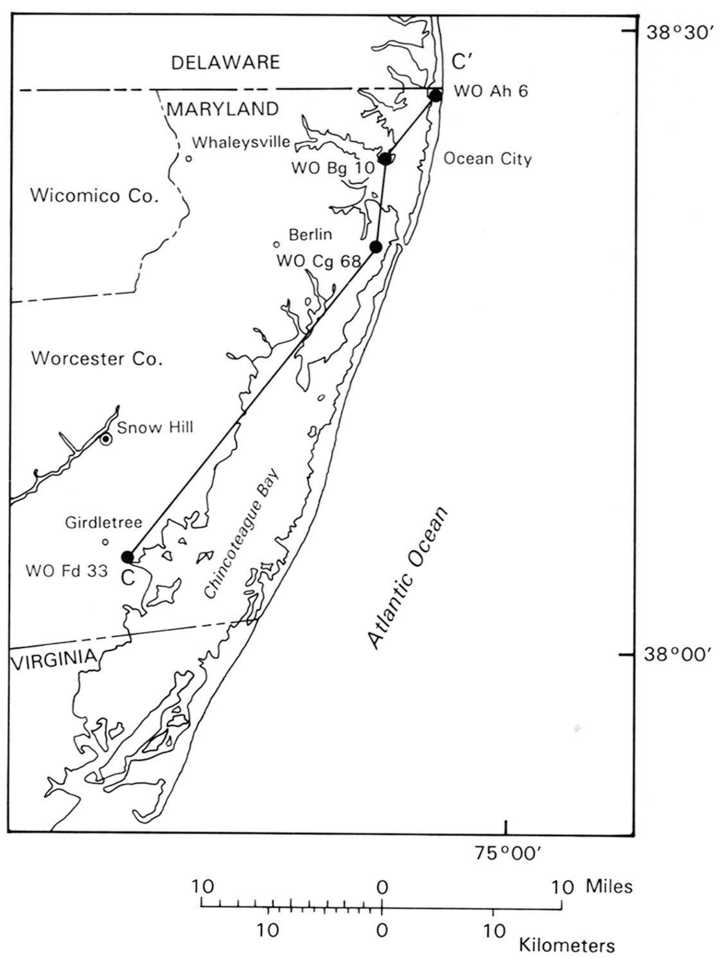


* WO Fd 33 is a core hole drilled by the U.S. Geological Survey (R. B. Mixon, oral communication, 1989). The lithostratigraphic correlations suggested here do not necessarily coincide with those of the U.S. Geological Survey.

Formation (or informal unit)	Series	System
Sinepuxent	Pleistocene	Quaternary
Beaverdam Sand	? Pliocene	Tertiary
Pocomoke beds		
Ocean City beds	? Upper Miocene	
Manokin		
St. Marys	? Upper to Middle Miocene	
Choptank and Calvert undifferentiated	? Middle to Lower Miocene	

(Holocene units not differentiated)

Hydrogeology by John M. Wilson (1993)



EXPLANATION

——— ? ——— Line of correlation, queried where uncertain.

Line of correlation showing major unconformity, queried where uncertain.

WO Bg 10
Isle of Wight
Alt. = 4 ft.

Well number, location and altitude in feet.

873 ft.
TDL

Total depth logged in feet below land surface.