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Simulation of Future Water-Level Conditions and Saltwater Encroachment in the Ocean City-Manokin Aquifer System at Ocean City, Maryland, Using Water-Use Projections Through 2025

by

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Prepared in cooperation with
The Town of Ocean City

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CONTENTS

	Page
Key results	1
Introduction	2
Purpose and scope	2
Location of the study area	2
Previous studies	2
Methods of investigation	2
Acknowledgements	3
Ground-water flow and saltwater distribution	4
Hydrogeology	4
Columbia aquifer	4
Upper confining bed	4
Pocomoke aquifer	4
Upper part of lower confining bed	5
Ocean City aquifer	5
Basal part of lower confining bed	5
Manokin aquifer	5
St. Mary's Formation	5
Choptank aquifer	5
Continuation of sediments offshore of Ocean City	6
Ground-water pumpage and water levels	6
Saltwater distribution	6
Ground-water withdrawals, water levels, and chloride concentrations through 2005	7
15th Street well field	7
44th Street well field	8
Gorman Avenue well field	8
Model simulations of ground-water flow and chloride distribution	9
Description of the Ocean City ground-water flow model	9
Boundary conditions	9
Hydrologic properties	10
Ground-water recharge and evapotranspiration	10
Model calibration	10
Simulated water levels for 1995, 2000, and 2005	11
Description of the solute-transport model	11
Conceptual framework for the SUTRA model	12
Boundary conditions	12
Simulation of the offshore brackish-water plume	13
Simulated chloride concentrations for historical pumpage to 2005	14
15th Street well field	14
44th Street well field	14
Gorman Avenue well field	15
Results of model simulations through 2025	15
15th Street well field	15
44th Street well field	16
Gorman Avenue well field	16
Summary and conclusions	17
References	18

CONTENTS—CONTINUED

Page

Appendixes

A. Selected well and test-hole records, Worcester County, Maryland 19
B. Chloride data used for the calibration of the cross-sectional models from 1980 to 2005 20
C. Descriptions of drill cuttings from well WO Bh 102 21
D. Water-quality analysis from well WO Bh 102 22

ILLUSTRATIONS

Figure **Page**

1. Map showing location of study area in the mid-Atlantic Coastal Plain and the general line of section for the three cross-sectional solute-transport models through Ocean City, Maryland 23
2. Map showing locations of key wells and test holes used for hydrogeologic control 24
3. Generalized hydrogeologic section along south-north direction showing the water plants, production well fields, and aquifers in Ocean City, Maryland 25
4. Map showing locations of test holes, production and observation wells, and well fields in Ocean City, Maryland 26

5-7. Bar graph showing:
   5. Total annual ground-water withdrawals from the Ocean City aquifer at the South Division Street, 15th Street, and 44th Street well fields and the Manokin aquifer at the Gorman Avenue well field 27
   6. Average daily withdrawal rates during the month of maximum withdrawals from the Ocean City aquifer at the South Division Street, 15th Street, and 44th Street well fields and from the Manokin aquifer at the Gorman Avenue well field 28
   7. Maximum, average, and minimum monthly withdrawal rates from the Ocean City aquifer at the 15th Street well field........ 29

8. Water levels measured in observation well WO Bh 98 (Ocean City aquifer, 15th Street well field) 29
9. Bar graph showing maximum, average, and minimum monthly withdrawal rates from the Ocean City aquifer at the 44th Street well field 30
10. Water levels measured in observation well WO Bh 31 (Ocean City aquifer, 44th Street well field) 30
11. Bar graphs showing maximum, average, and minimum monthly withdrawal rates from the Manokin aquifer at the Gorman Avenue well field 31
12. Water levels measured in observation well WO Ah 6 (Manokin aquifer observation well, Gorman Avenue well field) 31
13. Map showing model area and grid used for the ground-water flow model 32
14. Cross section through Ocean City showing hydrogeologic framework and simulated layers........ 33

ILLUSTRATIONS—CONTINUED

Figure **Page**

15-19. Map showing the simulated potentiometric surface of the:
15. Columbia aquifer depicting the 1900 steady-state flow conditions 34
16. Pocomoke aquifer depicting the 1900 steady-state flow conditions 34
17. Ocean City aquifer depicting the 1900 steady-state flow conditions 35
18. Manokin aquifer depicting the 1900 steady-state flow conditions 35
19. Choptank-Calvert aquifer (undifferentiated) depicting the 1900 steady-state flow conditions 36

20-26. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the:
20. Manokin aquifer observation well WO Cg 72 at the 15th Street well field 37
21. Ocean City aquifer observation well WO Bh 98 at the 15th Street well field 38
22. Ocean City aquifer observation well WO Bh 31 at the 44th Street well field 39
23. Pocomoke aquifer observation well WO Bh 85 at the 44th Street well field 39
24. Manokin aquifer observation well WO Bh 89 at the 44th Street well field 40
25. Manokin aquifer observation well WO Ah 37 at the Gorman Avenue well field 41
26. Manokin aquifer observation well WO Ah 6 at the Gorman Avenue well field... 42

27-34. Map showing the simulated potentiometric surface of the:
27. Ocean City aquifer, using the August 1995 withdrawal 43
28. Manokin aquifer, using the August 1995 withdrawal 43
29. Ocean City aquifer, using the August 2000 withdrawal 44
30. Manokin aquifer, using the August 2000 withdrawal 44
31. Ocean City aquifer, using the August 2005 withdrawal 45
32. Manokin aquifer, using the August 2005 withdrawal 45
33. Ocean City aquifer, using the December 2005 withdrawal.. 46
34. Manokin aquifer, using the December 2005 withdrawal 46

35. Model area and grid used in the cross-sectional model 47

36-38. Simulated 1900 prepumping chloride concentrations in observation wells at the:
36. 15th Street cross-sectional model 48
37. 44th Street cross-sectional model.. 49
38. Gorman Avenue cross-sectional model 50

39-44. Measured, simulated, and estimated chloride concentrations in the:
39. Ocean City aquifer production well B (WO Bh 27) using the15th Street cross-sectional model.. 51
40. Ocean City aquifer production well C (WO Bh 30) using the 15th Street cross-sectional model.. 51
41. Ocean City aquifer production well A (WO Bh 28) using the 44th Street cross-sectional model 52
42. Ocean City aquifer production well B (WO Bh 29) using the 44th Street cross-sectional model.. 53

ILLUSTRATIONS—CONTINUED

Figure **Page**

39-44. Measured, simulated, and estimated chloride concentrations in the:

(Cont'd) 43. Ocean City aquifer production well C (WO Bh 41) using the 44th Street cross-sectional model 53

44. Manokin aquifer production well A (WO Ah 34) using the Gorman Avenue cross-sectional model 54

45. Bar graph showing actual (2000-2005) and estimated (2006-2025) average daily withdrawal rates during the month of maximum withdrawals from the 15th Street, 44th Street, and Gorman Avenue well fields in Ocean City 55

46-49. Map showing the:

46. Simulated August 2025 potentiometric surface of the Ocean City aquifer 56

47. Simulated August 2025 potentiometric surface of the Manokin aquifer 56

48. Simulated December 2025 potentiometric surface of the Ocean City aquifer 57

49. Simulated December 2025 potentiometric surface of the Manokin aquifer 57

50. Simulated water levels in the Ocean City aquifer observation well WO Bh 98 at the 15th Street well field using the projected maximum withdrawal of 6 million gallons per day in 2025 58

51. Simulated 2005 and 2025 chloride concentrations at the 15th Street cross-sectional model and in the Ocean City aquifer production wells WO Bh 27 and WO Bh 30 59

52. Simulated water levels in the Ocean City aquifer observation well WO Bh 31 at the 44th Street well field using the projected maximum withdrawal of 4 million gallons per day in 2025 60

53. Simulated 2005 and 2025 chloride concentrations at the 44th Street cross-sectional model and in the Ocean City aquifer production wells WO Bh 28, WO Bh 29, and WO Bh 41 61

54. Simulated water levels in the Manokin aquifer observation well (WO Ah 6) at the Gorman Avenue well field using the projected maximum withdrawal of 8 million gallons per day in 2025 62

55. Simulated 2005 and 2025 chloride concentrations at the Gorman Avenue cross-sectional model and in the Manokin aquifer production wells WO Ah 33, WO Ah 34, and WO Ah 38 63

TABLES

Table **Page**

1. Generalized stratigraphic column for Ocean City, Maryland 64

2. Ocean City production well designations, aquifer pumped, well design capacity, and 2005 well capacity 65

3. Annual withdrawals from the South Division Street, 15th Street, 44th Street, and Gorman Avenue well fields, 1969-2005 66

4. Average daily rates during the month of maximum withdrawals from well fields in Ocean City, 1969- 2005 67

TABLES—CONTINUED

Table		Page
5.	Average daily rates of the annual average pumpage from ground-water users other than the Town of Ocean City for 1995 and 2005	68
6.	Minimum, average, and maximum rates of monthly withdrawals from all Ocean City well fields, 1970-2005	69
7.	Aquifer and confining-bed properties used in the flow model	70
8.	Comparison of simulated and measured water levels using least squares analysis for the entire simulation time for each aquifer	71
9.	Deepest water levels during summer pumpages at the Ocean City well fields from 1995 to 2025 in the Manokin aquifer at Gorman Avenue and in the Ocean City aquifer at the South Division Street, 15th Street, and 44th Street well fields	72
10.	Aquifer and fluid properties used in the cross-sectional models	73
11.	Measured, simulated, and estimated chloride concentrations in production wells at the three Ocean City well fields for 1980-2005	74
12.	Comparison of the earliest measured chloride concentrations with simulated 1900 flow conditions	75
13.	Maximum, average, and minimum daily rates of withdrawal from the 15th Street, 44th Street, and Gorman Avenue well fields used in the 2005-2025 flow model simulations	76
14.	Simulated summer and winter water levels in wells in the 15th Street, 44th Street, and Gorman Avenue well fields in 2005 and 2025	77
15.	Simulated chloride concentrations in production wells at the 15th Street, 44th Street, and Gorman Avenue well fields in 2005 and 2025	77

PLATE

Plate		Page
1.	Hydrogeologic section A – A'	End of report

ABBREVIATIONS AND ACRONYMS USED IN THIS REPORT

bls	below land surface
ft	feet
ft/day	feet per day
ft/mi	feet per mile
GAP	Ground-water Appropriation Permit
gpm	gallons per minute
gpm/ft	gallons per minute per foot
GWSI	Ground Water Site Inventory
hrs	hours
in.	inch
in./yr	inch per year
K	hydraulic conductivity
kg/m^3	kilograms per meter cubed
kg/ms	kilograms per meter per second
lsd	land surface datum
m	meter
m^2	meter squared
m/s^2	meter per second squared
m^2/s	meter squared per second
MCL	Maximum Contaminant Level
MDE	Maryland Department of the Environment
mgal	million gallons
mgd	million gallons per day
MGS	Maryland Geological Survey
mgy	million gallons per year
mg/L	milligrams per liter
mi	miles
NWIS	National Water Information System
pCi/L	picocuries per liter
Pt-Co	platinum-cobalt
RMS	root mean square
SMCL	Secondary Maximum Contaminant Level
SUTRA	Saturated and Unsaturated Transport model
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
ybp	years before present
°C	degrees Celsius
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter

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KEY RESULTS

A three-dimensional ground-water flow model (Visual MODFLOW) and three two-dimensional solute-transport models (SUTRA, version 2D3D.1) were constructed to represent the aquifer system beneath Ocean City, Maryland. The models were populated with hydrogeologic information and historical water-level and chloride data collected through 2005. The flow model and cross-sectional models were used to simulate water levels and chloride concentrations at Ocean City's well fields through 2025, using Ocean City's future development plan of maximum pumpages of 6 million gallons per day from the 15th Street well field, 4 million gallons per day from the 44th Street well field, and 8 million gallons per day from the Gorman Avenue well field by 2025. The key results of this study are as follows:

- At the 15th Street well field, the simulated water level in the Ocean City aquifer in August 2025 was about 115 feet below sea level. The model indicates about 75 feet of remaining available drawdown (the height of the water column above the 80-percent management level). Simulated chloride concentrations in the 15th Street wells range from about 55 to 60 milligrams per liter in 2025, representing an average simulated increase of about 5 milligrams per liter over 2005 levels.
- At the 44th Street well field, the simulated water level in August, 2025 in the Ocean City aquifer was about 81 feet below sea level (about 50 feet deeper than in 2005), with about 119 feet of available drawdown. The 2025 simulated average chloride concentrations ranged from about 150 to 250 milligrams per liter, compared with about 125 to 215 milligrams per liter chloride in 2005.
- At the Gorman Avenue well field, the deepest average water level in the Manokin aquifer simulated in August, 2025 was about 34 feet below sea level (about 15 feet deeper than the 2005 simulated water level), with approximately 306 feet of available drawdown. The highest simulated average chloride concentration in the Gorman Avenue well field was about 150 milligrams per liter in 2025, compared with about 130 milligrams per liter in 2005.
- An exploratory well (WO Bh 102), drilled in 2004 to a depth of 580 feet at the corner of 14th Street and St. Louis Avenue, indicated that the ground water at the basal part of the Manokin aquifer tested 889 milligrams per liter chloride. Brackish water at the basal part of the Manokin aquifer encroached the farthest inland beneath Ocean City at 44th Street, less at 15th Street, and the least at Gorman Avenue.
- The model suggests that the water levels at the 15th Street well field, which prior to 2003 had returned to above sea level during the winter, only recover to about 80 feet below sea level in winter, 2025. Winter 2025 water levels at the 44th Street and Gorman Avenue well fields (about 23 feet and 8 feet below sea level, respectively) also do not recover to above sea level, but the water levels are closer to sea level than at the 15th Street well field.

INTRODUCTION

The Town of Ocean City, Maryland relies on two confined, hydraulically connected aquifers (the Ocean City and Manokin aquifers) for its water supply. The year-round residential population is projected to grow from 8,200 in 2005 to 14,400 in 2025, and the peak summer seasonal population is projected to grow from 347,000 to more than 381,000 in 2025 (S. Mogilnicki, Whitman, Requardt and Associates, written commun., 2005). Increased pumpage from the Ocean City and Manokin aquifers will affect future water levels in these aquifers, and the increased pumpage could increase the amount of brackish water being drawn into the aquifers. In 1988, the Maryland Geological Survey (MGS) developed a ground-water flow and solute-transport model to determine the extent of salt-water intrusion into these aquifers, and to predict water levels and chloride concentrations through 2010 (Achmad and Wilson, 1993). The present study updates the 1993 report and extends the analysis through 2025.

PURPOSE AND SCOPE

This report describes and presents the results of a ground-water flow model and three solute-transport models of the ground-water system in Ocean City, Maryland. The models were used to simulate water levels and chloride concentrations as pumpage rates increase from 10.53 million gallons per day (mgd) in 2005 to 18.0 mgd in 2025. The ground-water flow and solute-transport models of the Ocean City and Manokin aquifer system described in Achmad and Wilson (1993) were recompiled and updated for this study.

LOCATION OF THE STUDY AREA

The Town of Ocean City, located about 100 miles (mi) east-southeast of Baltimore, occupies the southern eight miles of Fenwick Island, located on the Atlantic Coast in Worcester County, Maryland (fig. 1). The study area covers an area 55 miles wide and 115 miles long to accommodate the regional framework for the ground-water flow and cross-sectional solute transport models.

PREVIOUS STUDIES

The freshwater aquifers at Ocean City have been described by Rasmussen and Slaughter (1955), Weigle (1974), and Achmad and Wilson (1993). Weigle (1974) separated the Ocean City aquifer from the Manokin aquifer, quantified the hydraulic conductivities, and mapped water-level contours in the Columbia, Pocomoke, Ocean City, and Manokin aquifers. Achmad and Wilson (1993) documented that the water levels fluctuate below sea level during the summer season, and recover to above sea level during the winter and spring. The model simulation reported in Achmad and Wilson (1993) indicated that the high seasonal pumpage of public supply wells of 12.1 mgd at Ocean City for the 1991 ground-water withdrawal did not exceed the 1.6 inch per year (in./yr) average net ground-water recharge to the deeper aquifers.

Based on weekend population growth projections for Ocean City (270,154 in 1995 to 323,329 in 2020), the projected upper limit of the maximum day demand in 2020 is 18.0 mgd (Whitman, Requardt and Associates, 1997). The projection was based on the upper limit of consumption of 55.4 gallons per capita per day of 1986 to 1995 among the 13 census tracts along Fenwick Island.

METHODS OF INVESTIGATION

Hydrogeologic and pumpage data collected through 2005 from the Columbia, Pocomoke, Ocean City, and Manokin aquifers in Ocean City and the surrounding area were incorporated into a three-dimensional ground-water flow model using Visual MODFLOW (Guiger and Franz, 2000). Visual MODFLOW, which includes a pre- and post-processor, is based on the U. S. Geological Survey (USGS) MODFLOW-96 (Harbaugh and McDonald, 1996). Visual MODFLOW was used to simulate water levels through 2025. Cross-sectional two-dimensional solute-transport models were developed through each of the three well fields using the USGS Saturated and Unsaturated Transport Model (SUTRA Version 2D3D.1) (Voss and Provost 2002; Winston and Voss, 2003). The SUTRA model was used to simulate the effects of projected maximum seasonal pumpage of 18.0 mgd on water levels and chloride concentration distribution in the aquifers beneath the Ocean City area.

The hydrogeologic framework of both the ground-water flow model and the saltwater intrusion model were derived from stratigraphic and hydrogeologic information presented in MGS Reports of Investigations No. 24 (Weigle, 1974), No. 37 (Weigle and Achmad, 1982), and No. 57 (Achmad and Wilson, 1993). A generalized stratigraphic column and cross section for the Ocean City area are shown in table 1 and plate 1, respectively. Locations of key wells for hydrogeologic control are shown in figure 2.

Data from the production and observation wells used in the model were obtained from the USGS Ground Water Site Inventory (GWSI) database. Well construction and other information for selected wells completed between 1991 and 2005 are listed in Appendix A; information for previously drilled wells is found in Achmad and Wilson (1993). The base map of the Ocean City model area was reconstructed from a Maryland State Highway Administration Digital Grid map (scale 1:24,000) overlain on a USGS Quadrangle map (scale 1:100,000). The water-use data were obtained from Maryland Department of the Environment (MDE) and USGS Water Science Center personnel (Baltimore and Dover offices). Water levels and chloride data collected by both the USGS and the Town of Ocean City were obtained from the personnel of the USGS Dover Office. Chloride concentrations of water samples from wells used in the cross-sectional model are listed in Appendix B. Drill cuttings from well WO Bh 102, a test well drilled during the project, are described in Appendix C. Water-quality data from well WO Bh 102 are presented in Appendix D.

ACKNOWLEDGEMENTS

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GROUND-WATER FLOW AND SALTWATER DISTRIBUTION

HYDROGEOLOGY

The Coastal Plain formations underlying Ocean City are part of a wedge of unconsolidated sediments that thicken southeastward from zero feet (ft) in the Baltimore-Washington area to more than 7,000 ft at the Atlantic Coast. On the lower Delmarva Peninsula, surficial deposits of Quaternary age overlie and truncate the subcropping Tertiary formations that become progressively older from east to west (Bachman and Wilson, 1984). At Ocean City the major fresh-water aquifers are sands in the Chesapeake Group (the Pocomoke, Ocean City, and Manokin aquifers) and the surficial Columbia aquifer (fig. 3). The aquifers are separated by relatively impermeable confining units that are largely comprised of clayey layers. At Ocean City, water in the Miocene sediments below the Manokin aquifer is brackish. Chloride concentrations from the St. Mary’s Formation (a confining bed that underlies the Manokin aquifer) ranged from 1,555 to 2,450 milligrams per liter (mg/L) in well WO Ah 35 (pl. 1). Chloride in the deeper Choptank aquifer (lower part of the Chesapeake Group) was 2,700 mg/L in well WO Ah 6 in northern Ocean City and 2,900 mg/L in well WO Bh 90 at 28th Street (Kantrowitz, 1969; Weigle and Achmad, 1982; Achmad and Wilson, 1993). The age, lithology, thickness, and water bearing-characteristics of the Columbia and Chesapeake Group aquifers are tabulated in table 1 and described in detail by Achmad and Wilson (1993). The general ground-water flow direction of the aquifer system is from northwest to southeast with an average gradient of 1 to 2 feet per mile (ft/mi).

Columbia Aquifer

At Ocean City, the 80- to 120-ft thick unconfined Columbia (water-table) aquifer is comprised of Plio-Pleistocene sands. The average annual precipitation at the Salisbury weather station (airport) is approximately 45 in./yr, of which about 18 in./yr becomes ground-water recharge to the water table (Achmad and Wilson, 1993). Part of the ground-water recharge flows through the Columbia aquifer and enters the Pocomoke, Ocean City, and Manokin aquifers where they subcrop beneath the Columbia aquifer west of Ocean City. Ground water from the Columbia aquifer also discharges to the Pocomoke River, coastal bays, and the Atlantic Ocean; some is lost to evapotranspiration, leaving a net ground-water recharge of about 1.6 inches (in.) (Achmad and Wilson, 1993) to the underlying Pocomoke, Ocean City, and Manokin aquifers. The water table is assumed to be a subdued reflection of the topography of the area; the highest elevation is 40 ft at Parsonsburg near Salisbury. The average elevation in the Ocean City area is only about 5 ft above sea level, making the Columbia aquifer susceptible to contamination from sea water. After 1927, water from the Columbia aquifer was no longer used for public supply at Ocean City (Weigle, 1974). Further inland in Worcester County, the Columbia aquifer is extensively used for agriculture and rural water supplies.

Upper Confining Bed

The upper confining bed is 15 to 20 ft thick (on average), and is composed of lenticular silts, clays, and fine sands that separate the Columbia aquifer from the Pocomoke aquifer (Weigle, 1974). In northeastern Worcester County, the confining bed is thin or absent, in which case the Columbia aquifer rests directly on the Pocomoke aquifer and water moves freely from one unit to the other. Where the confining bed is present, the vertical leakage is variable because the confining bed varies from fine sand to clay.

Pocomoke Aquifer

The thickness of the confined Pocomoke aquifer is variable, but usually ranges between 30 to 80 ft. It is thickest near Berlin. In northeastern Worcester County, the Pocomoke sands pinch out (Achmad and Wilson, 1993). The Pocomoke aquifer was a source for public supply at Ocean City until 1955 when it was replaced by wells pumping from the deeper Ocean City and Manokin aquifers (Weigle, 1974).

Upper Part of Lower Confining Bed

The upper part of the lower confining bed separates the Pocomoke aquifer from the Ocean City aquifer. It is a relatively homogeneous 20 to 40 ft-thick layer of clay and silt (Weigle, 1974) that increases in thickness to 100 ft in northern Ocean City. In the northeastern part of Worcester County, the middle part of the lower confining bed contains appreciable sand and is locally designated as the "Ocean City aquifer." Southwest of Ocean City, this aquifer becomes increasingly clayey, so that in the area of Snow Hill it is not differentiated from the lower confining bed (Weigle and Achmad, 1982).

Ocean City Aquifer

The Ocean City aquifer varies between 80 to 150 ft thick and is composed chiefly of fine to very coarse sand at about 200 to 350 ft below sea level underneath Ocean City. In the updip area near Willards, the aquifer pinches out. In northern Ocean City near Gorman Avenue the aquifer is about 50 ft thick and comprised of discontinuous, fine- to medium-grained sand in a predominantly clay/silt section (pl. 1). Since the early 1970's almost all public-supply wells located at the southern half of Ocean City withdrew water from the Ocean City aquifer. In much of the study area the water levels in the Ocean City and Manokin aquifers are similar, indicating that the two aquifers are hydraulically connected. The general direction of ground-water flow is from northwest to southeast with a gradient of about 1 ft/mi.

Basal Part of Lower Confining Bed

The confining bed between the Ocean City and Manokin aquifers varies in thickness and hydraulic properties. At 44th Street, the geophysical logs of well WO Bh 89 indicate that the confining bed is sandier than at either the 15th Street or Gorman Avenue well fields (pl. 1). This has facilitated the movement of water between aquifers in the vicinity of the 44th Street well field. Increased chloride concentrations from production well WO Bh 28 (screened in the Ocean City aquifer) has been attributed to upconing of brackish water from the Manokin aquifer (Achmad and Wilson, 1993). North and south of 44th Street, the clay layers in the lower confining bed more effectively isolate the Ocean City aquifer.

Manokin Aquifer

The Manokin aquifer ranges in thickness from 90 to 200 ft and consists primarily of fine to coarse gray sands, with beds of peat and lignite occurring locally in the sand. The aquifer thins out to the west-northwest and subcrops beneath the Columbia aquifer near Salisbury. At Gorman Avenue and 44th Street, the basal part of the Manokin aquifer is brackish (Achmad and Wilson, 1993). A test well (WO Bh 102) drilled in December, 2004 revealed that the brackish water (889 mg/L chloride) also occurs at the base of the Manokin aquifer at the 15th Street well field (app. D).

St. Mary's Formation

The St. Mary's Formation is a 160- to 200-ft thick, relatively impermeable clayey confining unit that underlies the Manokin aquifer and extends throughout the lower Eastern Shore. The St. Mary's Formation separates the Manokin aquifer from the underlying Choptank aquifer, which contains brackish water. The St. Mary's confining bed impedes brackish water from the underlying Choptank Formation from flowing upward into the Manokin aquifer.

Choptank Aquifer

Little information for the Choptank aquifer is available for the Ocean City area. At the Gorman Avenue well field, the aquifer occurs at about 700 ft below sea level (pl. 1), and the water is brackish (chloride concentration of 2,700 mg/L). The upper part is mostly sandy while the lower part is composed of finer sand and clay. The underlying Calvert Formation is also brackish at Ocean City and is about 630 ft thick, and is mostly a confining unit. In this report, the Choptank and Calvert Formations are undifferentiated.

Continuation of Sediments Offshore of Ocean City

Two marine acoustical profiles trending east-southeastward offshore Ocean City suggest that the Manokin aquifer, the St. Mary's Formation, and the underlying units continue seaward without structural change (Weigle and Achmad, 1982). Test hole no. 6008, located 8.75 mi offshore Ocean City, was drilled to a total depth of 396 ft below the ocean floor, in which Pleistocene and Ocean City-Manokin sediments were identified (F. A. Kohout, U.S. Geological Survey, written commun., 1976). These data aided interpretation of the acoustical profiles and further suggested the continuity of the hydrologic units offshore.

GROUND-WATER PUMPAGE AND WATER LEVELS

Ground water for public consumption in Ocean City is withdrawn from 24 public supply wells that provide water to three water-treatment plants located at 15th Street, 44th Street, and Gorman Avenue (fig. 4). The public supply wells are screened in the Ocean City and Manokin aquifers at depths from about 200 to 500 ft below sea level (fig. 3). Seven Manokin aquifer production wells are located in the northern part of Ocean City near the Gorman Avenue Water Plant. Six Ocean City aquifer production wells are located near the 44th Street Water Plant (including one well that provides water only for heating and cooling of the Ocean City Convention Center). Nine other Ocean City aquifer wells and two Manokin aquifer wells are located near the 15th Street Water Plant. The 15th Street Water Plant receives water from seven production wells near the water plant (the "15th Street well field"), and also from four wells near South Division Street (the "South Division Street well field") whose water formerly was treated at a now-closed treatment plant at South Division Street (Robert Stevens, Ocean City Water Department, written commun., 2003). Production well information is summarized in table 2.

The average daily rate during the month of maximum withdrawal from Ocean City public supply wells reached a peak of 14.07 mgd in 1995, with a total annual withdrawal of about 2.13 billion gallons (tabs. 3 and 4; figs. 5 and 6). Since then, ground-water withdrawals declined to about 1.71 billion gallons in 2005, with average daily rates during the month of maximum withdrawals declining to about 10.2 mgd (Judith Wheeler, U.S. Geological Survey, written commun., 2005).

In addition to the Town of Ocean City, there are 26 local ground-water users with ground-water appropriation permits (GAPs) within the model area. These include the towns and communities of Berlin, Snow Hill, Pocomoke City, Mystic Harbor, Pocomoke State Park; commercial operations include Purdue Farms, Holly Farms, Beatrice Foods, Ocean City Golf Course, Pine Shore Golf Course, Ocean Downs Race Track, Quality Inn, and General Motor Inn. These users were withdrawing a total of 4.87 mgd in 1995 and 7.09 mgd in 2005 (tab. 5) (Judith Wheeler, U.S. Geological Survey, written commun., 2005).

Annual ground-water withdrawals from public supply wells from the Ocean City and Manokin aquifers at Ocean City have exceeded 1 billion gallons since 1974 (tab. 3). Water use reached a maximum of 2.13 billion gallons in 1995, and has declined slightly since then. Ground-water consumption is seasonal in Ocean City, with peak demand during the summer months and lower demand in the winter months (tab. 6). The higher seasonal water demand in the summer and lower demand in the winter months allows water levels in the aquifers to recover in winter as aquifer recharge compensates for the minimum winter months' withdrawals. This annual recovery is seen at the 15th Street , 44th Street, and Gorman Avenue well fields (figs. 7 through 12). However, in 2004 and 2005 water levels recovered to only about 65 ft below land surface (bls) at 28th Street (WO Bh 98; fig. 8), suggesting that during 2004-2005 water levels in observation well WO Bh 98 were affected by the continuous pumping of an adjacent well, WO Bh 101.

SALTWATER DISTRIBUTION

The U..S. Environmental Protection Agency (USEPA) has established a Secondary Maximum Contaminant Level (SMCL) of 250 mg/L for chloride in drinking water. At that level, a salty taste is noticed by most water consumers. For the purpose of this report, fresh water is defined as water containing no more than 250 mg/L chloride; brackish water, between 250 and 9,400 mg/L chloride; and saltwater, more than 9,400 mg/L chloride (Davis, 1977; U.S. Environmental Protection Agency, 1992).

Ocean City is surrounded by salt water: to the east by the Atlantic Ocean, to the west by Assawoman Bay, and at depth beneath Ocean City where the aquifers contain brackish water. Although most ground water in the Columbia aquifer is fresh, Weigle (1974) documented chloride concentrations exceeding 250 mg/L in this aquifer between 30 and 120 ft bls in the vicinity of both Gorman Avenue and 66th Street, where the confining bed overlying the Columbia aquifer is breached and saltwater from Assawoman Bay and the Atlantic Ocean comes in contact with the water table. To prevent further contamination of the Columbia aquifer by brackish water and potential leakage to the underlying Pocomoke aquifer, ground-water withdrawals for public supply from these aquifers were discontinued after 1955 (Achmad and Wilson, 1993).

The general range of chloride concentrations at the three Ocean City well fields is as follows: 15th Street, less than 50 mg/L; 44th Street, 100 to 250 mg/L; Gorman Avenue well field, 100 to 150 mg/L. Chloride concentrations in the Ocean City production wells tend to increase with increased pumping rates, both seasonally and over the long-term. Wells in the 44th Street well field have the highest chloride concentrations of the three well fields. The chloride concentrations in well WO Bh 28 at the 44th Street well field have increased from 70 mg/L in 1975 to 215 mg/L in 1988, during which time the total annual withdrawal from the 44th Street well field was increased from 402 million gallons (mgal) to 958 mgal. Since 1996, chloride concentrations have been limited to 250 mg/L or less by limiting annual withdrawals from the 44th Street well field to less than 500 mgd annually. The decrease in withdrawals at the 44th Street well field is compensated by alternately increasing withdrawals from production wells located at the Gorman Avenue well field and the 15th Street well field (tabs. 3, 4; figs. 5, 6), both of which have lower chloride concentrations (U.S. Geological Survey, Maryland-Delaware-District of Columbia Water Science Center, written commun., 2008).

The presence of brackish water near the base of the Manokin aquifer was confirmed from water samples obtained from observation wells WO Ah 6 and Ah 37 at the Gorman Avenue well field (Weigle and Achmad, 1982). Chloride concentrations at the base of the Manokin aquifer were 300 mg/L at Gorman Avenue (WO Ah 6 [1969]), 1,030 mg/L at 44th Street (WO Bh 89 [1987]), and 889 mg/L at 15th Street (WO Bh 102 [2004]). The noticeably high chloride from WO Bh 89 was obtained from a screened depth of 495 to 510 ft, whereas a composite sample drawn from four separate screens between 388 and 510 ft was 520 mg/L in 1989, suggesting a higher chloride concentration in the deeper part of the aquifer.

Chloride concentrations in ground water at the base of the Manokin aquifer are reported as high as 1,030 mg/L (Achmad and Wilson, 1993) and are caused by upward leakage of brackish water from the St. Mary's Formation and/or from brackish-water encroachment from the offshore area of the aquifer system. Pore water squeezed from clay cores from the St. Mary's Formation (well WO Ah 35 at 139th Street) had chloride concentrations of 1,555 mg/L to 2,450 mg/L in 1975 (pl. 1). Water samples from wells WO Bh 90 (at 28th Street) and WO Ah 6 (at 137th Street), which are screened in the upper part of the underlying Choptank aquifer, had reported chloride concentrations of 2,900 mg/L and 2,700 mg/L respectively (Kantrowitz, 1969; Achmad and Wilson, 1993). Ground water above the base of the Manokin aquifer and below the semi-confined Columbia aquifer is usually fresh in the Ocean City area. Water samples from test well no. 6008 drilled 8.8 mi offshore to a total depth of 370 feet below the sea floor indicated relatively fresh to brackish ground water occurring between 228 ft (231 mg/L) and 366 ft (896 mg/L) (Wilson and Achmad, 1993). Cooper and others (1964) suggested that the high hydraulic head of discharging fresh water can keep saltwater at a far distance from the shoreline.

Ground-water Withdrawals, Water Levels, and Chloride Concentrations Through 2005

15th Street Well Field

Pumping at the 15th Street well field (including the South Division Street well field) has increased from 308 million gallons per year (mgy) in 1969 to approximately 1,071 mgy in 2005. Since 1995, new wells were drilled and larger-capacity pumps were installed at the 15th Street well field. In 1996 some of the Gorman Avenue well field withdrawals were transferred to the 15th Street well field, raising withdrawals there to 933 mgy (including the South Division Street well field) (tab. 3). Even though pumpage increased in 1996, chloride concentrations remained below 50 mg/L in well B at Worcester Avenue (WO Cg 33), well B at 14th Street (WO Bh 27), and well C at St. Louis Avenue (WO Bh 30). In 1999 and 2000, with additional production wells (well E at 3rd Street [WO Bg 58], well F at 28th Street [WO Bh 101], and well E at North Division Street [WO Cg 89]), the 15th Street well field was pumped at annual rates of about 1 billion gallons. In 2004 and 2005 the well field was again pumped at an annual total of more than 1 billion gallons. Even at these elevated withdrawals, chloride concentrations remained near 50 mg/L in 15th Street well field wells B, C, and F (WO Bh 27, Bh 30, and Bh 101) and South Division Street well field well C (WO Cg 33). Chloride concentrations in well E at North Division Street (WO Cg 89) reached 75 mg/L in 2003.

From 1999 to 2003 water levels measured in observation well WO Bh 98, at the same location as production well F (WO Bh 101*)*, were lowered to as much as 90 ft below sea level during the summer, but recovered to above sea level during the winter (fig. 8). However, in 2004 and 2005, water levels measured in observation well WO Bh 98 only recovered up to about 65 ft below sea level during the winter. Persistent year-round pumpage has the potential to accelerate the rate of chloride increase in production wells. Chloride concentrations in observation wells WO Bh 97 and Bh 98, however, are only minimally affected by increased pumpage from WO Bh 101. Chloride concentrations in the production wells at the 15th Street well field are lower than at the 44th Street and Gorman Avenue well fields (U.S. Geological Survey, written commun., 2005).

44th Street Well Field

Annual ground-water withdrawals from the Ocean City aquifer at the 44th Street well field increased from 402 mgal in 1975 to its maximum of approximately 958 mgal in 1988 (tab. 3; fig. 5). This was associated with increases in chloride from about 70 mg/L in 1975 to a maximum of 215 mg/L in 1988 in production well A (WO Bh 28). During 1975-1990 chloride concentrations reached a maximum of 110 mg/L in production well B (WO Bh 29), 130 mg/L in production well C (WO Bh 41), and 125 mg/L in production well D (WO Bh 81). The rate of chloride increase during 1975-1990 in production wells ranges from about 1.3 to 6.2 mg/L per year. The rapid increase of chloride in the 44th Street well field is due to a more permeable clay layer in the confining unit between the Manokin and Ocean City aquifers and comparatively higher chloride concentration in the upper part of the Manokin aquifer at 44th Street (Achmad and Wilson, 1993) (pl. 1) relative to the 15th Street and Gorman Avenue well fields. In 1988 withdrawal from the 44th Street well field reached a maximum of 958 mgal; since then, withdrawals decreased to as low as 168 mgal in 2004 and 179 mgal in 2005. During 1990-2005 chloride concentrations decreased in production wells A (WO Bh 28) and D (WO Bh 81). Decreases in chloride concentrations were also seen after 1988 in WO Bh 81 and WO Bh 28, although trends are difficult to see. In 2004, the chloride concentrations in production well A, WO Bh 28, approached 250 mg/L, the SMCL for fresh ground water. Chloride concentrations for 1998-2002 in production well G at 33rd Street (WO Bh 100) ranged from 25 to 48 mg/L (the lowest at the 44th Street well field), similar to the range of chloride in the 15th Street well field.

Chloride in Manokin observation well WO Bh 90 has fluctuated between 420 and 620 mg/L during 1986-2004; any correlation between increasing pumpage and increasing chloride concentration is difficult to see because of the large chloride fluctuations throughout the year. Chloride in the Pocomoke aquifer observation well WO Bh 85 has not been affected by the increased pumpage.

Gorman Avenue Well Field

The annual withdrawal from the Manokin aquifer at the Gorman Avenue well field has increased from 8.5 mgal in 1973 to a peak of 1.49 billion gallons in 1992 (tab. 3), due to the addition of new wells and the installation of higher-capacity pumps (tab. 2). Production subsequently decreased to 462 mgy in 2005. Although there is much variation in chloride concentrations, there has been an overall increasing trend in several production wells from 1990 to the present, with concentrations generally between 100 and 150 mg/L. The rate of chloride increases in the production wells range from near zero at well F (WO Ah 45 at 125th Street) to 2.6 mg/L per year in well D (WO Ah 39, at 141st Street) and the major production wells to the north. Chloride concentrations in a Manokin observation well at 137th Street (WO Ah 36) fluctuated between 140 and 190 mg/L during 1975-2005, with the overall chloride trend increase difficult to discern. Chloride concentrations in Manokin observation well WO Bh 34 at 100th Street were less than 50 mg/L during 1985-2005, and the chloride concentrations have been minimally affected by the rate of withdrawal from the Gorman Avenue well field because it is located further south from the pumping center.

MODEL SIMULATIONS OF GROUND-WATER FLOW AND CHLORIDE DISTRIBUTION

DESCRIPTION OF THE OCEAN CITY GROUND-WATER FLOW MODEL

The ground-water flow model covers an area extending east-west from 74° 00' W to 75° 40' W, and north-south from 37° 50' N to 38° 40' N (fig. 13). The model area includes most of northern Worcester County and extends about 60 mi offshore near the continental slope where it is assumed that the aquifers are exposed to the ocean. The 90.0 mi by 56.1 mi model area was discretized into 40 columns and 44 rows with variable distances between grid lines ranging from 2,376 ft to 47,570 ft.

In this study, Visual MODFLOW, a proprietary software (Guiger and Franz, 2000), was used to simulate ground-water flow in the Coastal Plain aquifer system at Ocean City. The three-dimensional MODFLOW model used in 1993 (Achmad and Wilson, 1993) was a quasi-three dimensional model with vertical flow between the aquifer represented by a leakance term. Since Visual MODFLOW requires the explicit input of layer thickness and vertical and horizontal conductivities for both the aquifers and confining units, the Ocean City model was restructured into a nine-layer hydrologic framework that includes the following units from top to bottom: (1) the unconfined surficial Columbia aquifer, (2) the upper confining bed, (3) the Pocomoke aquifer, (4) the upper part of the lower confining bed, (5) the Ocean City aquifer, (6) the basal part of the lower confining bed, (7) the Manokin aquifer, (8) the St. Mary’s confining bed, and (9) the Choptank and Calvert aquifers (undifferentiated) (fig. 14).

Boundary Conditions

Model boundaries were located to correspond with natural boundaries. For example, at locations where the aquifer intercepts a large surface-water body, a constant head boundary condition is assigned to the boundary cells; where the aquifer is terminated, a no-flow boundary condition was usually assigned to the boundary cells. At locations where the subcropping Pocomoke and Ocean City aquifers are truncated by the Columbia aquifer, a low hydraulic conductivity value was assigned so that leakage from overlying and underlying aquifers could occur, but lateral flow would be prevented. When aquifers continue beyond the boundaries of the model, specified head or specific flux boundary conditions were assigned to the boundary cells to provide a continuation of flow across the boundary.

The boundary conditions assigned to the model were specified on the basis of flow characteristics that prevail at each boundary (Franke and others, 1984). Recharge from precipitation was represented as a specified flux boundary condition assigned to Layer 1 (the surficial aquifer). The cells of Layer 1 that correspond to the Pocomoke River, the coastal bays (Assawoman, Isle of Wight, and Chincoteague Bays) and the Atlantic Ocean were constant-head boundaries. The bay and ocean boundary cells were assigned a zero constant head and the river-boundary cells were assigned the elevation of the surface water. In this study, the simulated base flow and the water-table aquifer were not calibrated. The southern and northern boundary cells were assumed to be ground-water divides and were designated no-flow boundaries. To test the validity of this assumption, the southern and northern boundary cells were assigned a constant-head boundary, and the model was run. The results showed no significant differences (less than 1 ft) in the water levels between no-flow and constant-head boundary conditions at Ocean City, because the boundaries are located far from the pumping centers. The eastern boundary is located near the continental slope where the aquifers are exposed to the ocean; these cells were assigned constant-head boundary conditions.

Hydrologic Properties

The hydraulic data supplied to the flow model used in this study were derived from the 1993 model (Achmad and Wilson, 1993). The aquifer transmissivities were calculated from specific capacities and aquifer tests of wells (Weigle, 1974; Weigle and Achmad, 1982; Achmad and Wilson, 1993). Visual MODFLOW required lateral hydraulic conductivities for each layer that were calculated by dividing transmissivity values by the saturated thickness of the aquifer. The vertical conductivities of both the aquifers and confining beds were estimated at 1/10 of the lateral conductivities (Freeze and Cherry, 1979). The hydraulic properties used in the flow model are summarized in table 7.

Ground-Water Recharge and Evapotranspiration

In the model, recharge to the water-table aquifer (Layer 1) was assigned a value of 18 in./yr based on average values previously reported for the model area (Achmad and Wilson, 1993). The recharge was applied as a uniform flux distributed evenly to model areas above sea level. The effective ground-water evapotranspiration rate is a function of the depth to water table. It was assumed that an 18 in./yr evapotranspiration rate occurs at locations where water levels are within 3 ft of the land-surface elevation, and that evapotranspiration decreases with depth and reduces to zero beyond a depth of 8 ft. The annual average net ground-water recharge simulated for steady-state conditions for the Ocean City model was 1.6 in./yr (Achmad and Wilson, 1993).

Model Calibration

The ground-water flow model must reasonably replicate measured water levels at steady-state and transient flow conditions before it can be used to simulate the effects of future pumpage. Model calibration is a trial-and-error process that involves adjusting the initial values of the hydrologic properties usually by about 10 to 20 percent to obtain the best match between simulated and measured water levels. The steady-state flow condition is essential for the initiation of the transient flow. The steady-state calibration for the Ocean City model involved simulation of the 1900 (i.e., pre-pumping) flow conditions, when flow into the system presumably equaled outflow from the system, and water levels remained the same, independent of time. Because water-level data for 1900 are limited, the steady-state calibration was based on simulating a reasonable flow pattern (figs. 15 through 19).

The transient calibration involved matching measured water levels with water levels simulated using the historical pumpage from 1900 to 2005. The first 100 years, from 1900 to 2000, were simulated using annual average pumping rates that produced annual average water levels. Pumpage between 2001 and 2005 was simulated using average monthly withdrawal rates to model the effects of seasonal pumpage on water levels. The ground-water withdrawals from the public supply wells were aggregated and reported as sums for the well fields supplying four water plants (the South Division Street, 15th Street, 44th Street, and Gorman Avenue Water Plants). After the South Division Street Water Plant was deactivated in 1997, pumpage from public supply wells at the South Division Street Water Plant were added to the amount from the 15th Street Water Plant. Wells supplying the three active water plants in Ocean City are identified in table 2.

Hydrographs of simulated and measured water levels at selected observation wells are shown in figures 20 through 26. Historical water levels were obtained from the USGS National Water Information System (NWIS) and were compared with simulated water levels that reflected withdrawal rates reported by major users to MDE between 1900 to 2005. The Visual MODFLOW calibration was analyzed using least squares regression analysis, matching a total of 6,860 points from 35 observation wells. Simulated and measured water levels are compared using statistical parameters described in table 8. In general, the smaller the calculated value of the parameter, the closer the simulated water level is to the measured value. The model calculated an average water level for a cell node at the duration of the time step. The smaller the cell size and the shorter the time step, the better the simulation of the water level opposite the well screen.

Comparison of simulated and measured water levels during the 1900-2005 simulation for the Columbia, Pocomoke, Ocean City, and Manokin aquifers, and St. Mary's confining bed indicated a mean absolute error ranging from 2.9 to 15.6 ft. Ranges of other statistical parameters were as follows: mean error –5.6 to 3.2 ft; standard error of the estimate, 0.08 to 0.5 ft; root mean square (RMS), 3.6 to 24.3 ft (tab. 8). The simulation uses average monthly or annual pumpage, outputting average monthly or annual water levels. The water levels measured reflect the fluctuation of the pumpage occurring in the well. In Ocean City, the need for water supply is seasonal, which causes more deviation of measured water levels from the simulated water levels. Seasonal fluctuation in water levels cause higher differences between the measured and simulated values shown by the absolute error of 15.6 ft and RMS of 24.3 ft; however, the maximum standard error of estimate is 0.5 ft.

Simulated Water Levels for 1995, 2000, and 2005

Cones of depression in the simulated potentiometric surface of the Ocean City aquifer are located near the 15th Street and 44th Street well fields, where the Ocean City aquifer is heavily pumped. Simulated potentiometric surfaces showing water levels in the Ocean City and Manokin aquifers at seasonal high withdrawal rates during the summers of 1995, 2000, and 2005 are shown in figures 27 through 32, respectively. In summer 1995, the deepest cone of depression (about 29 ft below sea level) was located in the 44th Street well field, reflecting greater pumpage at 44th Street than at 15th Street (fig. 27; tab. 9). In summer 2000 and 2005, water levels in the Ocean City aquifer were deeper at the 15th Street well field (figs. 29, 31; tab. 9). The summer monthly rates of withdrawal from the Ocean City aquifer at the 15th Street well field for 1995, 2000, and 2005 were 2.79, 4.04, and 3.76 mgd; the withdrawal rates from the Ocean City aquifer at the 44th Street well field for 1995, 2000, and 2005, were 3.82, 2.49, and 1.97 mgd (tab. 9). The substantial 2000 and 2005 drawdowns at the 15th Street well field in well WO Bh 98 was caused by increased pumpage from the Ocean City aquifer at the 15th Street well field and by the short distance of observation well WO Bh 98 to the newly activated (1998) production well WO Bh 101 (figs. 2, 8; tab. 1). Prior to 2003, water levels in WO Bh 98 during the winter had returned to above sea level. Beginning in 2003, water levels in the well have remained at least 60 ft below sea level during the winter.

A cone of depression in the simulated potentiometric surface of the Manokin aquifer is located at the Gorman Avenue well field, where most production from the Manokin aquifer occurs. The cell-averaged water levels simulated in the Manokin aquifer for the summers of 1995, 2000, and 2005 were 17, 10, and 19 ft below sea level, respectively, and the summer rates of withdrawal from the Manokin aquifer for 1995, 2000, and 2005 were 6.1, 4.4, and 4.5 mgd, respectively (figs. 28, 30, 32; tab. 9).

The effects of summer and winter pumping rates on water levels in the Ocean City and Manokin aquifers can be seen by comparing figure 31 to 33 and figure 32 to 34. The water levels in the Columbia, Pocomoke, and Choptank aquifers in the Ocean City area showed only minimal change. The difference between summer and winter simulated drawdowns for 2005 was 32 ft in the Ocean City aquifer at the 15th Street well field and 16 ft in the Manokin aquifer at the Gorman Avenue well field.

DESCRIPTION OF THE SOLUTE-TRANSPORT MODEL

Solute-transport models simulate the movement of solutes in the ground-water flow system by advection, dispersion, and diffusion (Achmad and Wilson, 1993). Advection, the transport of solutes with the flow of ground water, occurs at a rate equal to the average linear velocity of the ground water. Dispersion of the solutes occurs both in the direction of flow (longitudinal dispersion) and perpendicular to the flow direction (transverse dispersion). Diffusion of solutes from a higher concentration to a lower concentration is due to the kinetic activities of the molecular constituents. The SUTRA computer program used in these simulations (Voss and Provost, 2002) mathematically simulates fluid movement and transport of dissolved substances in a two-dimensional cross-section having a thickness of 1 meter (m). The SUTRA program applies a hybrid finite-element and integrated finite-difference method to approximate the equations describing density-dependent ground-water flow and solute transport, solving for pressure and solute distribution in the system (Achmad and Wilson, 1993).

Conceptual Framework for the SUTRA Model

Three cross-sectional models were developed to simulate the relationship between ground-water withdrawals and changes in chloride concentrations at the 44th Street, Gorman Avenue, and 15th Street well fields. Two of the cross-sectional models (the Gorman Avenue and the 44th Street models) are recalibrated models first presented in Achmad and Wilson (1993). The 15th Street model was developed specifically during this project. The three models were constructed along lines parallel to the regional direction of ground-water flow (west-northwest to east-southeast), extending from several miles west of Whaleysville in northwestern Worcester County to the upper part of the continental slope. The models traversed the 15th Street, 44th Street, and Gorman Avenue well fields, parallel to the general line of section shown in figure 1. The models were approximately 80 mi long and 1,900 ft thick, and consisted of five aquifer layers: the Columbia aquifer, Pocomoke aquifer, Ocean City aquifer, Manokin aquifer, and the undifferentiated Choptank-Calvert Formation. The confining units were not explicitly represented in the model; rather, inter-layer flow was restricted by having highly anisotropic aquifers in which horizontal permeability greatly exceeded vertical permeability in a ratio of 1 to 10^{-4} (Achmad and Wilson, 1993). The model had a 1-m nominal thickness, and was discretized into 120 cell columns and 42 cell rows or 121 node columns and 43 node rows. The vertical grid spacing ranged from 33 ft to 100 ft and the lateral grid spacing ranged from 1,760 ft to 15,840 ft (fig. 35). The conceptual framework, aquifer matrix, and fluid properties of the cross-sectional SUTRA model are the same as described in Achmad and Wilson (1993) (tab. 10).

The model locations have distinct hydrogeologic differences. At the Gorman Avenue well field, the basal part of the lower confining bed is thicker than elsewhere and the thickness of the Ocean City aquifer is reduced to about 50 ft. At the 44th Street well field, the confining bed between the Ocean City aquifer and Manokin aquifer is sandier than it is to the north. At the 15th Street well field, the Ocean City aquifer is well developed, and a 20- to 70-ft-thick confining bed separates it from the Manokin aquifer (pl. 1). Plate 1 also shows that a clay bed about 40 ft thick toward the bottom of the Manokin aquifer separates the upper (fresh water) from the lower (brackish water) Manokin aquifer, and that it impedes the upwelling of the brackish water from the base of the Manokin and St. Mary's Formations.

Boundary Conditions

The model was designed to include natural boundaries where possible. At locations where the flow system was terminated, boundary conditions were specified that would accurately simulate flow at the boundaries. The bottom of the model was assigned a no-flow boundary sufficiently deep within the undifferentiated Choptank-Calvert Formation to minimize the effect of the artificial boundary on the Ocean City–Manokin aquifer system. The other three sides of the cross-sectional model were bounded with specified pressure boundary conditions and the equivalent hydraulic gradient that produced ground-water flow fluxes.

The upper boundary Layer 1 (the Columbia aquifer) was made a specified-pressure boundary. The onshore part was assigned a pressure equivalent to hydraulic head of the water table and chloride concentration of zero. The offshore portion of the Columbia aquifer was assigned a zero pressure and 19,000 mg/L chloride. The boundary nodes at the continental slope were assigned pressures equal to the density of seawater times the depth of the node below sea level, and chloride concentration of 19,000 mg/L.

Simulation of the Offshore Brackish-Water Plume

Relatively fresh to brackish ground water has been documented 8.75 mi offshore of Ocean City from pore-water samples obtained from USGS test hole no. 6008, which had chloride concentrations as low as 231 mg/L (Hathaway and others, 1976). The relatively fresh water is a relict from a time when sea level was much lower. The presence and extent of the brackish-water plume offshore in the coastal aquifers is related to the hydrologic and transport properties of the aquifer system, the area's seasonal recharge, and prior sea-level position (Meisler and others, 1984; Meisler, 1989). According to Belknap and Kraft (1977), Holocene sea levels rose about 25 ft in the last 4,000 years relative to the coast of Delaware. Belknap and Kraft's (1977) sea-level curve is applicable to the Ocean City area because it accounts for both eustatic sea-level rise and tectonic subsidence in the Baltimore Canyon Trough, an offshore depositional basin. The sea-level curve of coastal Delaware (Belknap and Kraft, 1977) was used as a reference curve for the rate of sea-level rise used in the transport model to simulate steady-state prepumping conditions (arbitrarily selected as 1900). Although the actual 25-ft sea-level rise occurred gradually, the rise was simulated in the model in two increments: a 15-ft rise occurring 4,000 years before present (ybp), and a 10-ft rise occurring 2,000 ybp. Initially (at 4,000 ybp), the shoreline was assumed to occur at the top of the column at node 121; after the 15-ft sea-level rise, the shoreline was assumed to occur at the top of the column at node 88 of the model; the subsequent 10-ft rise represented the shoreline moving to its present location. For the initial model conditions, the entire cross-sectional model was assumed to be saturated with fresh water; however, the higher-density seawater at the continental slope gradually dispersed toward the shore. Each sea-level rise was simulated by assigning appropriate pressures and fluxes representative of the sea-level position relative to the boundary nodes of the model. The water table, derived from the hydraulic heads of the flow model under the 1900 steady-state conditions, generated fresh-water fluxes throughout the Columbia aquifer and also at the western boundary.

The shoreline was placed at a model node at the top of column 88 after the first incremental 15-ft rise, and consequently had a simulated sea level that was 10 ft below the present level. The eastern boundary nodes, representing the continental slope (all nodes at column 121 in the model), were all below sea level and were assigned pressures equal to the value obtained from equation

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

(from Achmad and Wilson 1993)

where P is pressure in kiloPascals,

ρ is density of sea water in kilograms per meter cubed (kg/m^3),

g is the gravitational acceleration in meter per second squared (m/s^2),

h is the elevation head above sea level in meters (m)

z is the depth of node below sea level in meters

The nodes of the Columbia aquifer representing land surface that were now below sea level after the rise (nodes on the top of columns 88 to 121) were assigned equivalent pressures that ranged from 15 ft of hydraulic head at the seaward side and decreased to zero ft at the shoreline, resulting from the pressure of sea water above the ocean floor. Chloride concentrations on the seaward part of the Columbia aquifer were equal to 19,000 mg/L. The nodes of the Columbia aquifer representing the land surface that remained above land surface after the initial 15-ft rise were assigned pressures equal to the initial water-table potentiometric surface plus 15 ft and chloride concentration equal to zero mg/L. The cross-sectional model was run to cover a period of 2,000 years.

The second sea-level rise in the model (a 10-ft rise occurring 2,000 ybp) raised the shoreline to its current position (node on the top of column 66). The eastern boundary nodes at the continental slope were all below sea level and were assigned pressures equal to the value obtained from the equation $P = \rho g\,(h+z)$, and chloride concentration equal to sea water (19,000 mg/L). The nodes of the Columbia aquifer representing the current sea bottom were assigned equivalent pressures that ranged from 10 ft of hydraulic head at the seaward side and decreased to zero ft at the shoreline and chloride concentration of

19,000 mg/L. The nodes of the Columbia aquifer representing the land surface (nodes on the top of columns 1 to 66) were assigned pressures equal to the water-table potentiometric surface and chloride concentration of zero mg/L. The cross-sectional model was again run to cover a period of 2,000 years.

Adjustments to the model parameters were made to produce results similar to the 1993 cross-sectional models (Achmad and Wilson, 1993). The sensitivity of the model output to hydraulic and transport properties and model boundary conditions were considered during adjustment. For example, the extent of the brackish-water plume offshore was more sensitive to changes in the freshwater fluxes developed at the western boundary than the lateral permeability of the aquifer system. Increasing the vertical permeability caused the plume to be thicker but shorter laterally. Testing model sensitivity to transport properties showed that a 25-percent change in fluid dispersivity produced a minimal change on the width of the plume, but altering the diffusivity by one order of magnitude caused instability in the numerical solution.

In applying the rate of ground-water withdrawal to the cross-sectional models, the actual rates had to be reduced to account for the 1-m thickness of the cross section. A reduction factor was estimated indirectly by comparing the drawdown obtained from the flow model with drawdown obtained from the cross-sectional model as the rate of withdrawal was systematically reduced. The rate that produced a comparable drawdown of the flow model was assumed to be the equivalent pumpage to be applied to the cross-sectional model. Because pressure in the transport model is expressed in Pascals and head in the flow model is expressed in meters, a rounding error occurs when the units are translated. The sensitivity of chloride change calculated in the transport model to head change in the flow model on average is about 1 mg/L to 5-10 m. The ground-water withdrawals used in the cross-sectional model simulations were about one-third the well-field rate of withdrawals, as was also the case with Achmad and Wilson (1993). The well-field ground-water withdrawals for the cross-sectional model were simulated as average 5-year segments for the period 1980 to 2025. For each well field, a linear regression of measured versus simulated chloride concentrations was used to evaluate how well each 5-year period simulated by the SUTRA model compared to field average values for the period 1980-2005 (tab. 11).

The ground-water flow part of the model (pressure heads) reached steady-state conditions within a few years, but the solute-transport model (chloride concentrations) took about 2,000 years to stabilize. Simulated chloride concentrations under 1900 pre-pumping conditions are illustrated for each of the three cross-sections in figures 36 through 38. Because there is no record of pressure and chloride distribution for year 1900, the steady-state calibration was based on estimated values. The simulated chloride concentrations were matched with the earliest measured values measured in the Ocean City well fields and test well no. 6008 (tab. 12). Most of the simulated chloride concentrations are within 15 percent of the measured values (tab. 12).

Simulated Chloride Concentrations for Historical Pumpage to 2005

15th Street Well Field

The average daily rates of the maximum monthly withdrawals ranged from 1.26 to 4.22 mgd between 1969 and 2005, with the highest maximum pumpage occurring in 1999 (tab. 4). Chloride concentrations obtained from production wells at the 15th Street well field were the lowest of the three well fields, ranging from about 46 to 55 mg/L in 2005. Simulated chloride concentrations for 1980-2005 are slightly higher than both the measured values (in many instances) and the linear regression estimates. Although the maximum daily withdrawal (including South Division Street) increased from 2.93 mgd (1990) to 3.76 mgd (2005) the chloride concentration has increased minimally (about 10 mg/L) (tab. 4; figs. 39, 40).

44th Street Well Field

The 44th Street well field began production in 1960. The average daily rates of the maximum monthly withdrawals at the 44th Street well field were increased from 1.06 mgd in 1969 to a maximum of 4.08 mgd in 1994, and then dropped to 1.96 mgd by 2005 (tab. 4). Chloride concentrations obtained from production wells ranged from about 71 to as much as 245 mg/L between 1980 to 2005 (figs. 41 through 43). The rate of annual increase, as determined by linear regression, ranged from 1.84 to 1.92 mg/L. For each 5-yr interval from 1980 to 2005, the average simulated chloride concentrations were within 20 mg/L of the 5-year average measured and regression-estimated values. The measured values show fluctuation, with the higher values from samples taken when the withdrawal rates were higher. Production well A (WO Bh 28) had the greatest average chloride concentration (about 225 mg/L) in 2005 (fig. 41); the values for wells B (WO Bh 29) and C (WO Bh 41) were lower (about 165 and 135 mg/L, respectively) (figs. 42, 43).

Gorman Avenue Well Field

The Gorman Avenue well field was developed in 1973 to reduce withdrawals from the 44th Street well field, where chloride concentrations had been increasing. The daily rates of the maximum monthly withdrawals ranged from 0.3 to 6.8 mgd between 1973 and 2005, with the highest maximum pumpage of 6.8 mgd occurring in 1992 (tab. 4).

Chloride concentrations from Gorman Avenue production wells A (WO Ah 34), B (WO Ah 33), and C (WO Ah 38) ranged from 71 to 128 mg/L between 1980 and 2005. For each 5-yr interval from 1980 to 2005, the average simulated chloride concentrations were within 17 mg/L of the 5-year average measured and regression-estimated values. The increase in chloride concentrations in these wells in 2005 is associated with increased well-field ground-water withdrawals (fig. 44).

RESULTS OF MODEL SIMULATIONS THROUGH 2025

The ground-water flow and cross-sectional models were used to evaluate the future ground-water potential of the Ocean City aquifer system to supply a maximum demand of 18 mgd in 2025. The average monthly withdrawals (in mgd) used in the flow model simulation from 2000 to 2025 are given in table 13 and figure 45. The pumping scenario was based on the currently available pumping capacity at the three Ocean City well fields (S. Mogilnicki, Whitman, Requardt and Associates, written commun., 2005) and constrained by restrictions on production wells susceptible to brackish-water upconing.

Based on the proposed development plan through 2025 (S. Mogilnicki, Whitman, Requardt and Associates, written commun., 2005), maximum monthly ground-water withdrawals from the 15th Street well field and the Gorman Avenue well field were incrementally increased to 6 mgd and 8 mgd, respectively, between 2005 and 2025, because chloride concentrations at these well fields have not yet approached 250 mg/L. Withdrawals from the 44th Street well field were incrementally increased only to 4 mgd through 2025 because of the potential for brackish-water upconing from the basal part of the Manokin aquifer through the sandy confining unit at this site. Production from the 44th Street well field was also limited to the summer season only. Simulated monthly maximum, average, and minimum withdrawals for the flow-model simulations from 2005 to 2025 are shown in table 13. Potentiometric-surface maps for the year 2025 of the Ocean City and Manokin aquifers are shown in figures 46 through 49. The specific conditions existing in the field may not be fully represented in the model, because the flow model and the transport model assumed homogeneity and generalization of hydrologic and transport properties. Nevertheless, the computed simulation provides useful insights into the temporal relationship between well-field withdrawal rates, water levels, and chloride distribution.

15th STREET WELL FIELD

Simulated cell-averaged water levels in the Ocean City aquifer at the 15th Street well field declined from 87 ft below sea level in summer 2005 to 115 ft below sea level in summer, 2025 (tab. 14; fig. 46). Simulated water levels in winter 2025 were 35 ft higher than summer 2025 water levels, which was similar to the difference (32 ft) between the summer and winter water levels observed in 2005 (fig. 50). The simulated 2025 water levels are about 75 ft above the 80-percent management level at the site, which at the well field is about 190 ft below sea level. The 80-percent management level, defined as

80 percent of the distance between the prepumping water level and the top of the aquifer, is used by MDE to guide decisions regarding new ground-water appropriation permits. New appropriations (or increases to existing appropriations) would not be granted if the new appropriation would result in regional head falling below the 80-percent management level. Winter water levels only recovered to about 80 ft below sea level, which is likely due to the recently activated production well WO Bh 101, which is close to well WO Bh 98.

Simulated chloride concentrations at the 15th Street well field production wells B and C (WO Bh 27 and WO Bh 30, respectively) increased by less than 5 mg/L over the simulation period (figs. 39, 40; tab. 15). Future chloride concentrations estimated from historical data using linear regression are slightly lower than those determined from the SUTRA model. Figure 51 shows cross-sectional chloride contours for 2005 and 2025.

44th STREET WELL FIELD

Simulated cell-averaged summer water levels in the Ocean City aquifer at the 44th Street well field declined from 28 ft below sea level in 2005 to 81 ft below sea level in 2025 (tab. 14; figs. 46, 52). Simulated water levels were 119 ft above the 80-percent management level at the well field (tab. 14). The simulated water-level decline between winter 2005 and winter 2025 is about 11 ft, which likely reflects increased pumpage at both the 15th Street and 44th Street well fields. The 2025 wintertime water levels recovered to about 23 ft below sea level.

Increases in simulated chloride concentrations between 2005 and 2025 in the Ocean City aquifer production wells at the 44th Street well field ranged from 20 to 35 mg/L (tab. 15). The maximum simulated chloride concentration in 2025 for the three Ocean City aquifer wells in the SUTRA cross-sectional model was 250 mg/L, which is the SMCL for chloride. Chloride concentrations projected to 2025 by linear regression from historical chloride data were similar to or slightly higher than those determined from the SUTRA model (figs. 41 through 43). Figure 53 shows cross-sectional chloride contours for the 44th Street well field for 2005 and 2025. Simulated chloride concentrations in production wells A and B (WO Bh 28 and WO Bh 29) are about 245 and 137 mg/L, respectively, in 2025 (figs. 41, 42), using a maximum simulated pumpage of 4 mgd in 2025. The simulated 2025 chloride concentration in production well C (WO Bh 41) is 153 mg/L (fig. 43). The three wells are all located within two city blocks of each other. Chloride concentrations are higher at WO Bh 28 because the basal part of the Lower confining unit separating the Ocean City and Manokin aquifers is sandier at well A than at wells B and C.

Data from the 44th Street and 15th Street well fields indicate decreasing chloride concentrations south of 44th Street. A production well planned for the Ocean City aquifer in 2007 at a site on 38th Street will take advantage of this lower chloride concentration (S. Mogilnicki, Whitman, Requardt and Associates, written commun., 2006).

GORMAN AVENUE WELL FIELD

Simulated cell-averaged summer water levels in the Manokin aquifer at the Gorman Avenue well field declined from 19 ft below sea level in 2005 to 34 ft below sea level in 2025 (tab. 14; figs. 32, 47, 54). Simulated water levels in the Manokin aquifer in 2025 are about 306 ft above the 80-percent management level (tab. 14). Simulated water-level declines in observation wells WO Ah 6, WO Ah 35, and WO Ah 37 were less than 30 ft. Wintertime water levels in 2025 recovered to approximately 8 ft below sea level.

Simulated 2025 chloride concentrations in Manokin aquifer production wells A, B, and C (wells WO Ah 33, 34, and 38, respectively) ranged from approximately 144 to 148 mg/L (tab. 15). Simulated chloride concentrations from the SUTRA model in production wells A, B, and C are similar to values estimated from linear regression on the historical data for each well (fig. 44). Figure 55 shows cross-sectional chloride contours at the Gorman Avenue well field for 2005 and 2025.

SUMMARY AND CONCLUSIONS

Hydrogeologic, water withdrawal, and chloride data from the Columbia, Pocomoke, Ocean City, and Manokin aquifers in the Town of Ocean City and surrounding area, collected between 1993 to 2005 were assembled and evaluated for use in the ground-water flow and solute-transport models. The ground-water flow model and solute-transport cross-sectional models were developed to determine the effects of increased ground-water withdrawals for the 2005 to 2025 planning period (S. Mogilnicki, Whitman, Requardt and Associates, written commun., 2005). The flow model was constructed using Visual MODFLOW (Guiger and Franz, 2000), which is based on the U. S. Geological Survey MODFLOW-96 (Harbaugh and McDonald, 1996). Three solute-transport cross-sectional models were developed using the USGS Saturated and Unsaturated Transport Model (SUTRA Version 2D3D.1, Voss and Provost 2002, updated 2003). The hydrogeologic framework for the ground-water flow model and the saltwater-intrusion model were based on data and information previously assembled and described in Achmad and Wilson (1993). An exploratory well (WO Bh 102) located at the 15th Street well field, was drilled to the base of the Manokin aquifer in December 2004 to provide additional information on the water quality near the 15th Street well field. The flow model and cross-sectional models were used to simulate the Town of Ocean City's development plan of increasing maximum (summer) withdrawals from a total of 10.23 mgd in 2005 to 18 mgd in 2025. Simulated withdrawal rates in 2025 increased to 6 mgd from the 15th Street well field, 4 mgd from the 44th Street well field, and 8 mgd from the Gorman Avenue well field. Maximum withdrawals were limited to 4 mgd at the 44th Street well field to minimize additional chloride intrusion into the Ocean City aquifer.

The model results suggest that in August 2025, the deepest cone of depression in the Ocean City aquifer will be at the 15th Street well field, where the simulated (or model-cell average) water level was 115 ft below sea level. The deepest simulated 2025 water level at the 44th Street well field was 81 ft below sea level in the Ocean City aquifer. The deepest simulated water level in the Manokin aquifer at the Gorman Avenue well field in 2025 was about 34 ft below sea level. The simulation results suggest that for the ground-water withdrawal rates used in the model, the water levels remain above the 80-percent management level in all three well fields. In the Ocean City aquifer, the remaining available drawdown (the height of the water column above the 80-percent management level) as determined from the simulated cell-averaged water levels in August 2025 is 75 ft and 119 ft at the 15th Street well field and at the 44th Street well field, respectively. At the Gorman Avenue well field, the remaining available drawdown in August 2025 in the Manokin aquifer is 306 ft. Winter water levels at the 15th Street well field, which prior to 2003 had returned to above sea level during the summer, only recovered to about 80 ft below sea level in 2025. The model also suggests that winter water levels at the 44th Street and Gorman Avenue well fields do not recover to sea level, although the water levels are greater than at the 15th Street wellfield.

Results from the cross-sectional solute-transport models suggest that chloride concentrations will increase by 2025 at all three well fields, with the largest increase occurring at the 44th Street well field. The simulated average chloride concentrations in the wells at the 15th Street well field range from 55 to 60 mg/L in 2025, an increase of less than 5 mg/L over 2005 levels. The 2025 simulated average chloride concentration in production wells A, B, and C at the 44th Street well field, range from about 150 to 250 mg/L, which is an increase of 25 to 35 mg/L from 2005. Chloride concentrations may approach 250 mg/L (the SMCL for chloride) in parts of the 44th Street well field in 2025 even when production is held to 2005 levels. Simulated chloride concentrations in 2025 at the Gorman Avenue well field range from about 145 to 150 mg/L, an increase of about 15 to 25 mg/L from 2005.

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

[ft, feet; lsd, land surface datum; in., inches; gpm, gallons per minute; gpm/ft, gallons per minute per foot; hrs, hours; Constr., construction; Co., company]

Well number	Permit number	Owner	Driller	Date drilled	Altitude of land surface (ft)	Depth drilled (ft below lsd)	Depth of well (ft below lsd)	Aquifer
WO Ah 49[1]	WO-88-0648	Town of Ocean City	A.C. Schultes	4/8/2004	8	455	425	Manokin
WO Bg 58[2]	WO-94-0481	Town of Ocean City	Hydro Group	12/2/1996	8	291	285	Ocean City
WO Bh 100[3]	WO-88-1050	Town of Ocean City	Van Constr. Co.	5/19/1992	4	310	295	Ocean City
WO Bh 101[4]	WO-94-0883	Town of Ocean City	Layne-Atlantic	6/24/1998	5	325	312	Ocean City
WO Bh 102[5]	WO-95-0148	Town of Ocean City	A.C. Schultes	12/13/2004	5	580	558	Manokin
WO Cg 89[6]	WO-94-1178	Town of Ocean City	Layne-Atlantic	2/26/1999	10	320	312	Ocean City

Screened intervals (ft below lsd)	Screen diameter (in.)	Static water level (ft below lsd)	Discharge (gpm)	Drawdown (ft)	Specific capacity (gpm/ft)	Pumping period (hrs)	Date water level and discharge measured	Well number
261-333 338-346 420-425	8 8 8	5	858	36	24.0	24	4/8/2004	WO Ah 49
237-241 244-248 254-259	8 8 8	2.5	747	57	13.1	24	12/2/1996	WO Bg 58
226-228 245-295	8 8	10	700	48	14.6	20	5/19/1992	WO Bh 100
237-239 250-274 280-307	8 8 8	6	725	135	5.37	24	6/24/1998	WO Bh 101
528-538	4	14	2	114	0.0175	24	12/21/2004	WO Bh 102
246-248 253-307	8 8	8	800	52	15.4	24	2/26/1999	WO Cg 89

[1]Production well G located at 120th Street and Route 1
[2]Production well E located at 3rd Street and St. Louis Avenue
[3]Production well G located at 33rd Street and Daybreak Avenue
[4]Production well F located at 28th Street and Coastal Highway
[5]Exploratory well located at 14th Street and St. Louis Avenue
[6]Production well F located at North Division Street and Caroline Avenue

Appendix B. Chloride data used for the calibration of the cross-sectional models from 1980 to 2005.

[mg/L, milligrams per liter]

15th Street well field

Production well B, WO Bh 27		Production well C, WO Bh 30	
Date sampled	Chloride concentration (mg/L)	Date sampled	Chloride concentration (mg/L)
8/7/1980	32.5	8/21/1980	36.5
8/12/1985	44	8/1/1985	39
8/12/1991	32	8/14/1991	37
8/7/1995	33	10/25/1995	35
5/23/2000	40	6/14/2000	146
8/8/2005	46	9/22/2003	43

44th Street well field

Production well A, WO Bh 28		Production well B, WO Bh 29		Production well C, WO Bh 41	
Date sampled	Chloride concentration (mg/L)	Date sampled	Chloride concentration (mg/L)	Date sampled	Chloride concentration (mg/L)
6/7/1980	135	8/21/1980	71	7/7/1980	80
8/14/1985	175	8/1/1985	92	8/12/1985	109
8/3/1990	185	8/12/1990	93	8/14/1990	115
8/9/1995	195	5/10/1995	113	8/21/1995	100
8/9/2000	208	8/2/2000	120	8/28/2000	115
8/1/2005	210	8/22/2005	134	8/15/2005	113

Gorman Avenue well field

Production well B, WO Ah 33		Production well A, WO Ah 34		Production well C, WO Ah 38	
Date sampled	Chloride concentration (mg/L)	Date sampled	Chloride concentration (mg/L)	Date sampled	Chloride concentration (mg/L)
8/15/1980	111	8/15/1980	89	8/15/1980	75
8/22/1985	118	8/12/1985	100	9/17/1985	74
8/3/1990	114	8/14/1990	82	7/23/1990	71
7/19/1995	120	9/18/1995	105	8/7/1995	105
8/9/2000	127.5	7/5/2000	100	8/30/2000	115
8/10/2005	102	8/1/2005	116	8/22/2005	116

Appendix C. Descriptions of drill cuttings from well WO Bh 102 (Located at the corner of 14th Street and St. Louis Avenue, Ocean City, Maryland)

[ft, feet]

Lithology	Thickness (ft)	Depth (ft)
No sample	40	40
Sand, fine to medium, silty; quartz is angular and clear; thin shell fragments, white; trace mica fragments.	20	60
Sand, fine to medium, up to coarse; quartz is angular mostly clear, some iron-tainted; trace shell fragments; trace wood fragments, brown.	20	80
Sand, fine to medium, quartz is angular and subangular, mostly clear, some iron-tainted; thin shell fragments, white; wood fragments, small sizes, brown, some dark brown.	20	100
Sand, fine to medium, some silt; quartz is angular and subangular, some iron-tainted; pinkish feldspars; trace shells; trace micas; some wood fragment, brown.	20	120
Sand, and small pebbles, some quartz, iron-tainted, and cherts from pebbles material; some shell fragments; wood fragments, brown and dark brown.	20	140
Sand, fine, clayey silt; quartz is angular and subrounded; coarse angular feldspars; trace shell fragments; some wood fragments, brown and dark brown.	20	160
Sand, fine to medium, silty; quartz is rounded; trace shell fragments; wood fragments; some feldspar fragments, grey, angular.	20	180
Sand, fine, some silt; trace micas; trace shell fragments, white; some wood fragments, brown; some feldspars fragments, grey.	20	200
Sand, fine, silty; quartz is rounded and clear; trace feldspars, fragments, grey; abundance of shell fragments, white; some wood fragments.	20	220
Sand, fine, some silt; some shell fragments; trace micas; some wood fragments.	20	240
Sand, medium to coarse, quartz is clear; some shell fragments, white; some wood fragments.	20	260
Sand, fine, silty; abundance of shell fragments, white; some wood fragments	20	280
Sand, fine, silty; clear; abundance lignitic wood fragments; abundance shell fragments, white.	20	300
Sand, fine to medium, clayey silt; abundance lignitic wood fragments; shell fragments, white.	20	320
Sand, fine, silty; abundance lignitic wood fragments; some shell fragments, white.	20	340
Sand, fine to medium, quartz grains mostly rounded; some wood fragments; some shell fragments, white.	20	360
Sand, medium to chiefly coarse, quartz mostly rounded and clear; some feldspars, grey; some shell fragments, white; some wood fragments.	20	380
Sand, medium, silty; quartz grains rounded, mostly clear; trace shell fragments, white; some lignitic wood fragments	20	400
Sand, fine to medium, quartz grains rounded, mostly clear, some iron tainted; some lignitic wood fragments; trace shell fragments, white.	20	420
Sand, chiefly medium, quartz rounded and clear; trace shell fragments.	20	440
Sand, fine to medium, quartz rounded and clear; some medium angular feldspars, grey; abundance of shell fragments, white; abundance lignitic wood fragments.	20	460
Sand, medium to fine, clayey silt; quartz grains clear; trace micas; trace feldspar.	20	480
Sand, medium to fine, clayey silt; quartz grains clear; small fragments of shells.	20	500
Silt, clayey; sand, medium to fine, quartz grains clear; abundance of shells; some wood fragments.	20	520
Silt, very clayey; sand, fine, quartz grains clear; few shell fragments.	20	540
Silt, very clayey; trace shell.	20	560
Silt, very clayey; trace shell.	20	580

Appendix D. Water-quality analysis from well WO Bh 102 (Manokin aquifer at the 15th Street Plant)

[Pt-Co, platinum-cobalt; mg/L, milligrams per liter; <, less than; µS/cm, microsiemens per centimeter; ^{0}C, degrees Celsius; µg/L, micrograms per liter; E, estimated; pCi/L, picocuries per liter; Th,Thorium; Cs, Cesium; Analyses performed on 0.45µ-filtered samples, unless otherwise noted.]

Well number	Sample date	Color (Pt-Co units)	Dissolved oxygen, unfiltered (mg/L)	pH, unfiltered	Specific conductance, unfiltered (µS/cm at 25 ^{0}C)	Temperature (^{0}C)	Calcium (mg/L)
WO Bh 102	12-27-04	10	<1	7.9	3800	24.9	32.1

Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity field, incremental titration (mg/L as $CaCO_3$)	Bicarbonate field, incremental titration (mg/L)	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Sulfate (mg/L)
42.1	29.6	712	367	448	889	0.30	10.3	134

Residue on evaporation at 180 ^{0}C (mg/L)	Ammonia (mg/L as N)	Nitrite + nitrate (mg/L as N)	Nitrite (mg/L as N)	Ortho-phosphate (mg/L as P)	Phosphorus (mg/L)	Organic carbon, unfiltered (mg/L)	Arsenic (µg/L)	Beryllium (µg/L)
2070	1.15	<0.060	<0.008	0.06	0.06	4.82	1.1	<0.12

Iron (µg/L)	Iron, unfiltered (µg/L)	Lead (µg/L)	Manganese (µg/L)	Manganese, unfiltered (µg/L)	Mercury (µg/L)	Thallium (µg/L)	Gross alpha-particle activity, reported as Th-230 (pCi/L)	Gross beta-particle activity, reported as Cs-137 (pCi/L)
<18	5090	<0.16	81.5	122	E.005	<0.08	<3	11

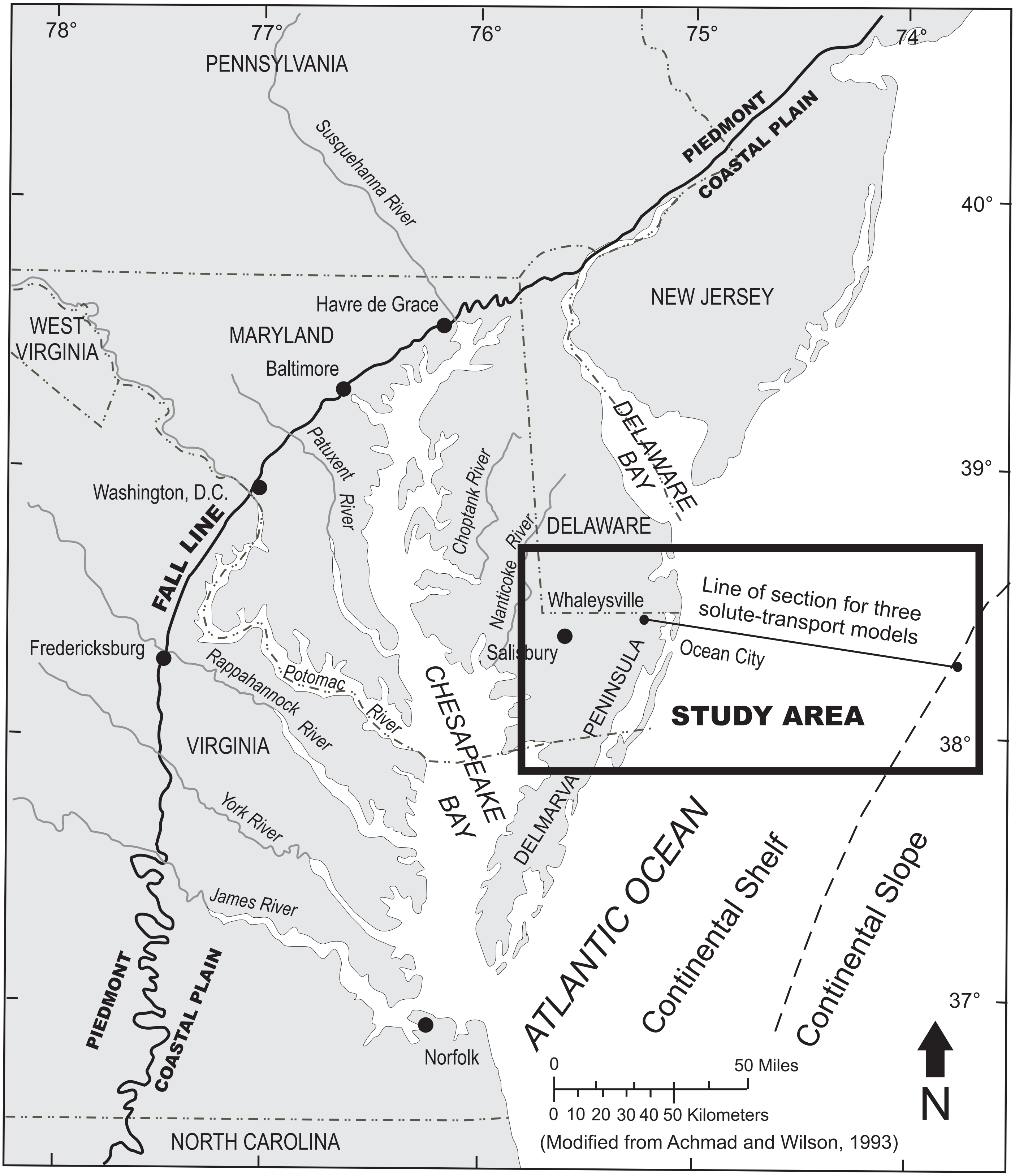
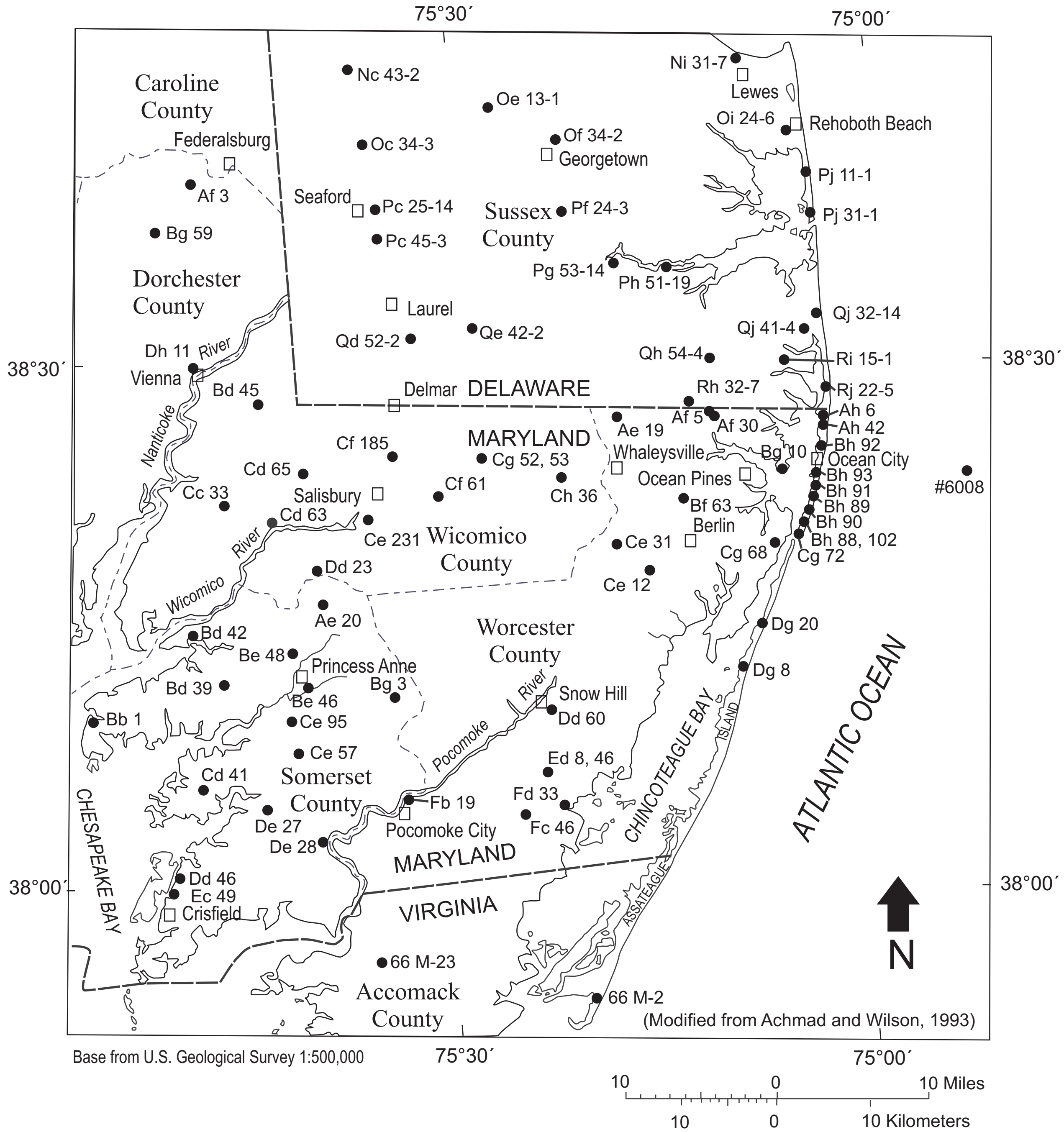


Figure 1. Location of study area in the mid-Atlantic Coastal Plain and the general line of section for the three cross-sectional solute-transport models through Ocean City, Maryland.



EXPLANATION

● Cg 72	Site location and well number (County prefix omitted from well number)
□	Town

Figure 2. Locations of key wells and test holes used for hydrogeologic control.

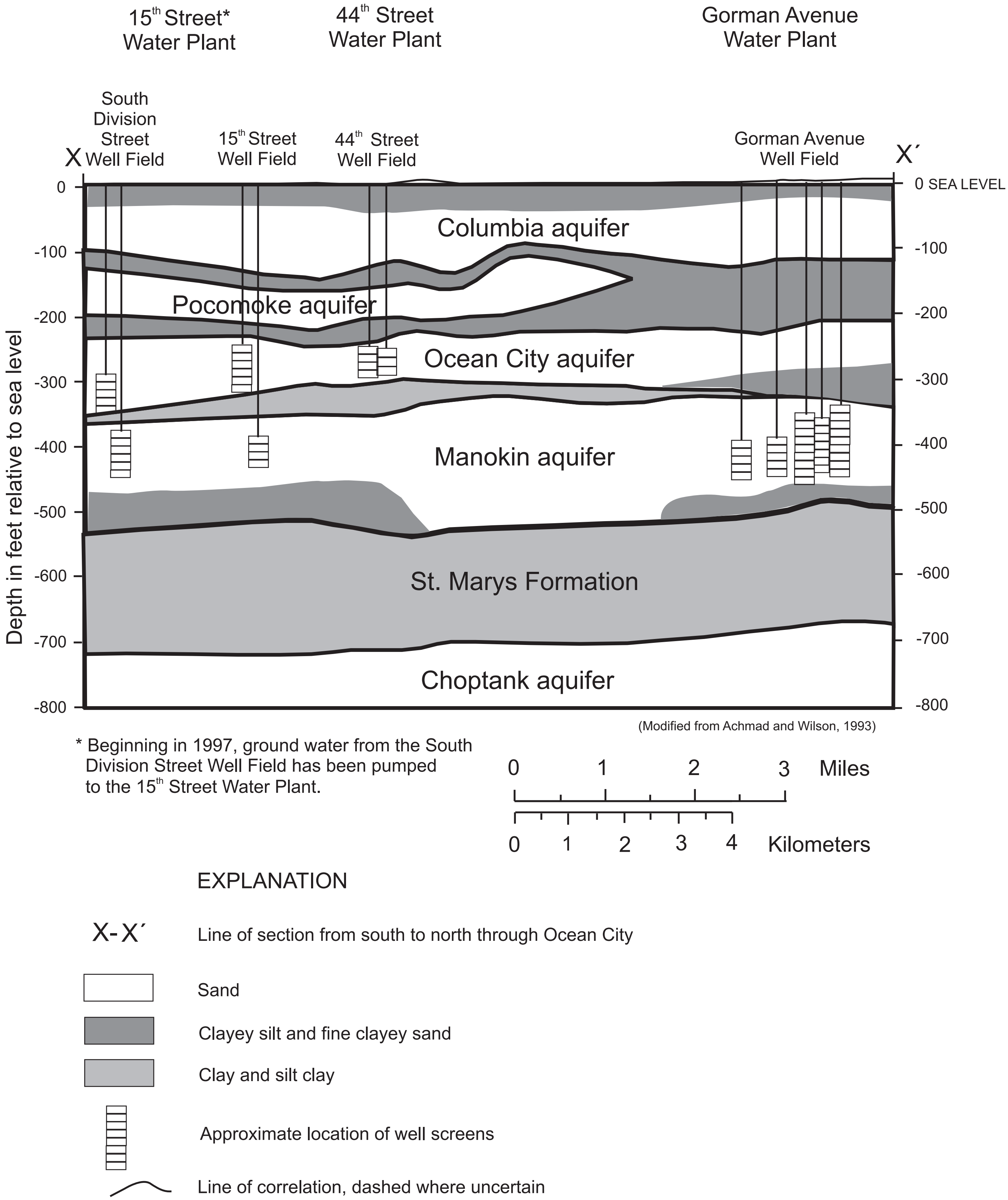


Figure 3. Generalized hydrogeologic section along south-north direction showing the water plants, production well fields, and aquifers in Ocean City, Maryland.

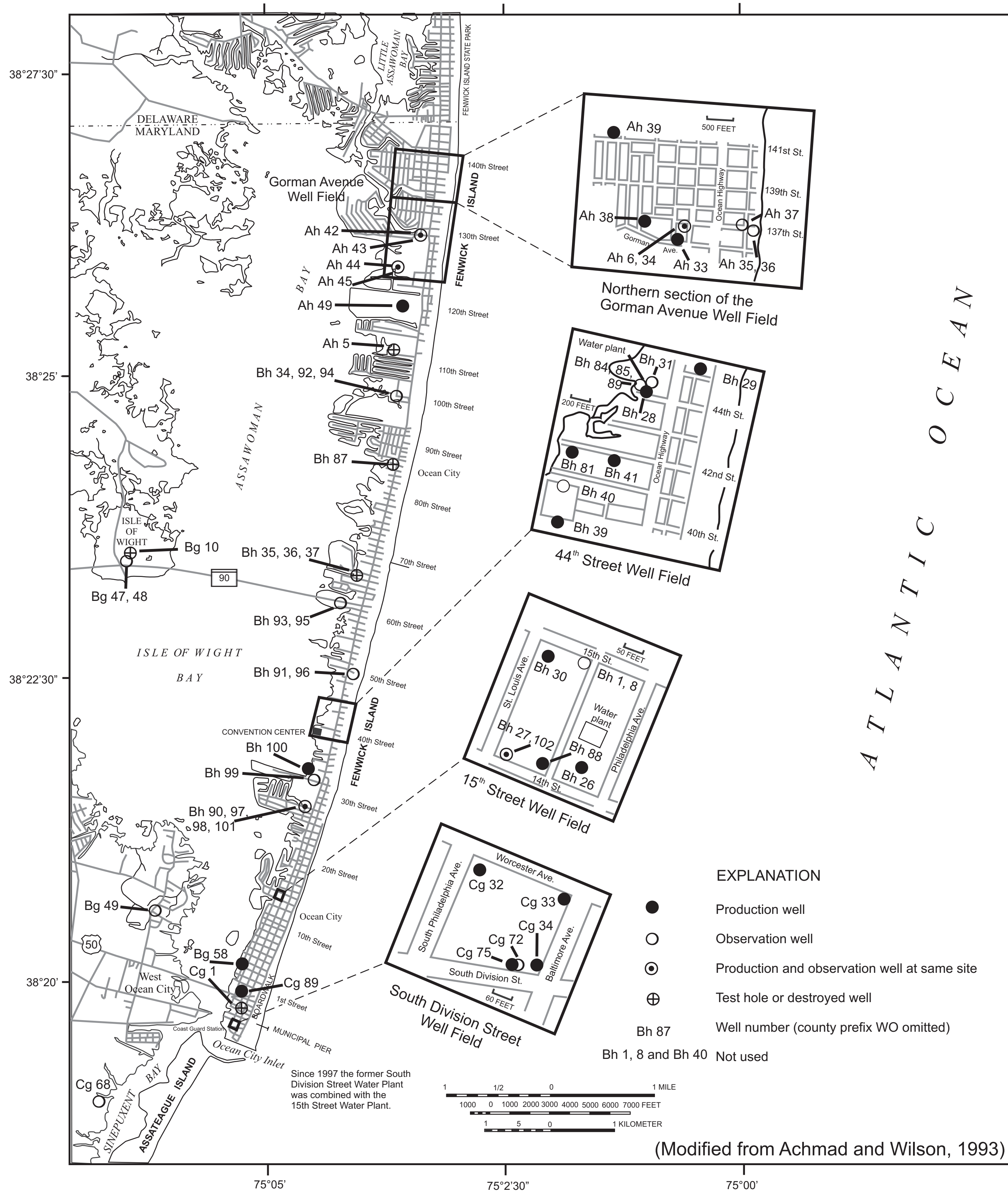


Figure 4. Locations of test holes, production and observation wells, and well fields in Ocean City, Maryland.

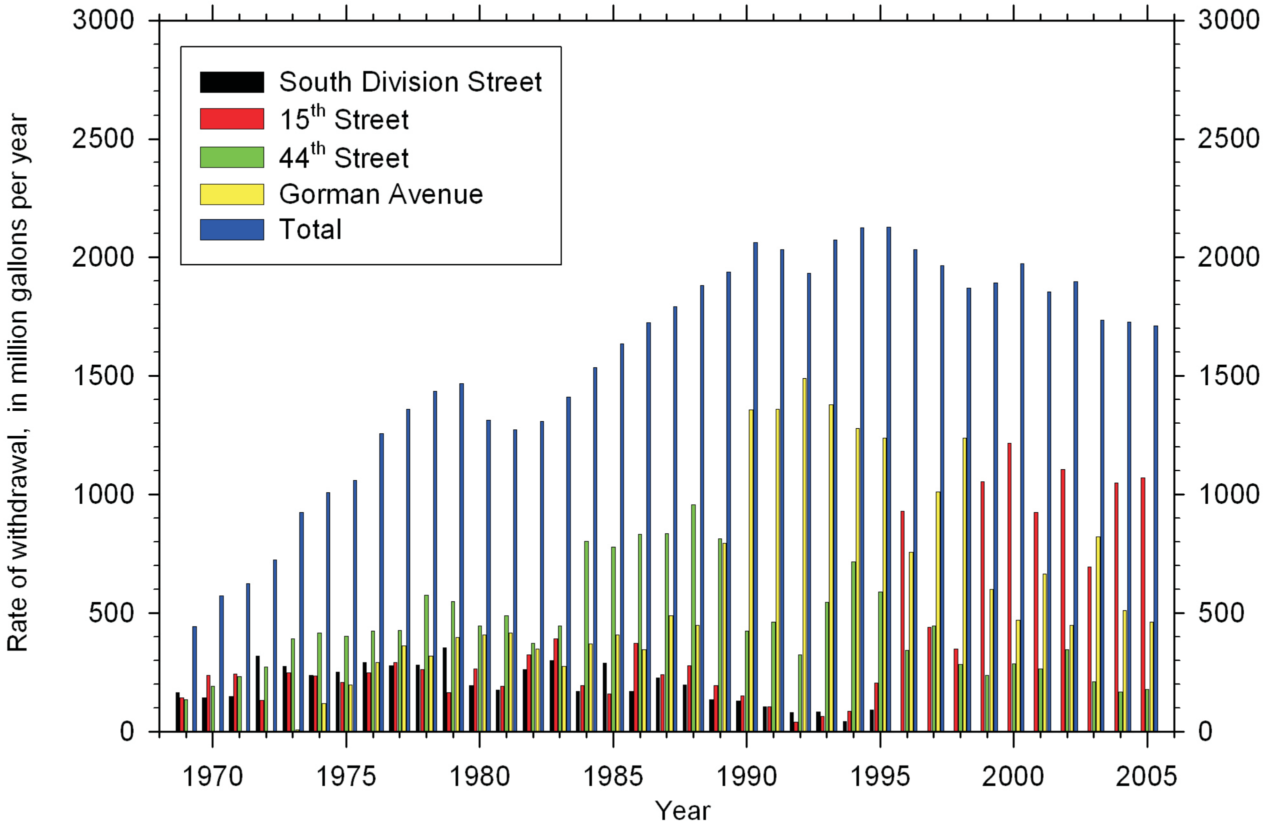


Figure 5. Total annual ground-water withdrawals from the Ocean City aquifer at the South Division Street, 15th Street, and 44th Street well fields and the Manokin aquifer at the Gorman Avenue well field.

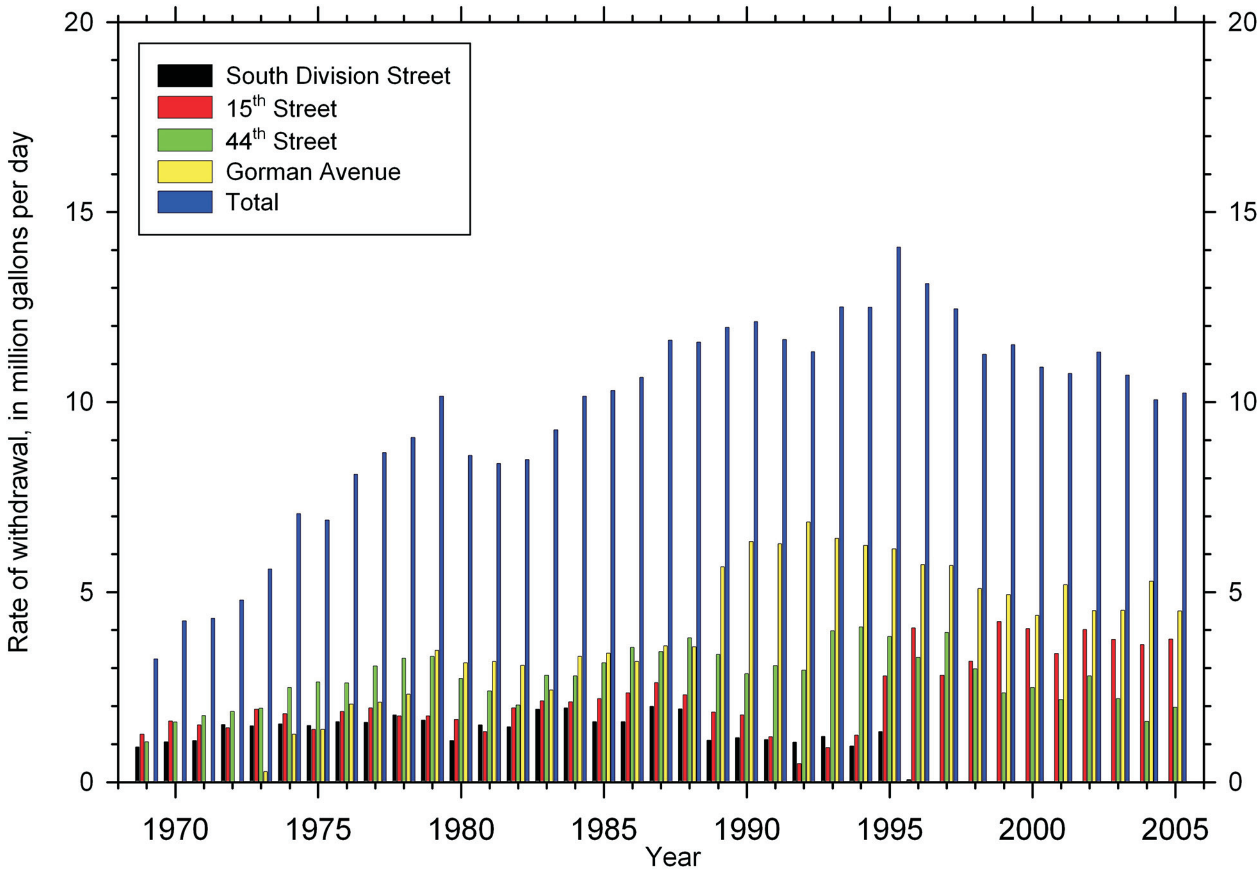


Figure 6. Average daily withdrawal rates during the month of maximum withdrawals from the Ocean City aquifer at the South Division Street, 15th Street, and 44th Street well fields and from the Manokin aquifer at the Gorman Avenue well field.

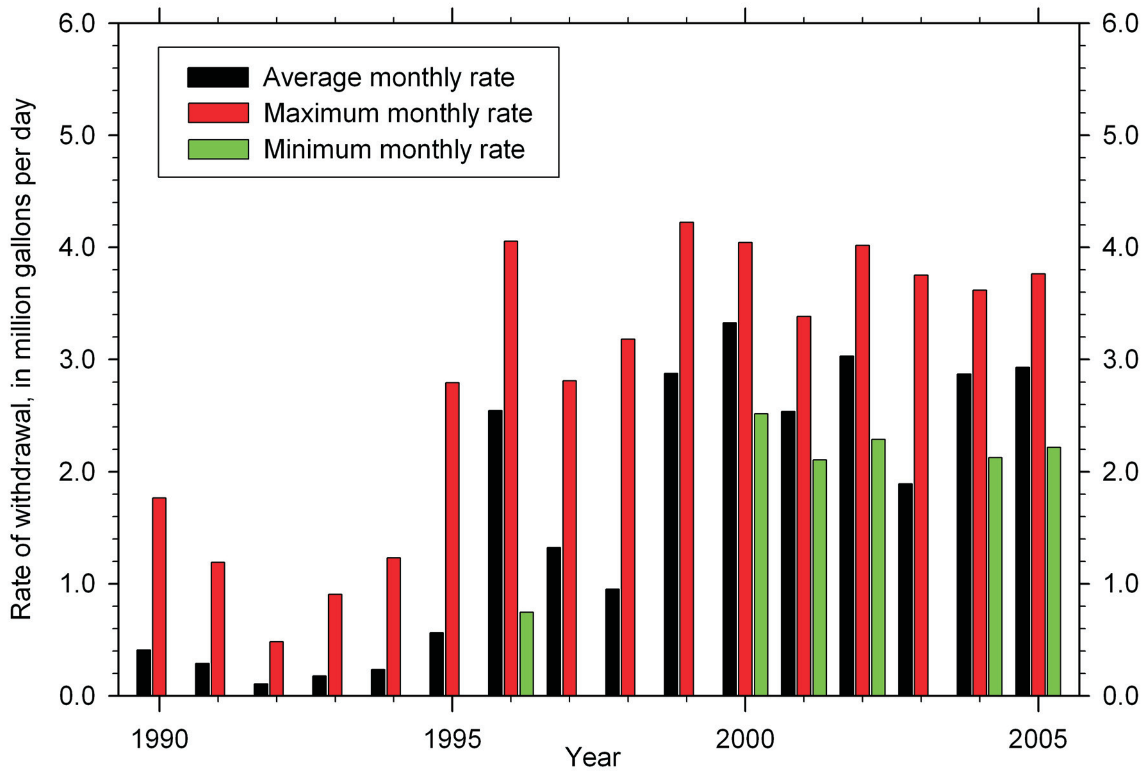


Figure 7. Maximum, average, and minimum monthly withdrawal rates from the Ocean City aquifer at the 15th Street well field. No bars are shown for years where minimum monthly rates were zero.

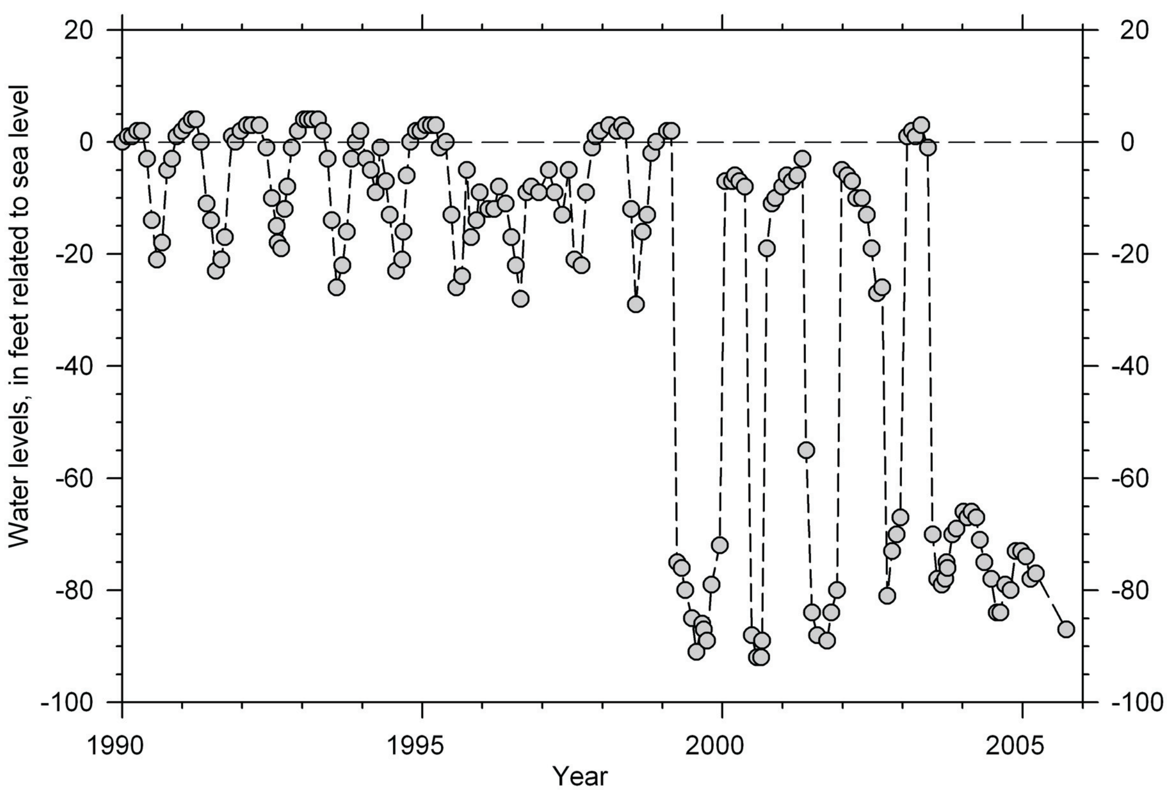


Figure 8. Water levels measured in observation well WO Bh 98 (Ocean City aquifer, 15th Street well field).

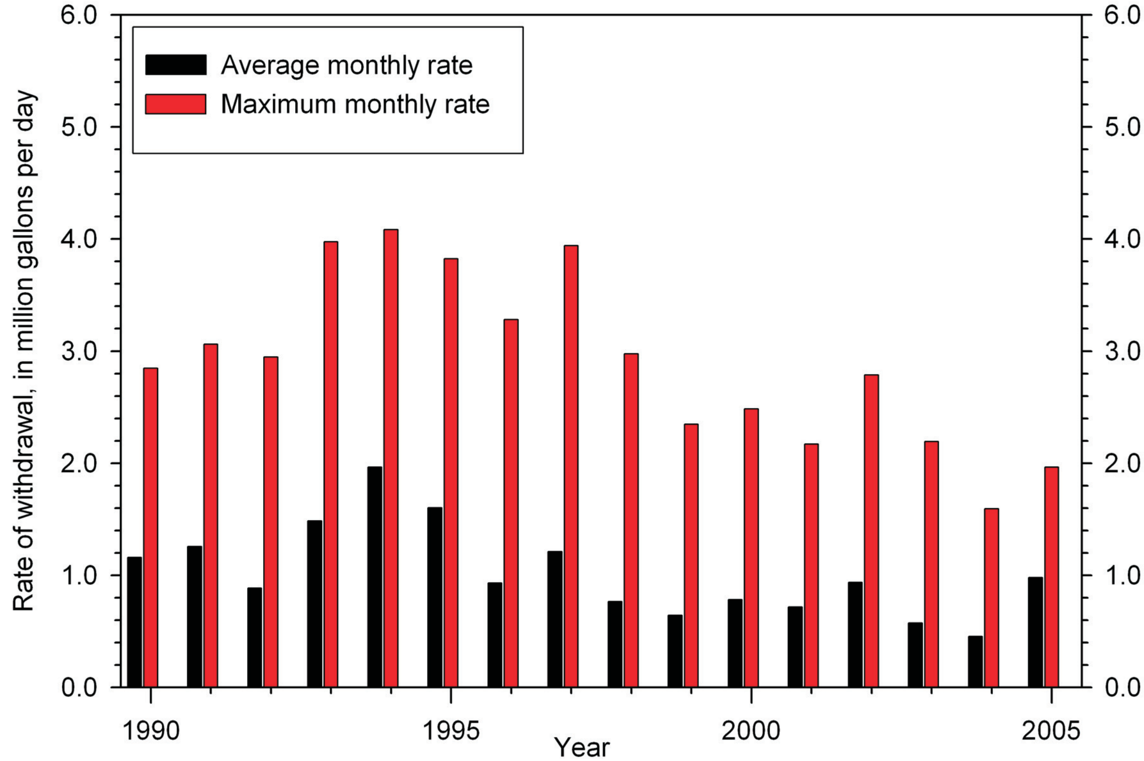


Figure 9. Maximum, average, and minimum monthly withdrawal rates from the Ocean City aquifer at the 44th Street well field. No bars are shown for years where minimum monthly rates were zero.

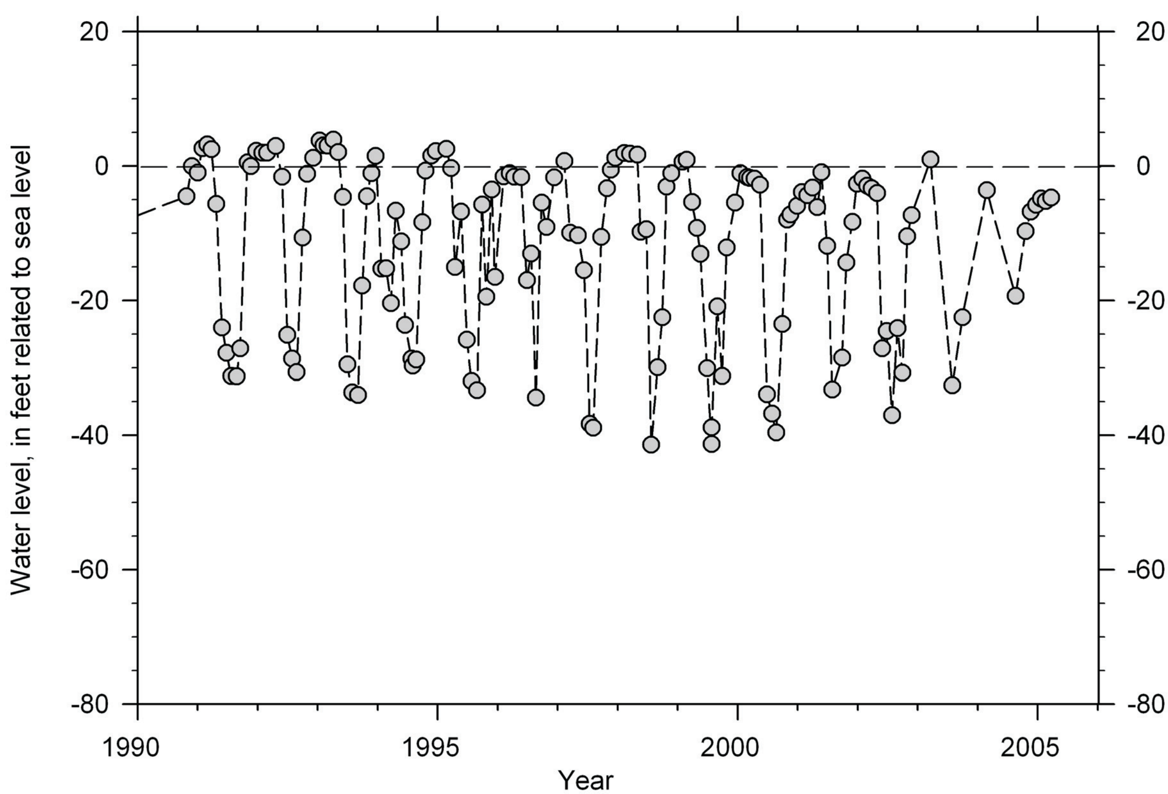


Figure 10. Water levels measured in observation well WO Bh 31 (Ocean City aquifer, 44th Street well field).

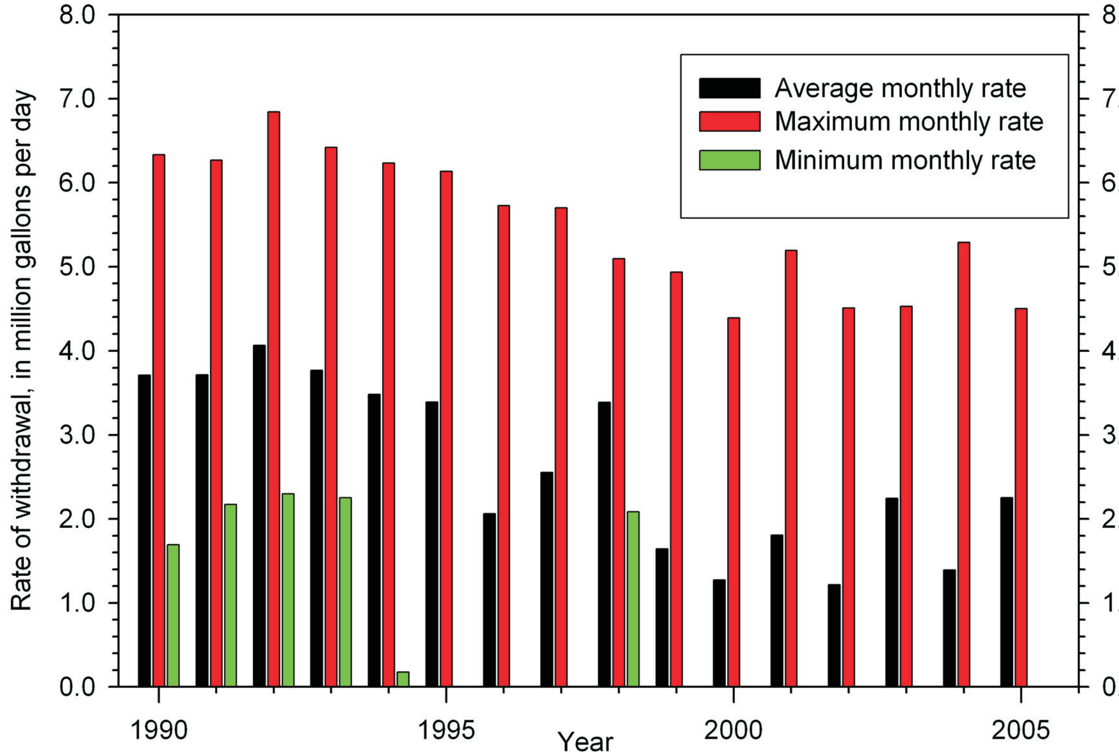


Figure 11. Maximum, average, and minimum monthly withdrawal rates from the Manokin aquifer at the Gorman Avenue well field. No bars are shown for years where minimum monthly rates were zero.

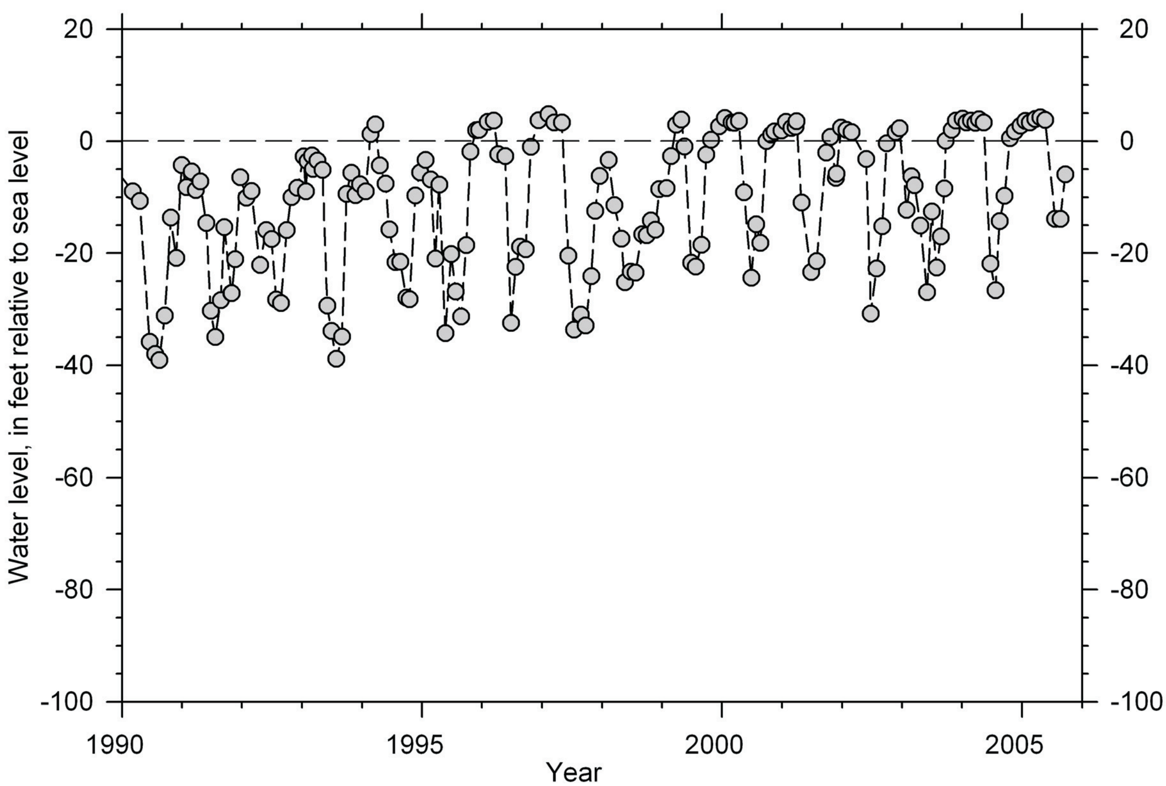


Figure 12. Water levels measured in observation well WO Ah 6 (Manokin aquifer observation well, Gorman Avenue well field).

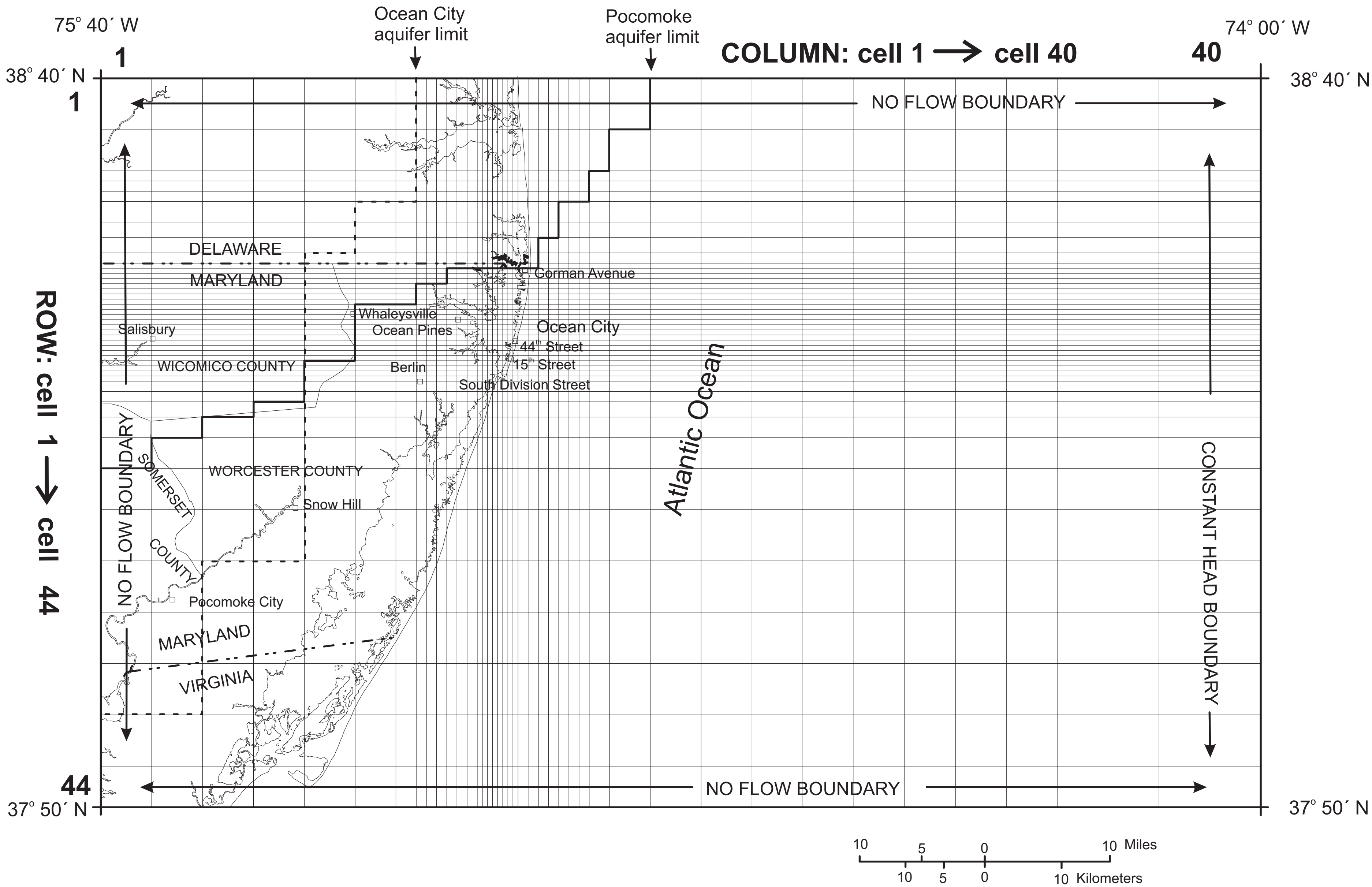


Figure 13. Model area and grid used for the ground-water flow model.

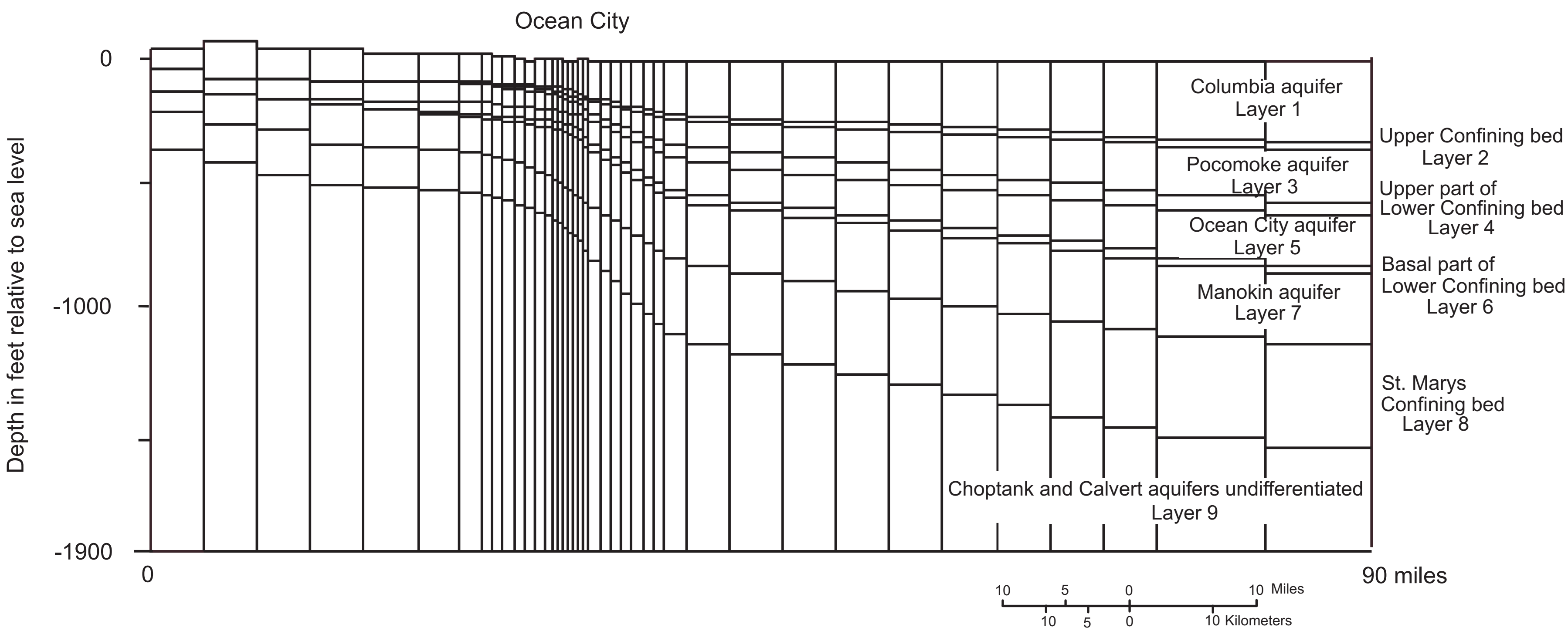


Figure 14. Cross section through Ocean City showing hydrogeologic framework and simulated layers.

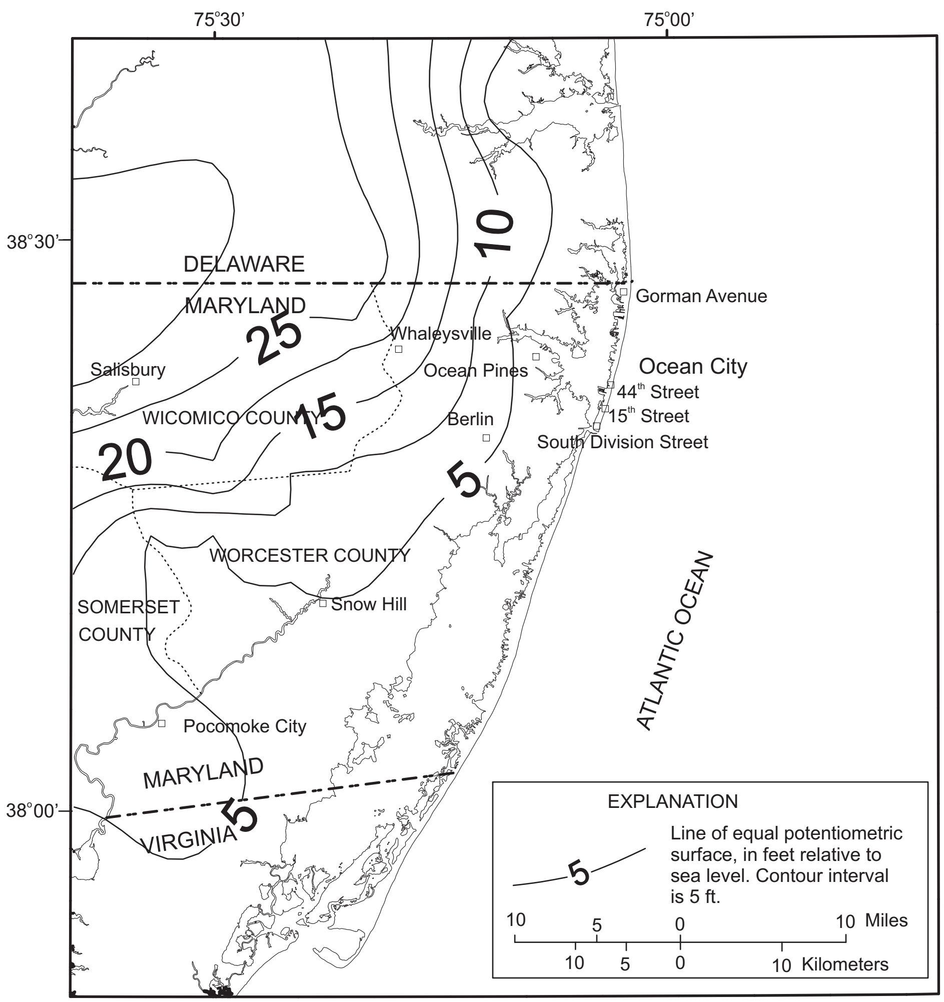


Figure 15. Simulated potentiometric surface of the Columbia aquifer depicting the 1900 steady-state flow conditions.

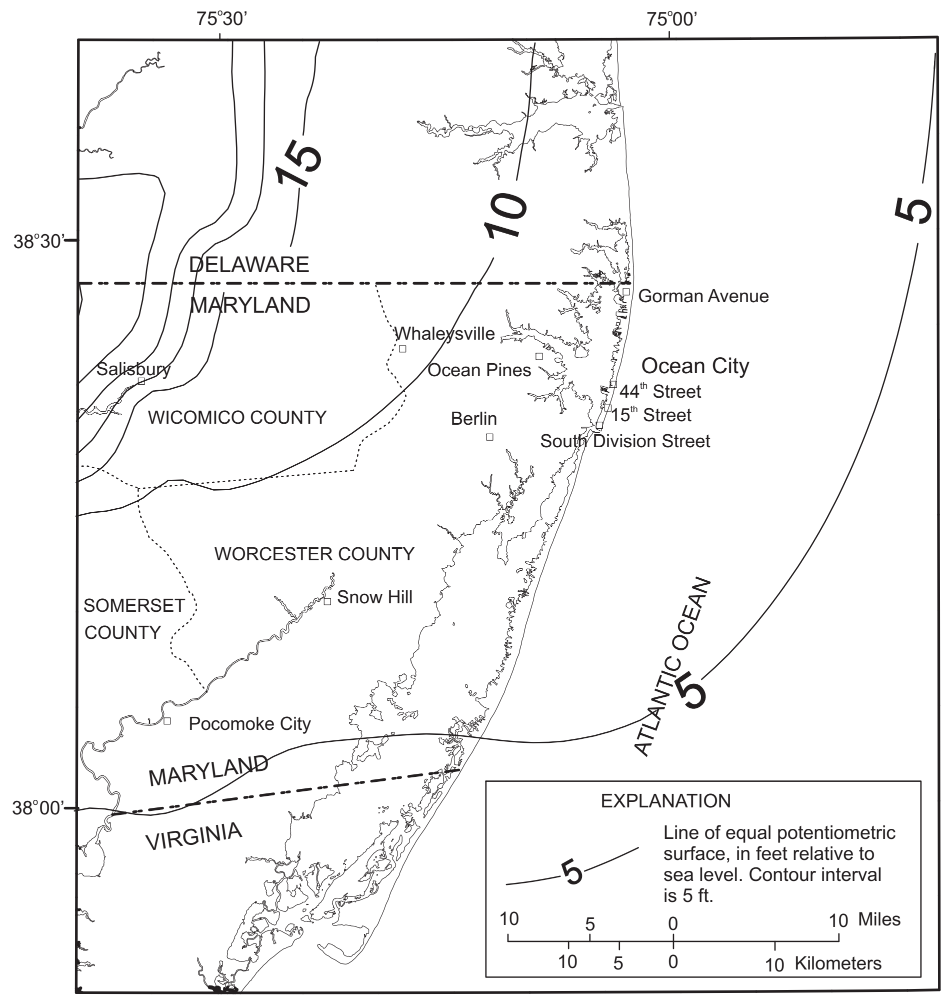


Figure 16. Simulated potentiometric surface of the Pocomoke aquifer depicting the 1900 steady-state flow conditions.

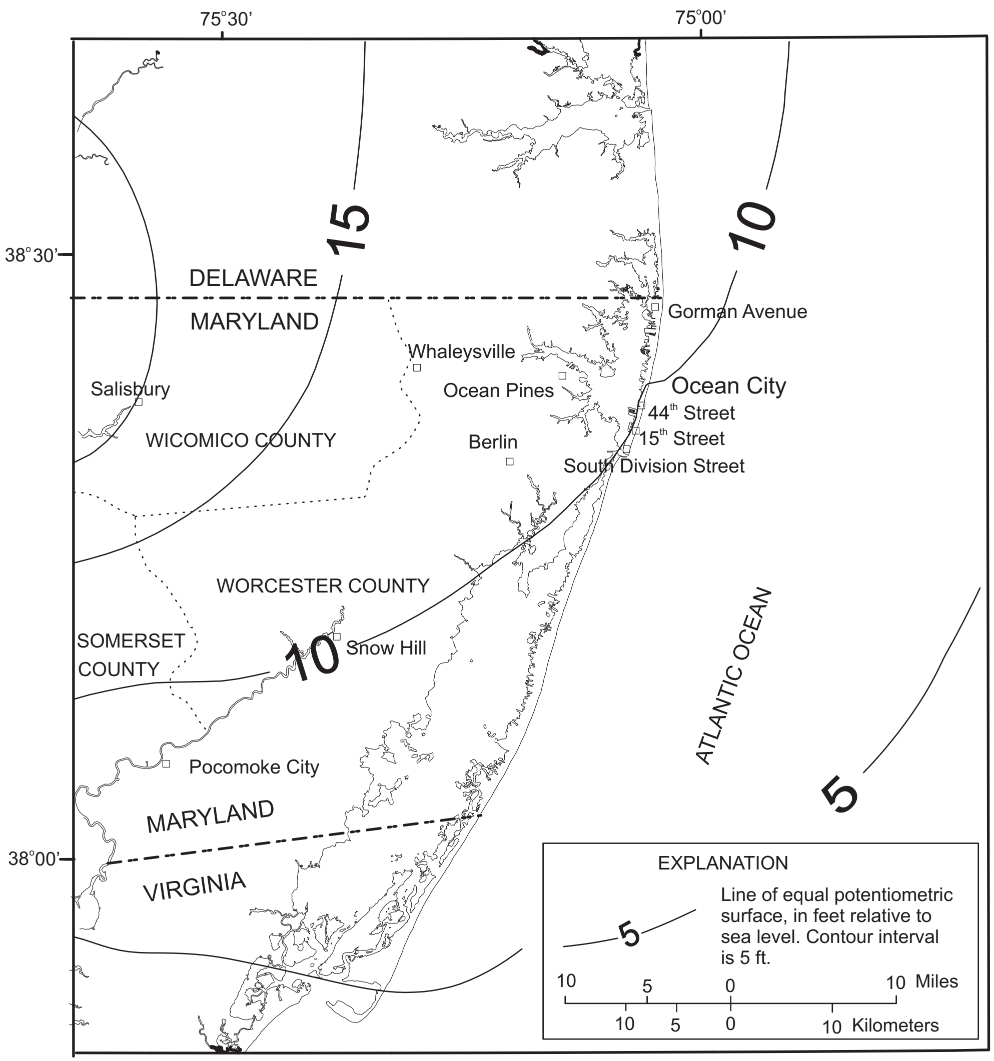


Figure 17. Simulated potentiometric surface of the Ocean City aquifer depicting the 1900 steady-state flow conditions.

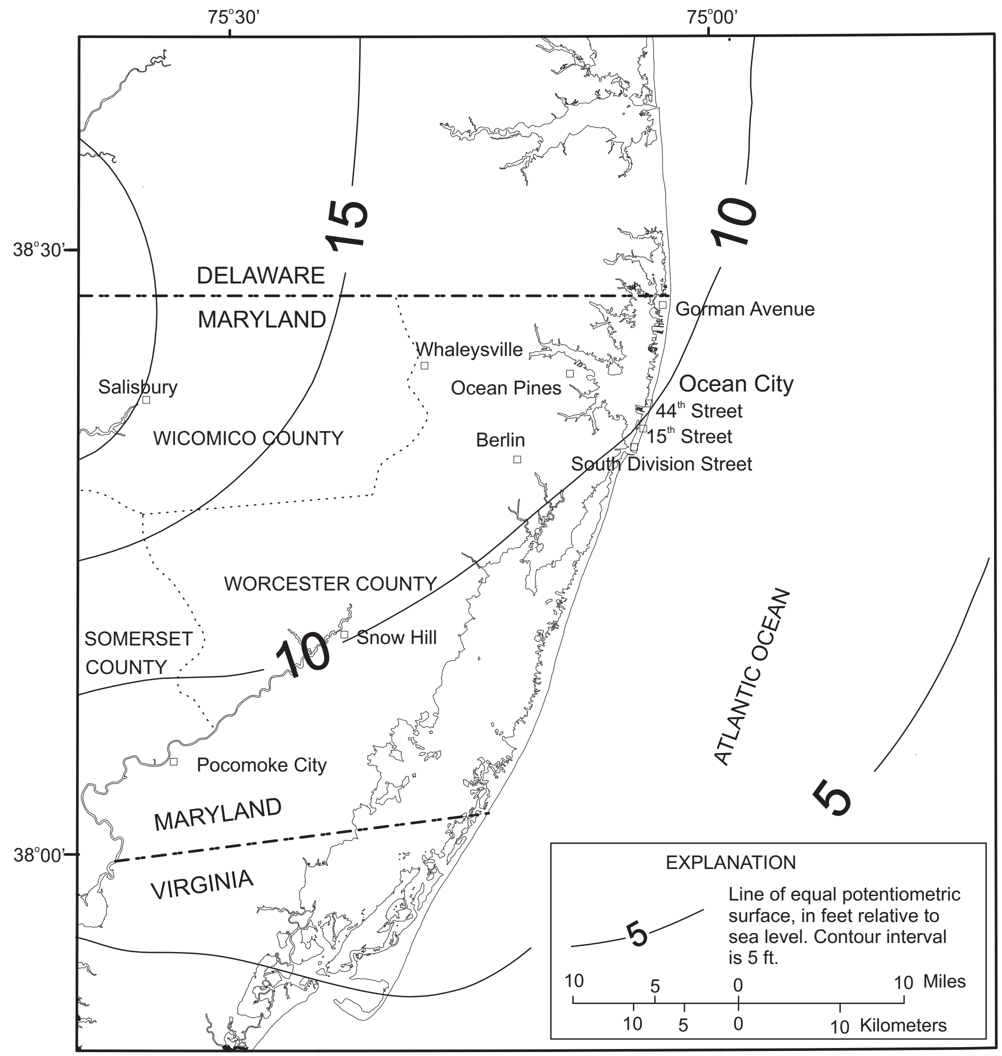


Figure 18. Simulated potentiometric surface of the Manokin aquifer depicting the 1900 steady-state flow conditions.

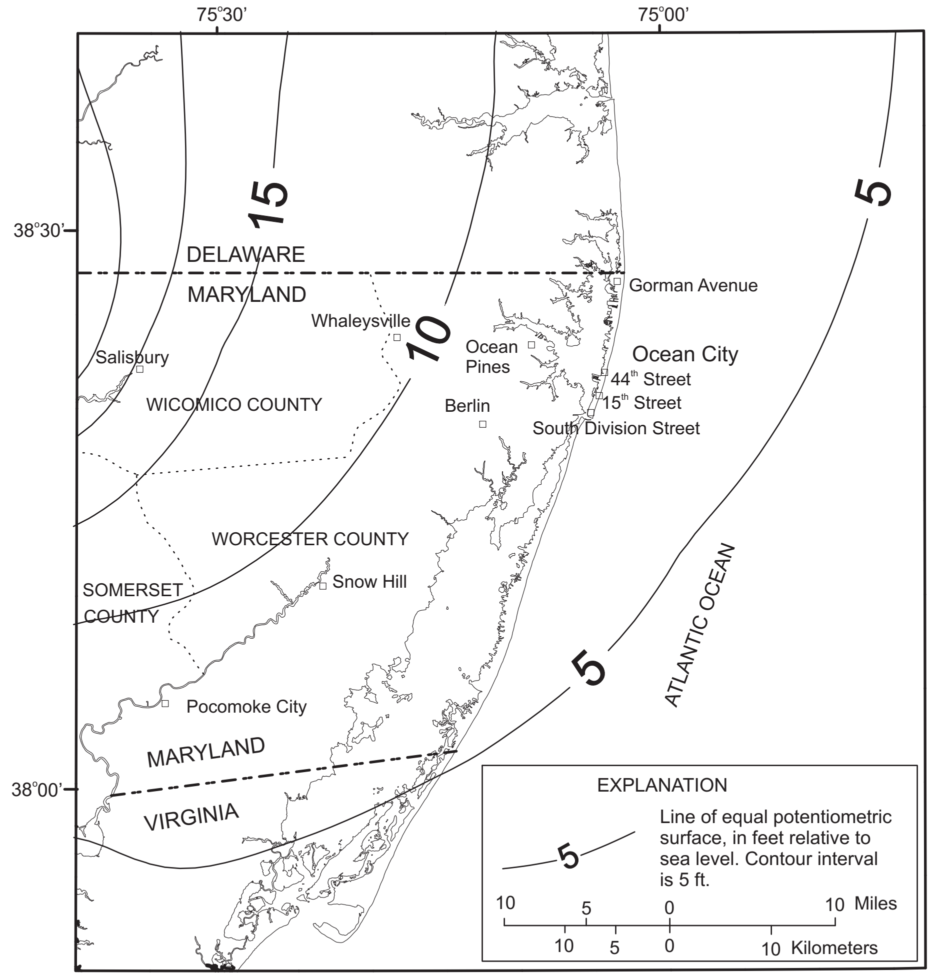


Figure 19. Simulated potentiometric surface of the Choptank-Calvert aquifer (undifferentiated) depicting the 1900 steady-state flow conditions.

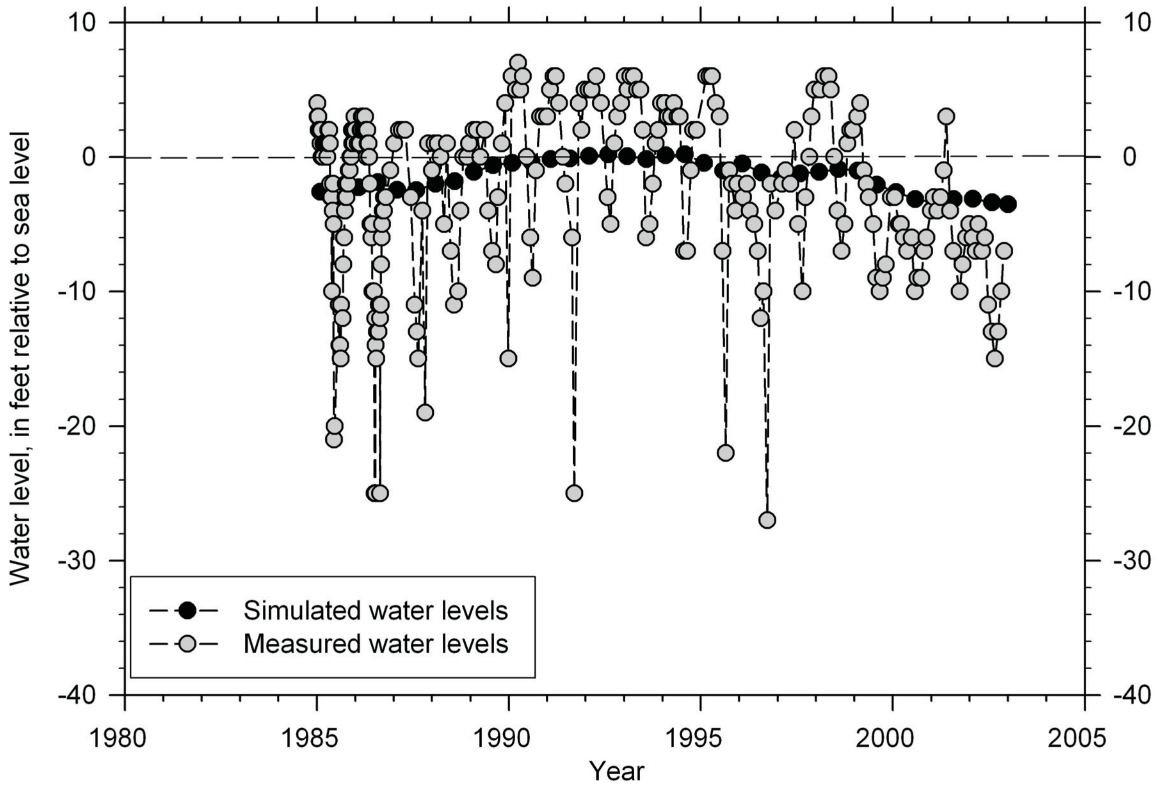


Figure 20. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Manokin aquifer observation well WO Cg 72 at the 15th Street well field.

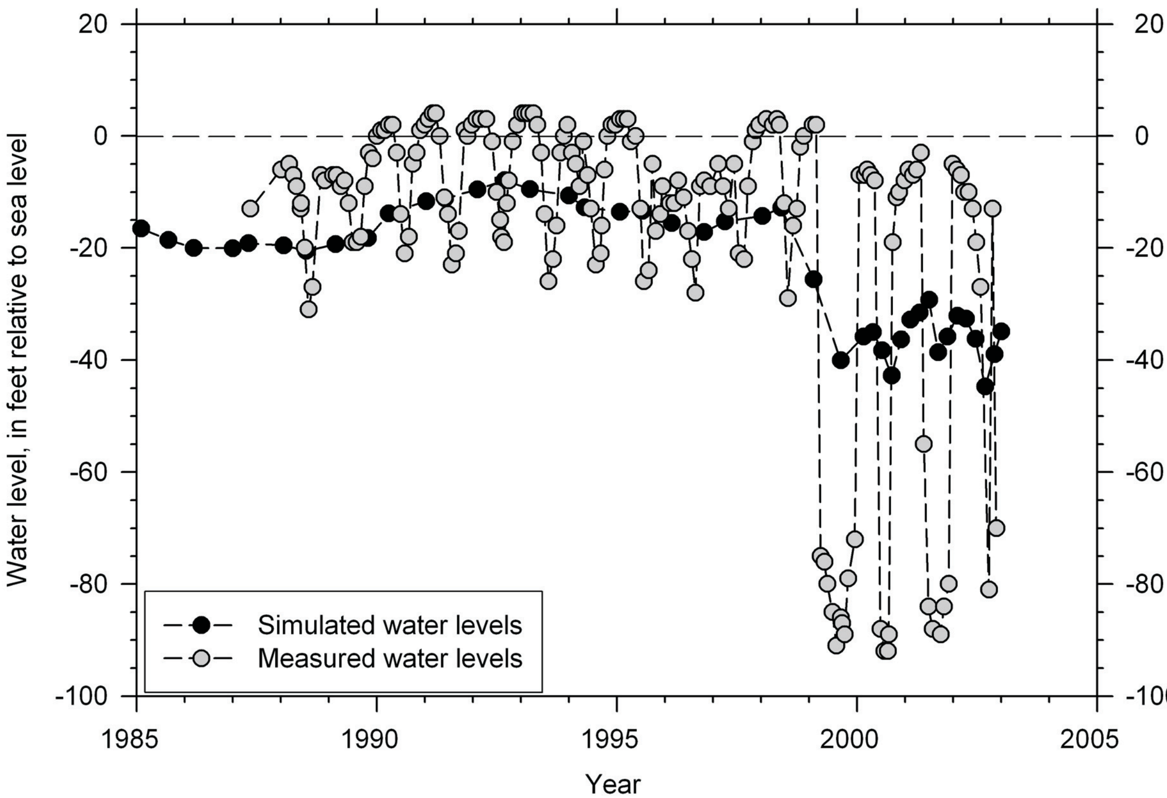


Figure 21. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Ocean City aquifer observation well WO Bh 98 at the 15th Street well field.

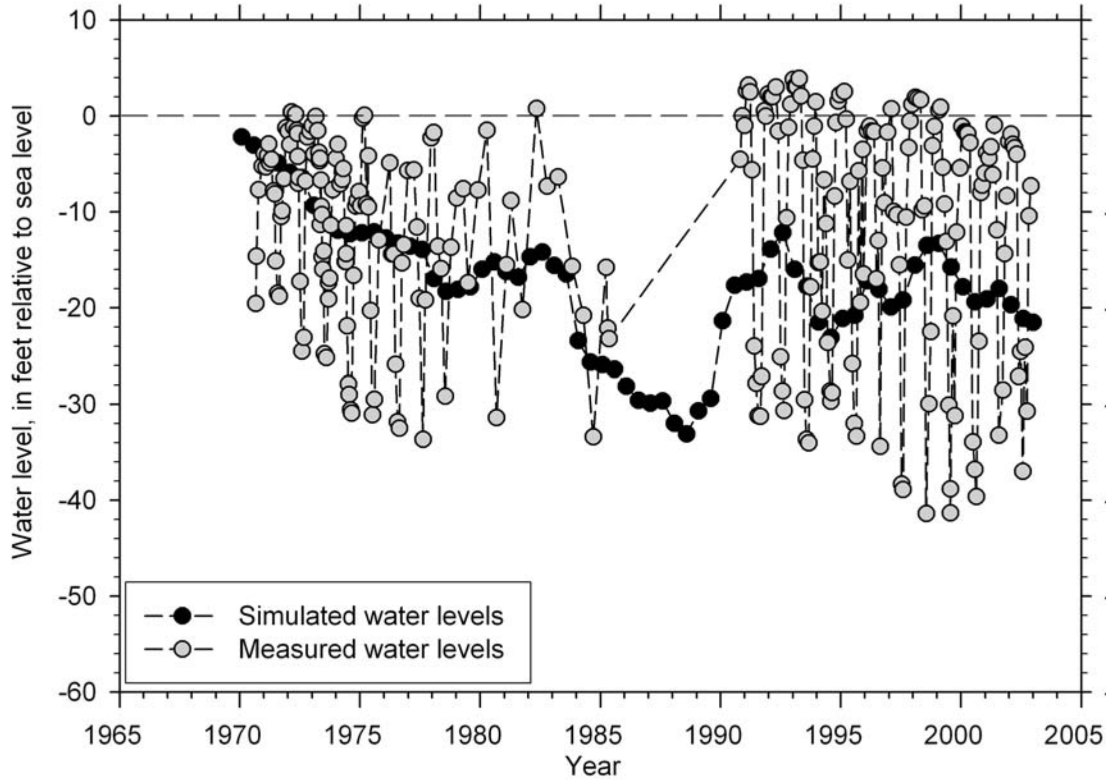


Figure 22. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Ocean City aquifer observation well WO Bh 31 at the 44th Street well field.

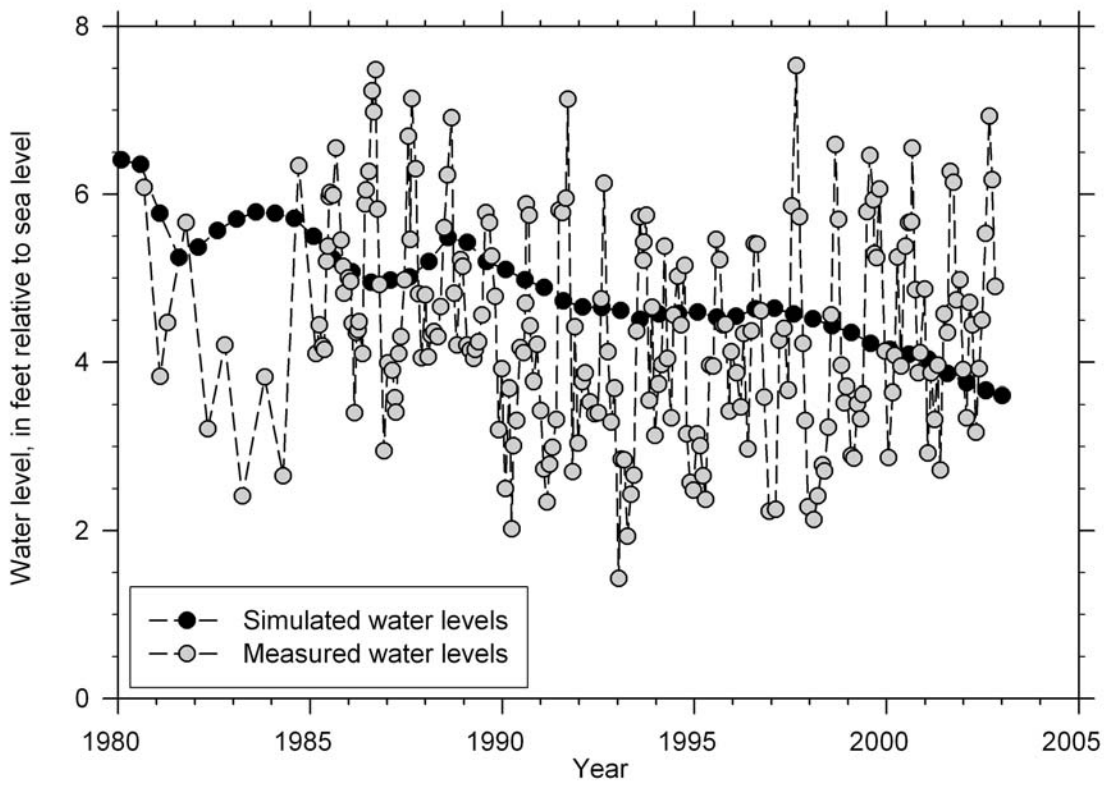


Figure 23. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Pocomoke aquifer observation well WO Bh 85 at the 44th Street well field.

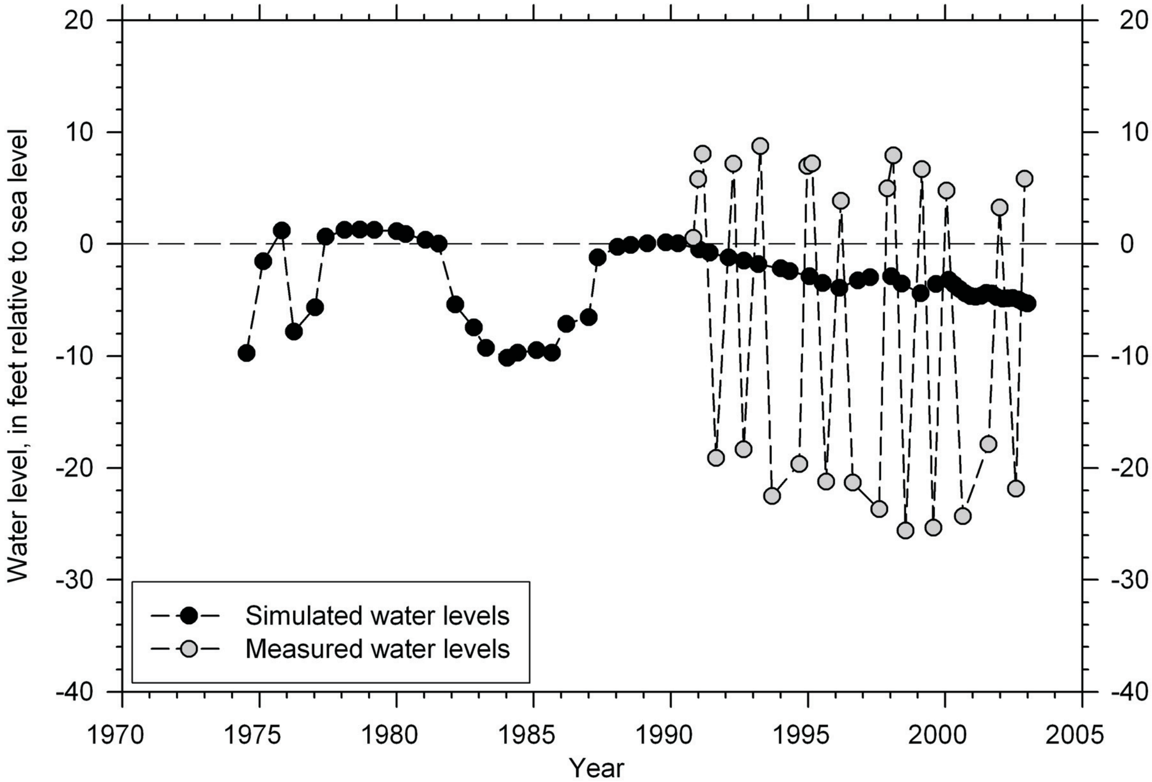


Figure 24. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Manokin aquifer observation well WO Bh 89 at the 44th Street well field.

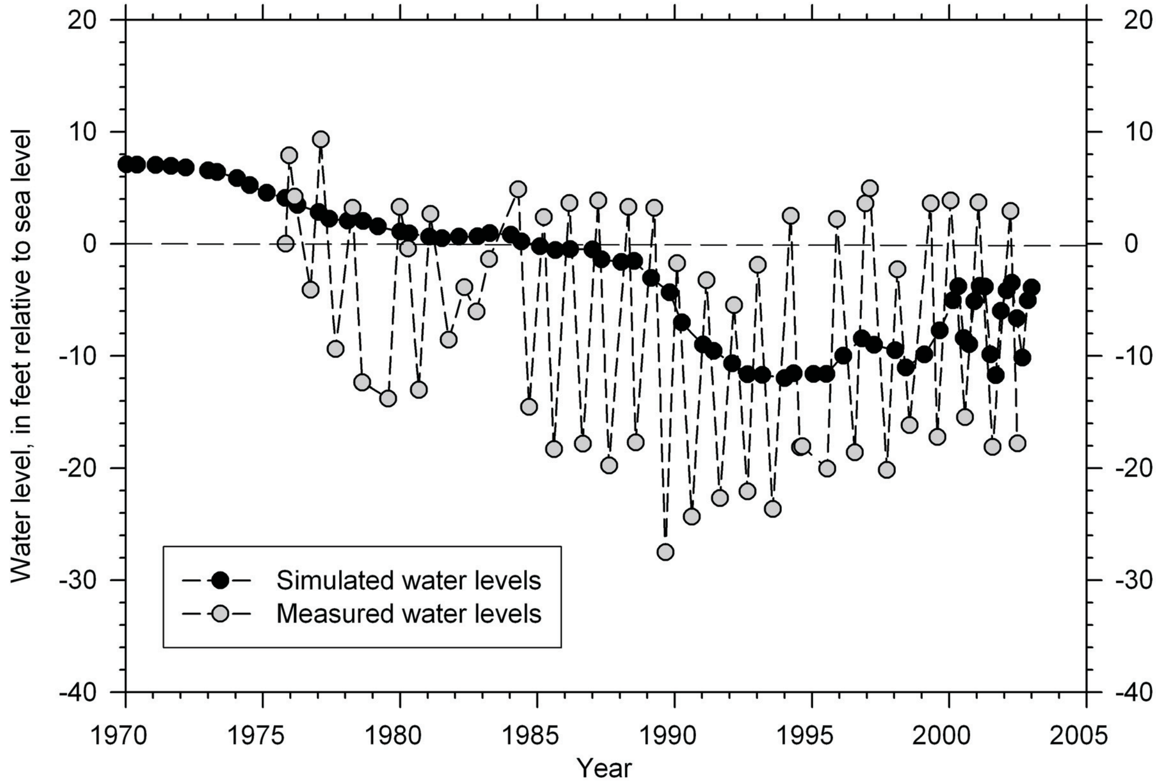


Figure 25. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Manokin aquifer observation well WO Ah 37 at the Gorman Avenue well field.

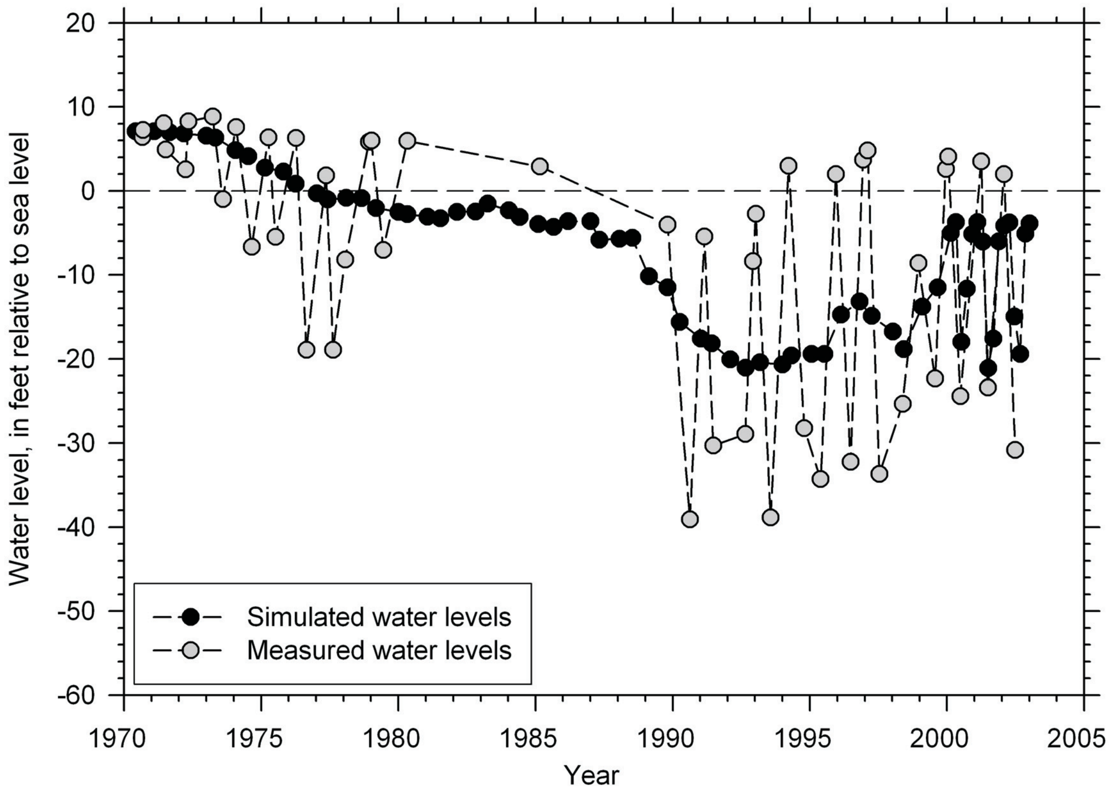


Figure 26. Comparison of simulated water levels using the monthly average withdrawal rates and water levels measured in the Manokin aquifer observation well WO Ah 6 at the Gorman Avenue well field.

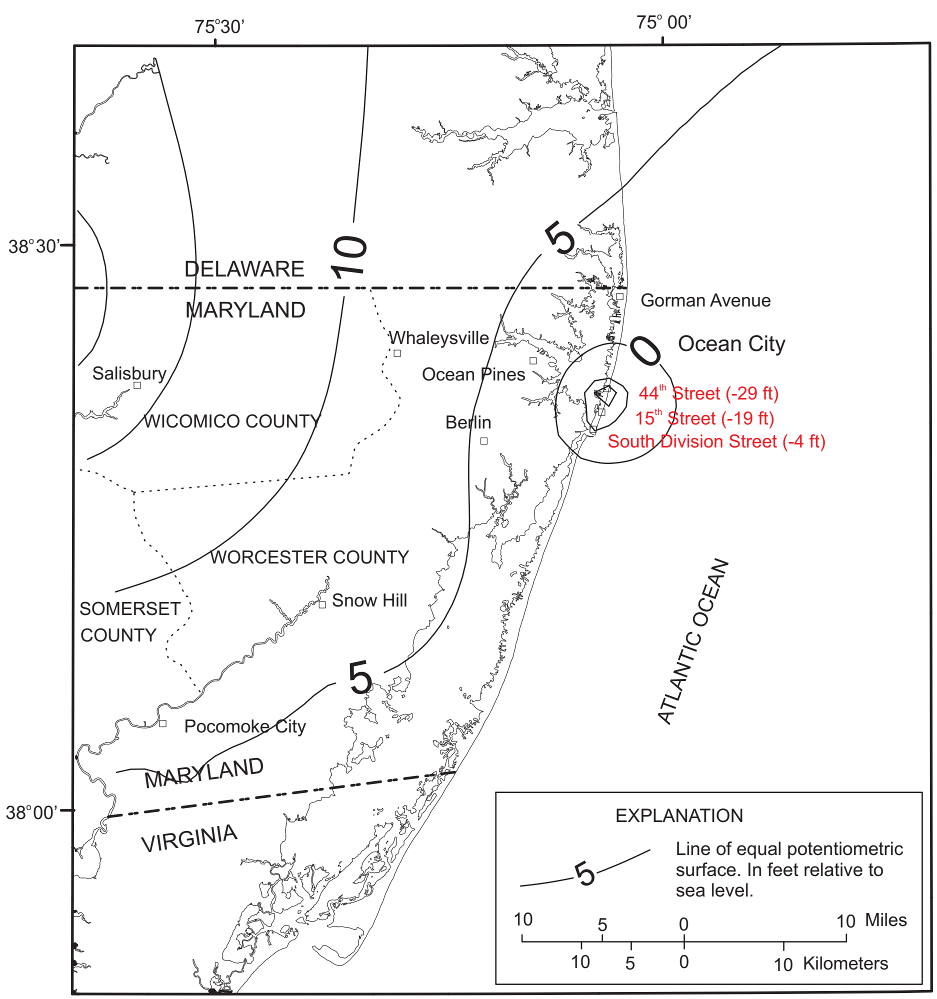


Figure 27. Simulated potentiometric surface of the Ocean City aquifer, using the August 1995 withdrawal.

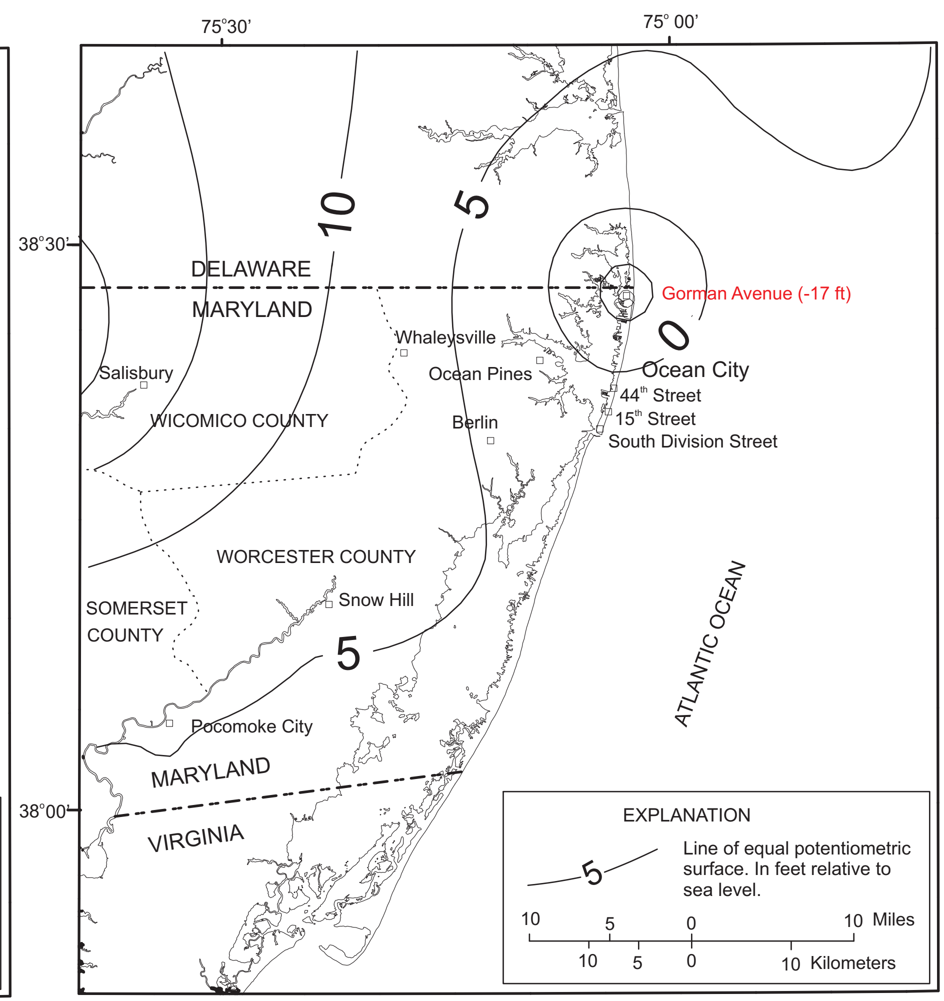


Figure 28. Simulated potentiometric surface of the Manokin aquifer, using the August 1995 withdrawal.

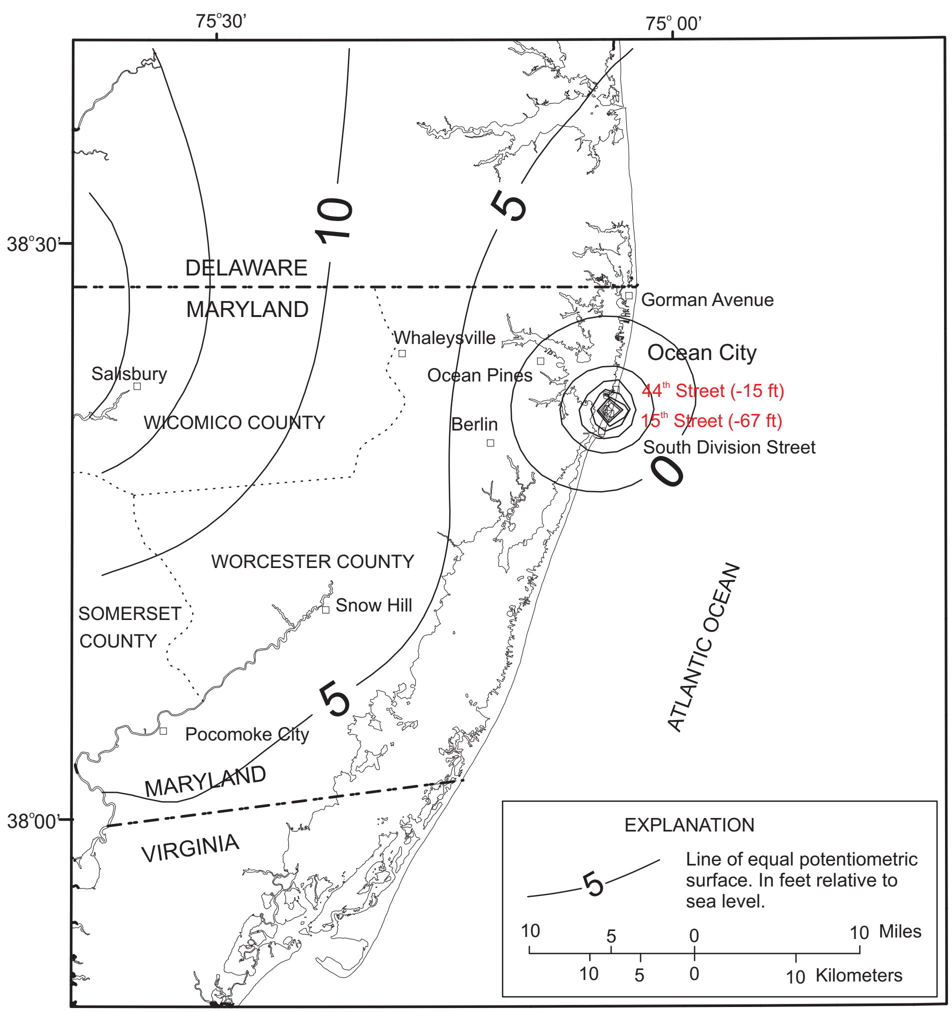


Figure 29. Simulated potentiometric surface of the Ocean City aquifer, using the August 2000 withdrawal.

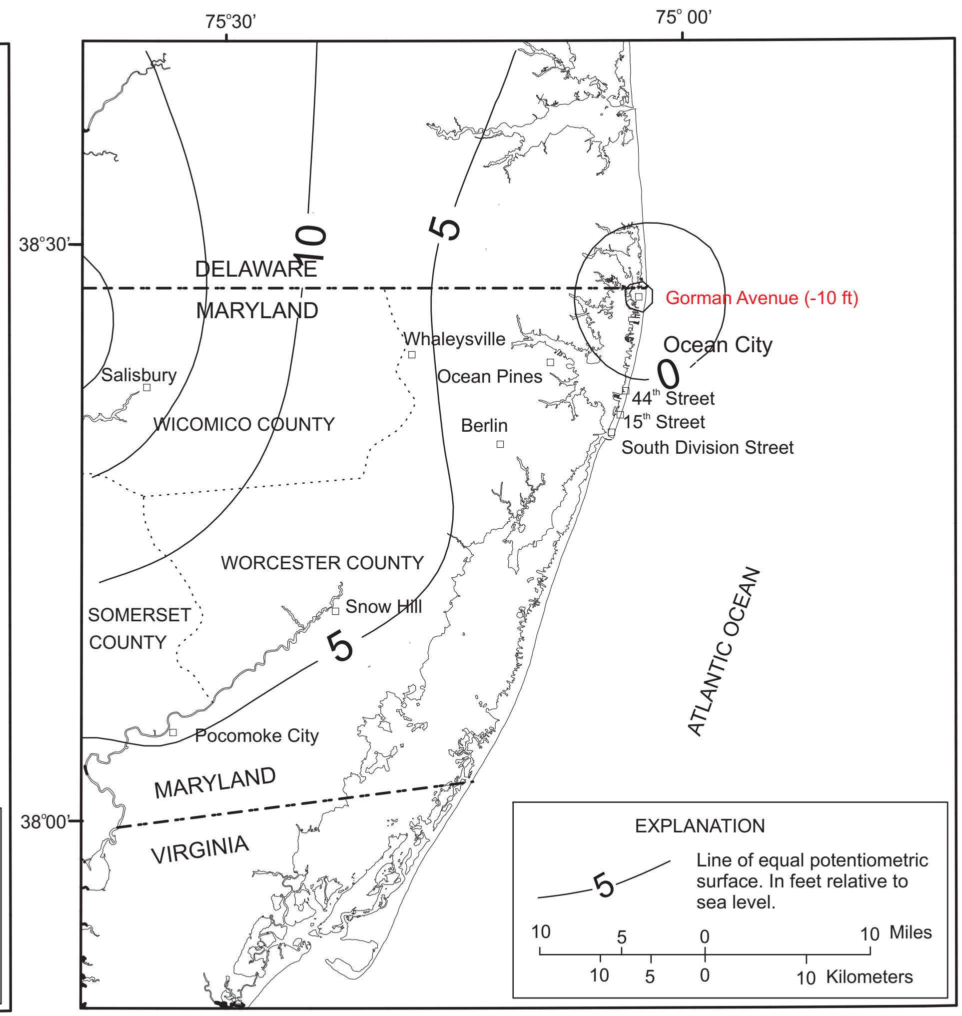


Figure 30. Simulated potentiometric surface of the Manokin aquifer, using the August 2000 withdrawal.

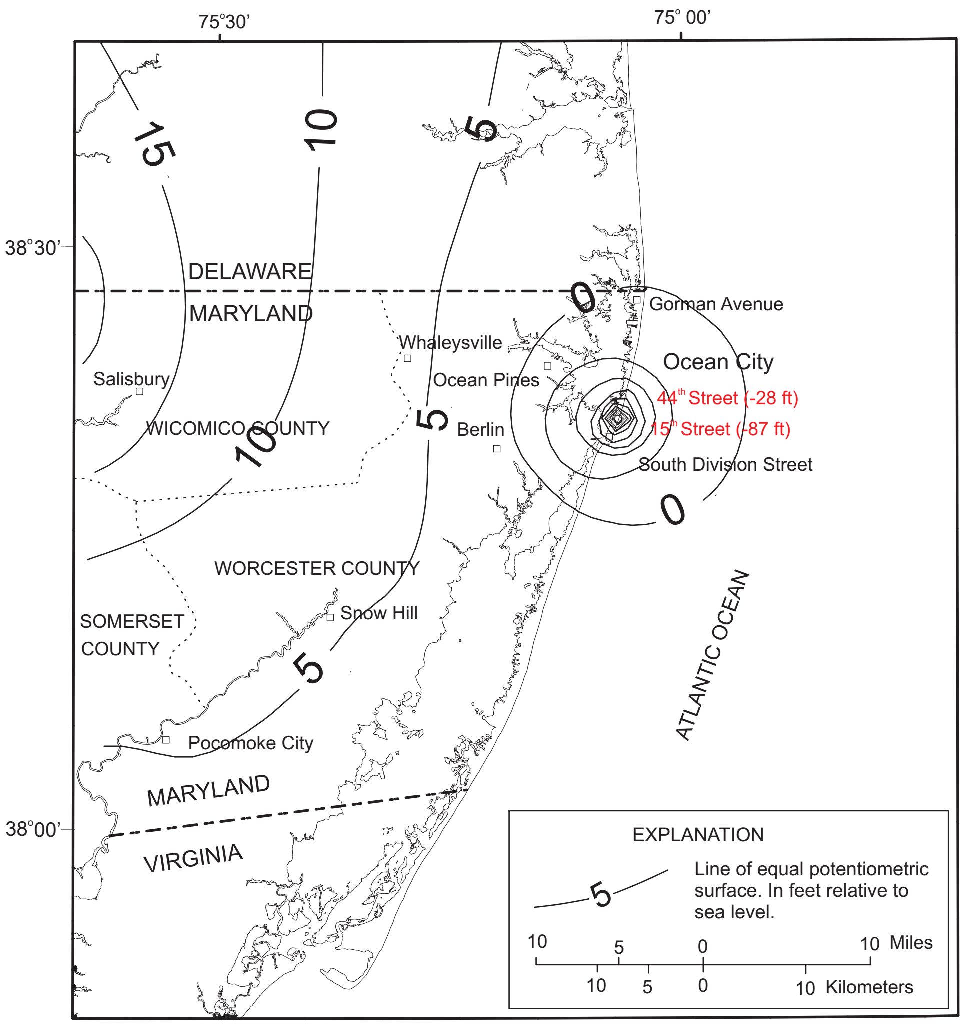


Figure 31. Simulated potentiometric surface of the Ocean City aquifer, using the August 2005 withdrawal.

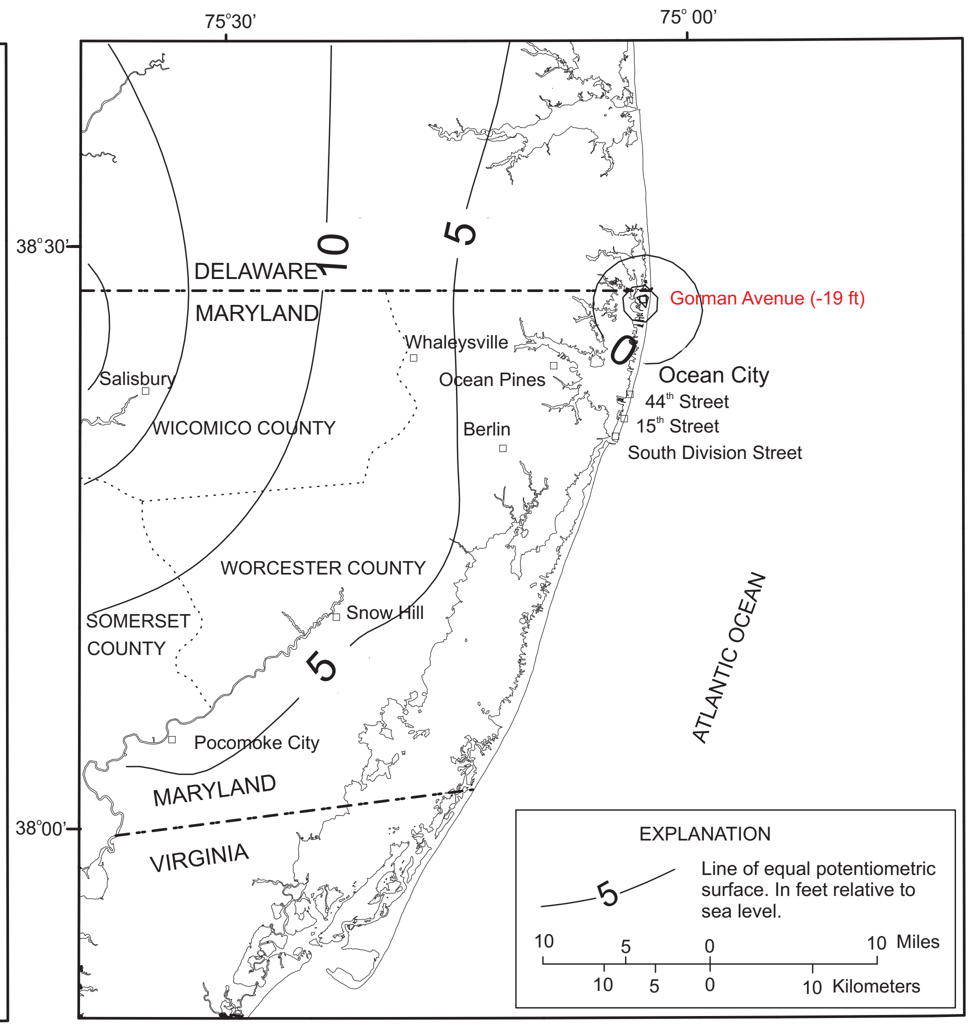


Figure 32. Simulated potentiometric surface of the Manokin aquifer, using the August 2005 withdrawal.

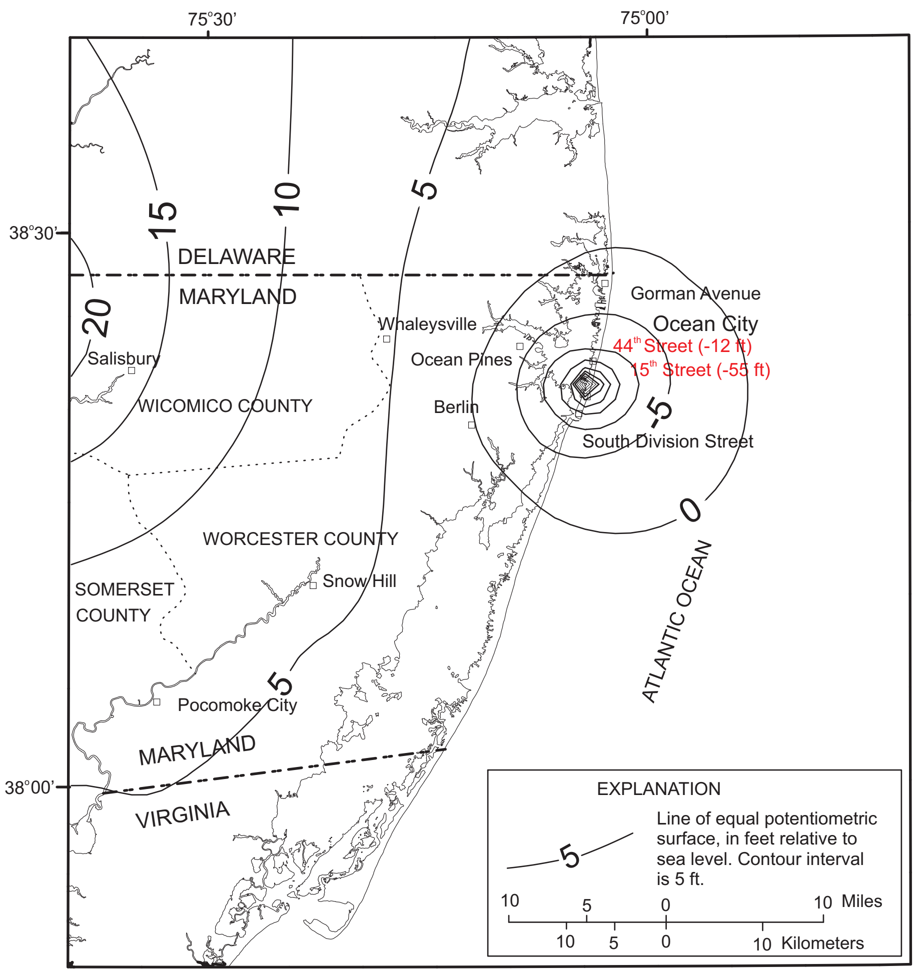


Figure 33. Simulated potentiometric surface of the Ocean City aquifer, using the December 2005 withdrawal.

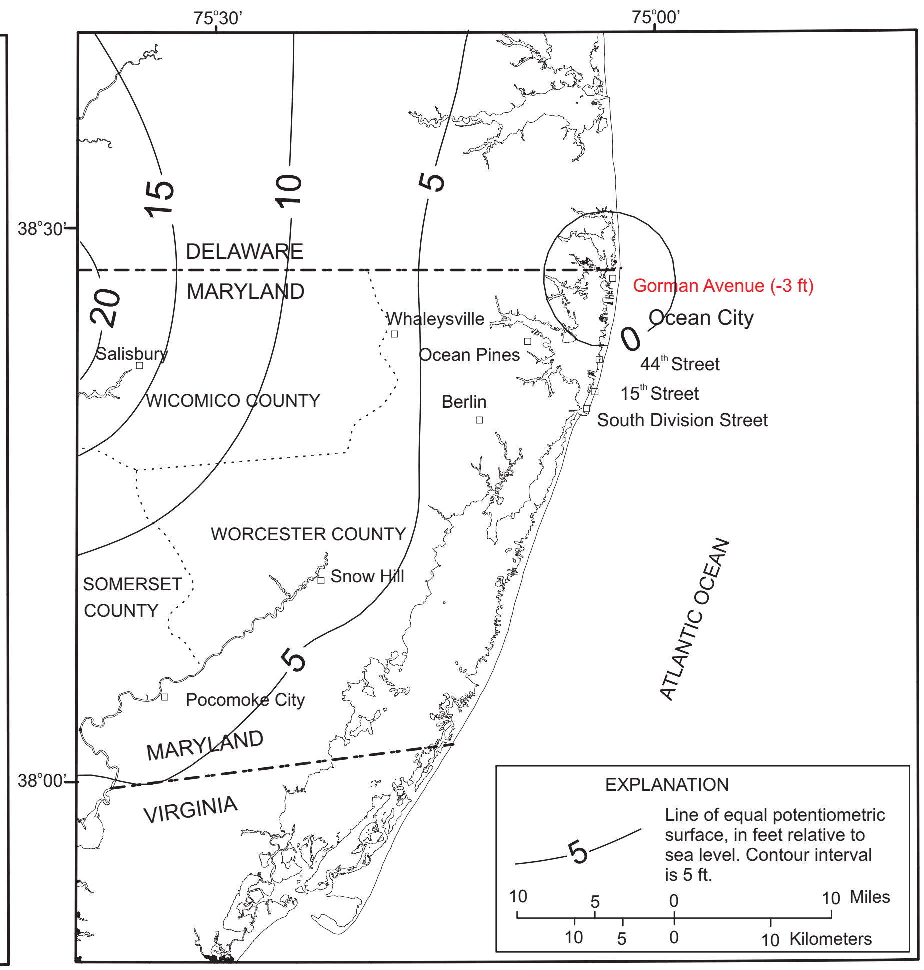


Figure 34. Simulated potentiometric surface of the Manokin aquifer, using the December 2005 withdrawal.

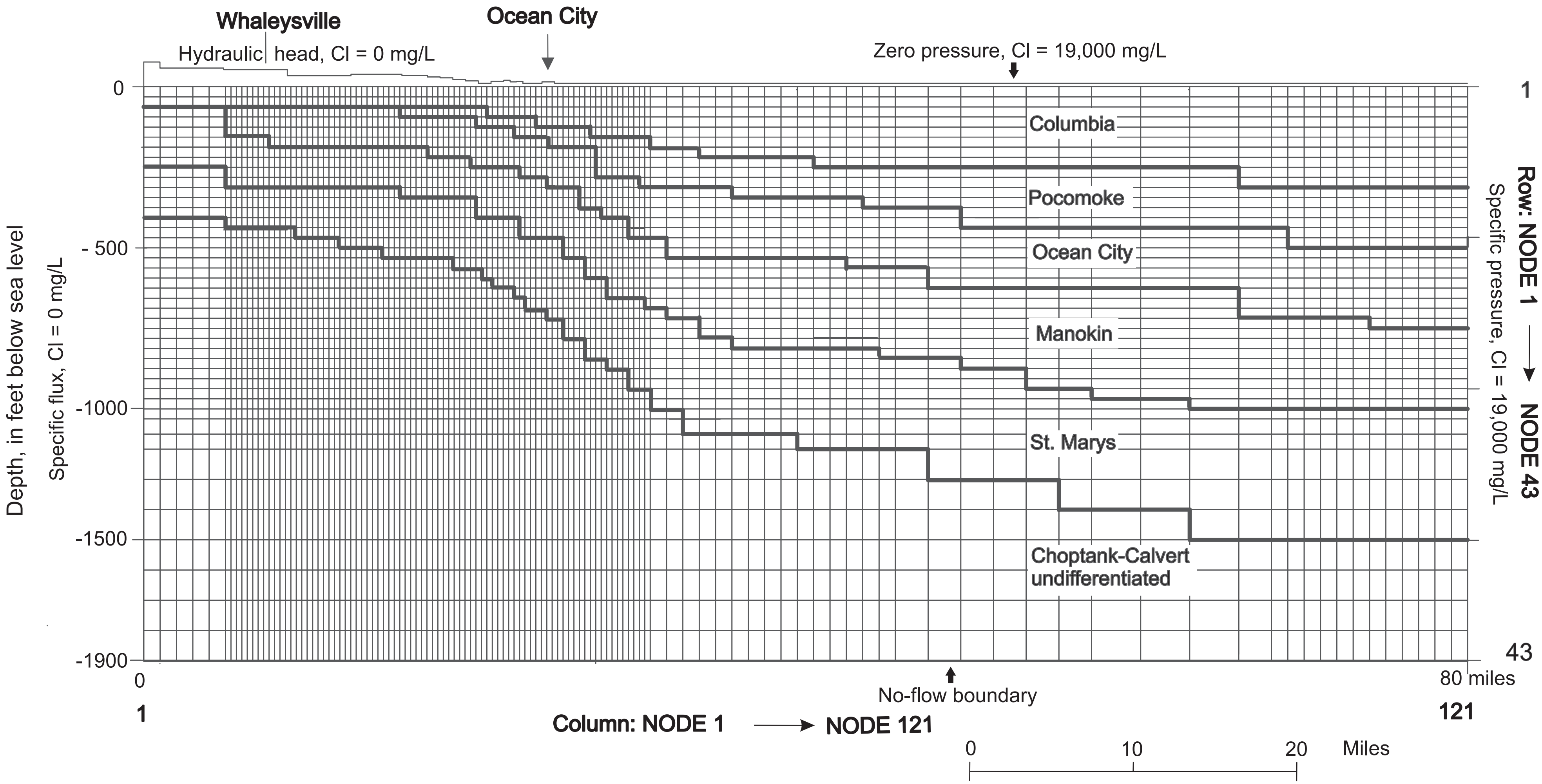
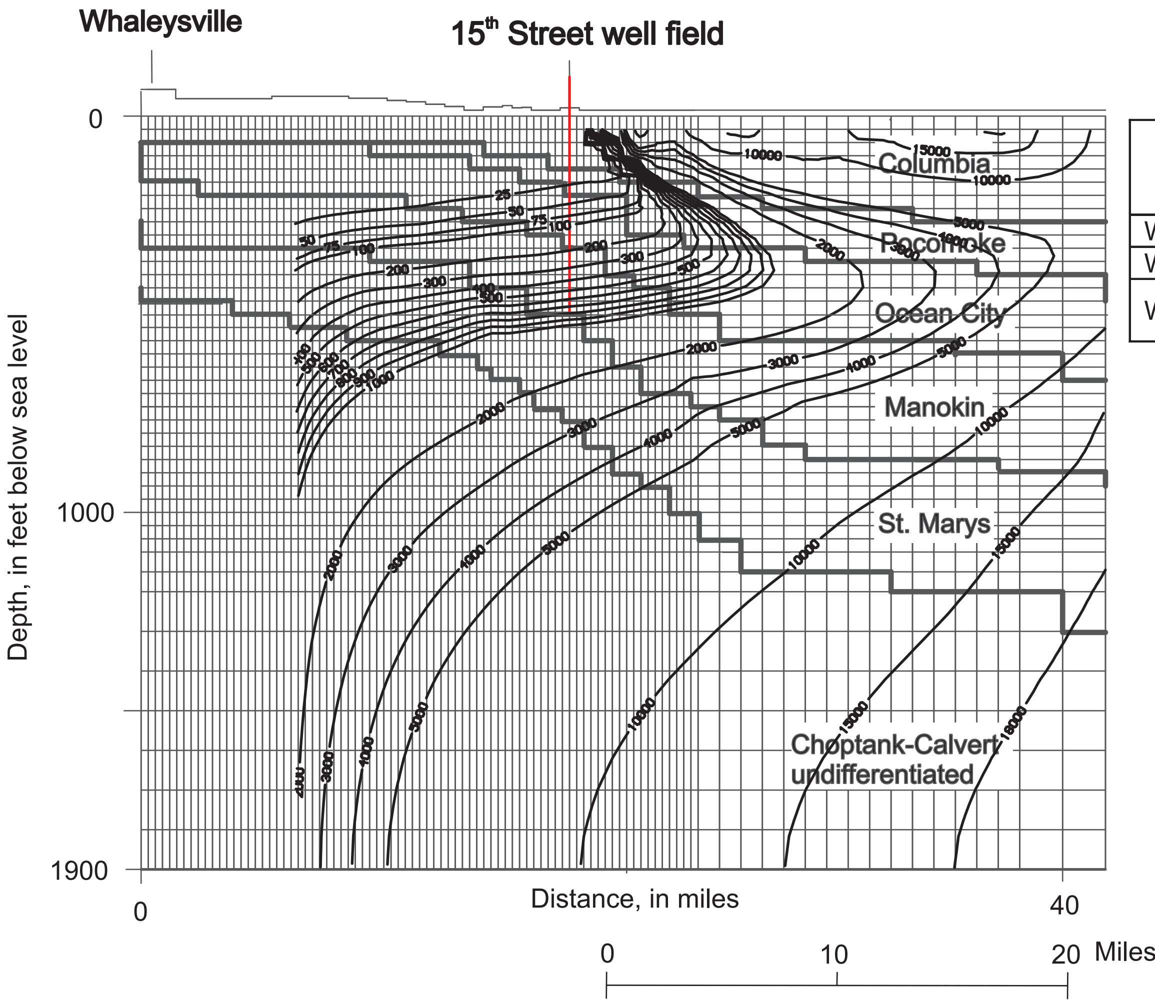


Figure 35. Model area and grid used in the cross-sectional model.

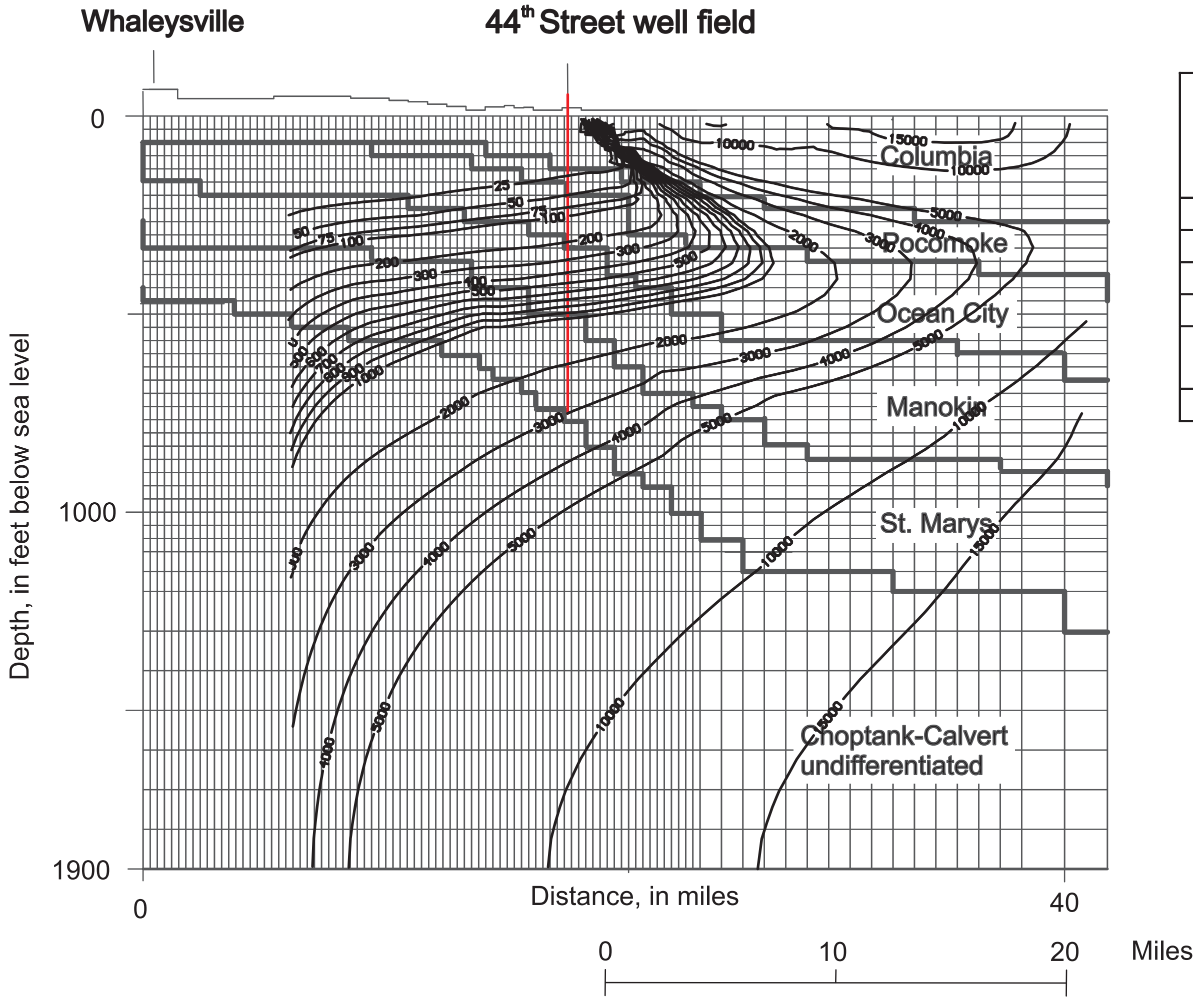


Well	Aquifer	Chloride (mg/L) Measured value (year)	Chloride (mg/L) Simulated value (1900)
WO Bh 8	Pocomoke	20 (1950)	23
WO Bh 1	Ocean City	30 (1951)	59
WO Bh 102	Manokin (base)	889 (2003)	865

EXPLANATION

50 — Isochlor of simulated chloride concentration, in milligrams per liter (mg/L). Contour interval varies.

Figure 36. Simulated 1900 prepumping chloride concentrations in observation wells at the 15th Street cross-sectional model.

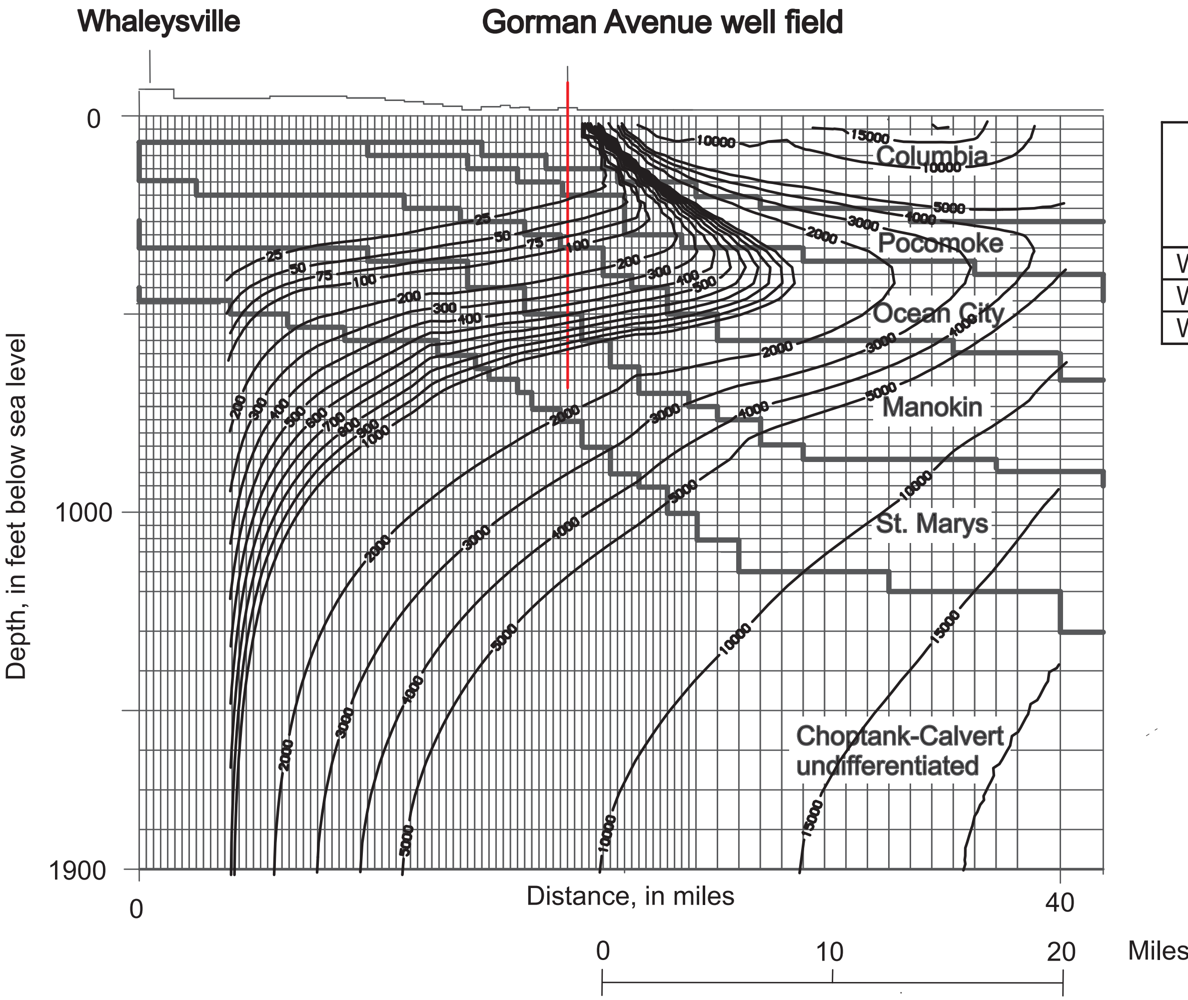


Well	Aquifer	Chloride (mg/L) Measured value (year)	Chloride (mg/L) Simulated value (1900)
WO Bh 84	Columbia	39 (1973)	19
WO Bh 85	Pocomoke	46 (1973)	49
WO Bh 28	Ocean City	160 (1985)	183
WO Bh 89	Manokin	520 (1989)	496
WO Bh 89	Manokin (base)	1,030 (1987)	1,080
WO Bh 90	Choptank	2,900 (1989)	2,904

EXPLANATION

Isochlor of simulated chloride concentration, in milligrams per liter (mg/L). Contour interval varies.

Figure 37. Simulated 1900 prepumping chloride concentrations in observation wells at the 44th Street cross-sectional model.



Well	Aquifer	Chloride (mg/L) Measured value (year)	Simulated value (1900)
WO Ah 36	Manokin	170 (1975)	210
WO Ah 6	Manokin	300 (1969)	370
WO Ah 6	Choptank	2,700 (1969)	1,995

EXPLANATION

50 — Isochlor of simulated chloride concentration, in milligrams per liter (mg/L). Contour interval varies.

Figure 38. Simulated 1900 prepumping chloride concentrations in observation wells at the Gorman Avenue cross-sectional model.

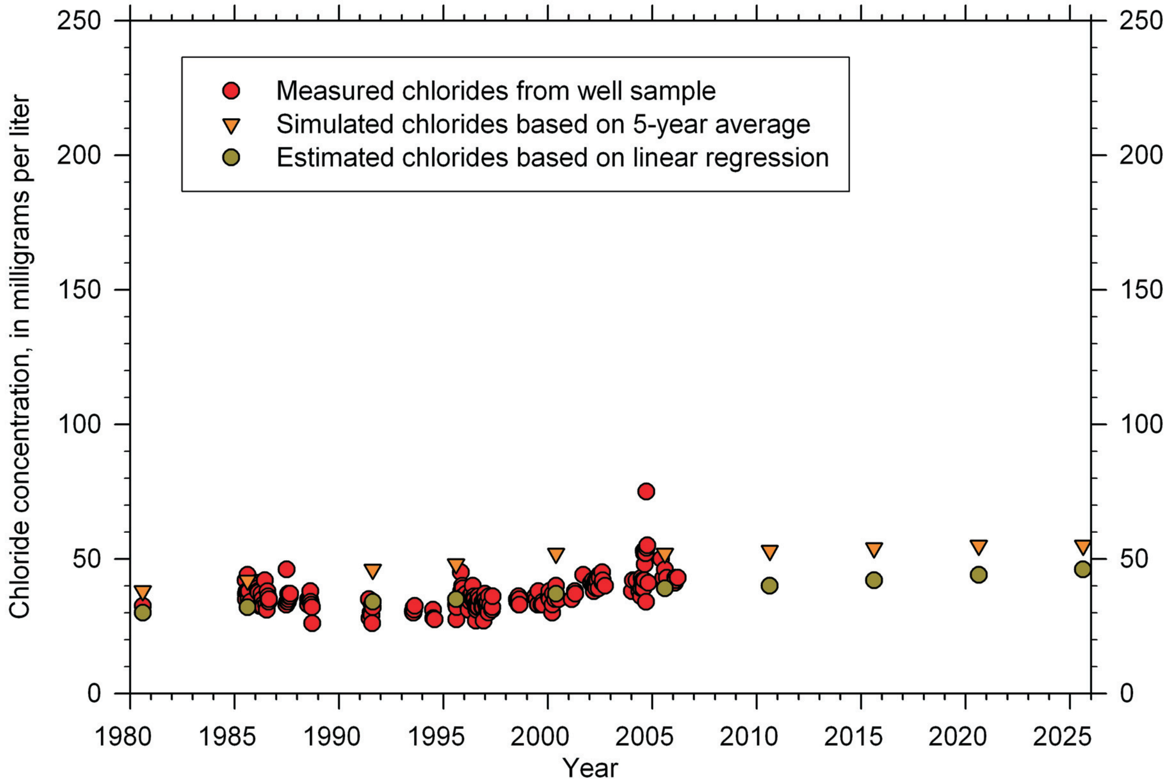


Figure 39. Measured, simulated, and estimated chloride concentrations in the Ocean City aquifer production well B (WO Bh 27) using the 15th Street cross-sectional model.

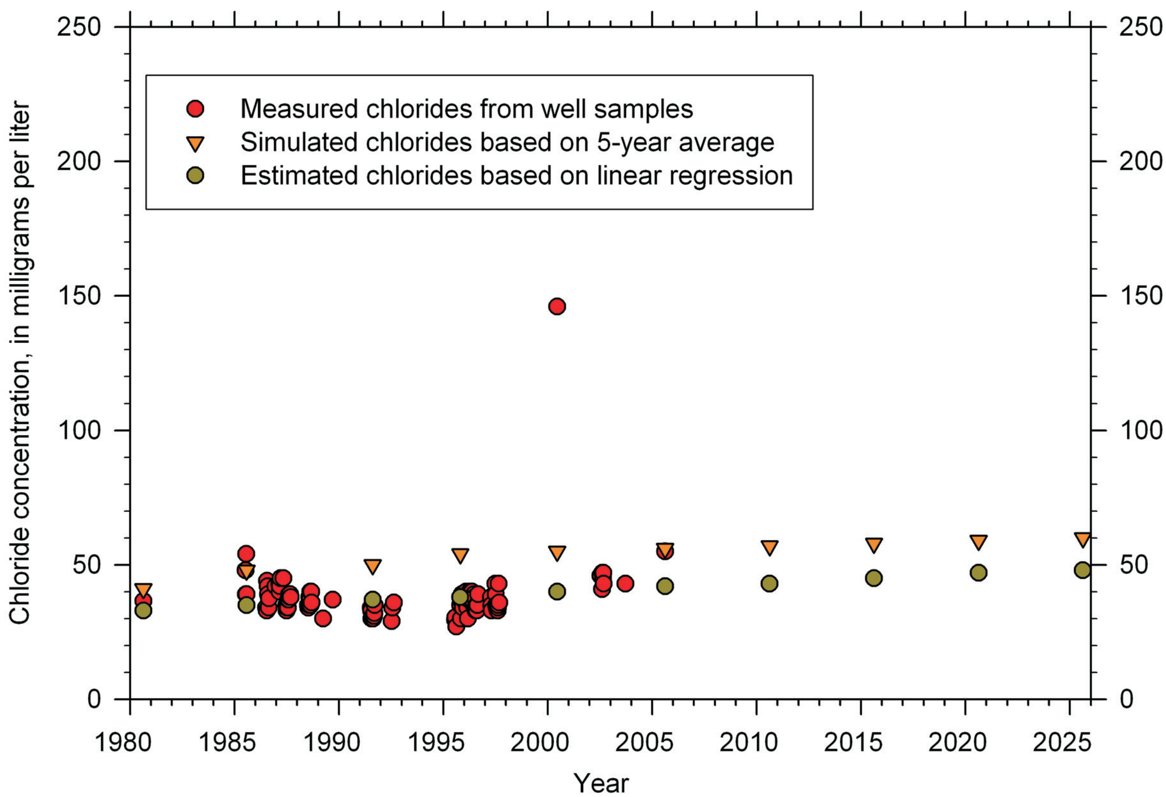


Figure 40. Measured, simulated, and estimated chloride concentrations in the Ocean City aquifer production well C (WO Bh 30) using the 15th Street cross-sectional model.

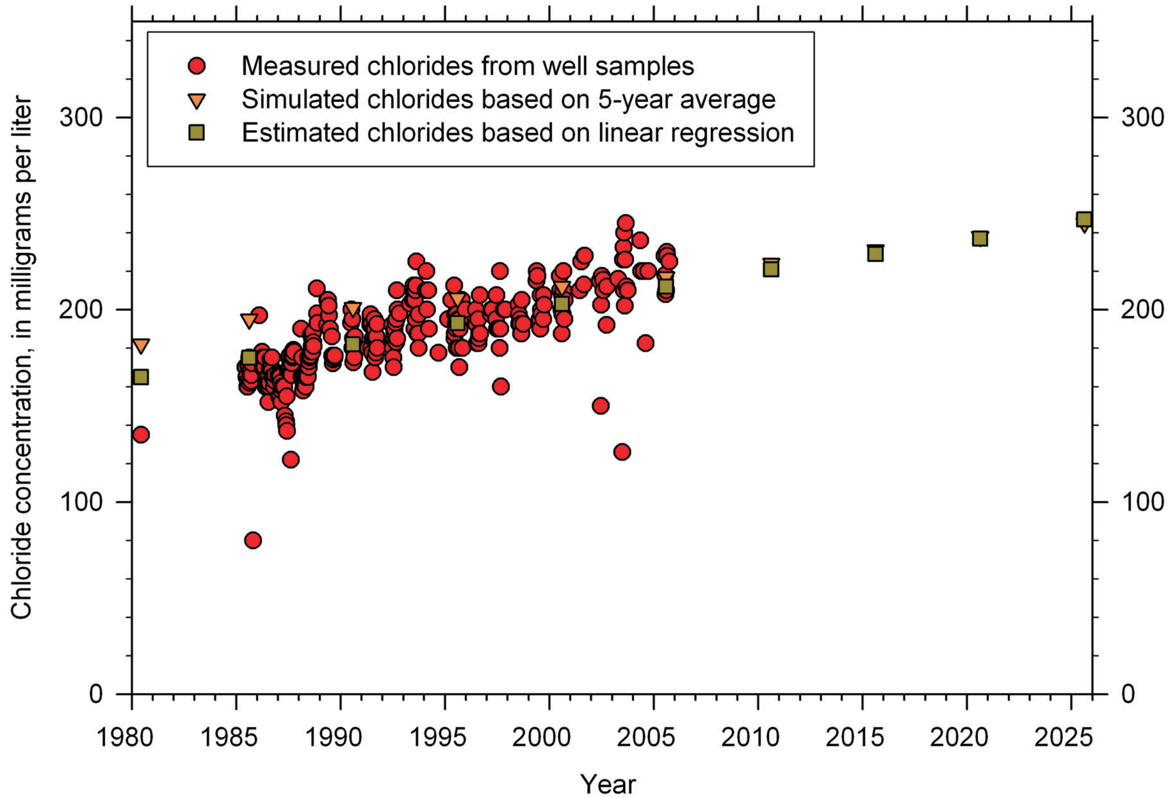


Figure 41. Measured, simulated, and estimated chloride concentrations in the Ocean City aquifer production well A (WO Bh 28) using the 44th Street cross-sectional model.

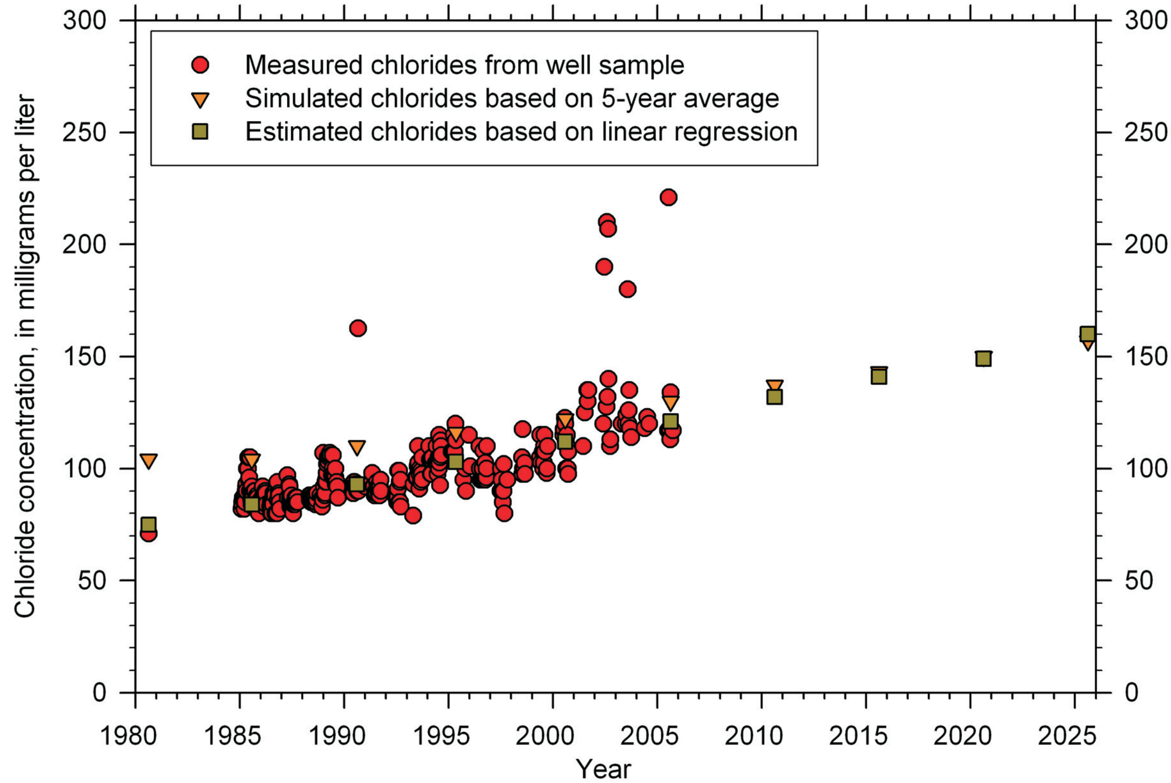


Figure 42. **Measured, simulated, and estimated chloride concentrations in the Ocean City aquifer production well B (WO Bh 29) using the 44th Street cross-sectional model.**

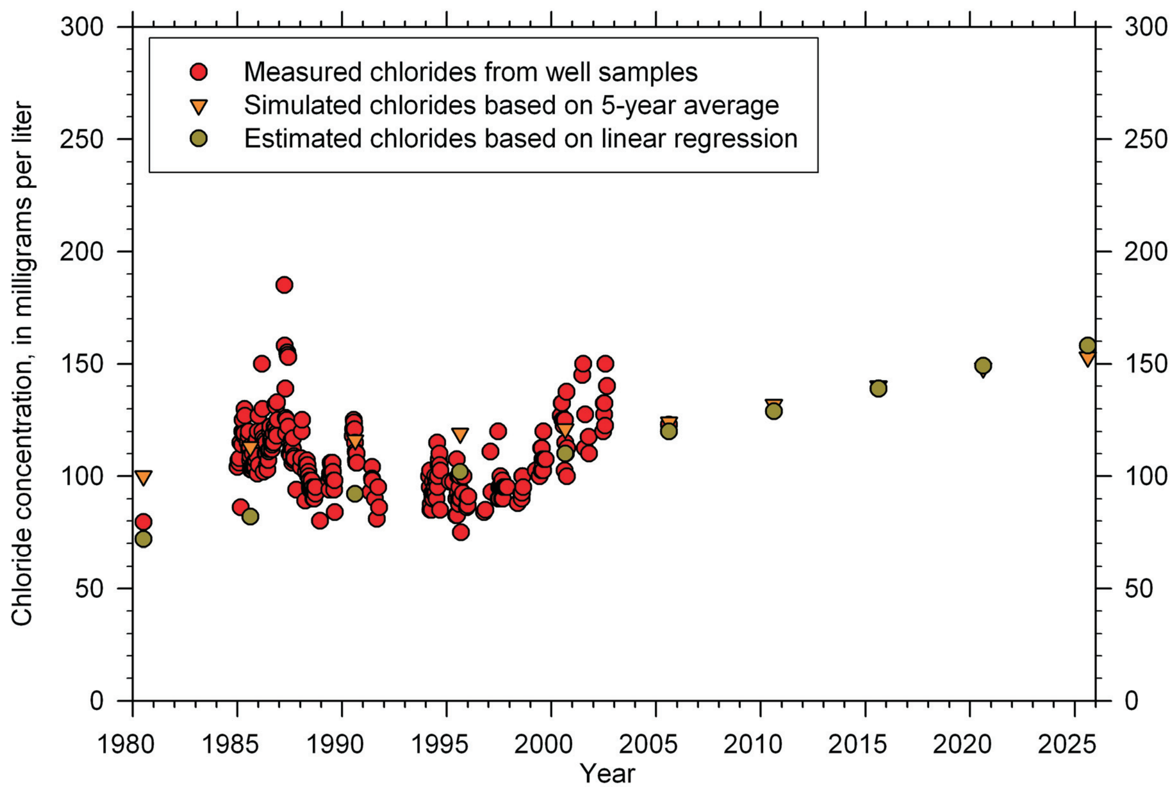


Figure 43. **Measured, simulated, and estimated chloride concentrations in the Ocean City aquifer production well C (WO Bh 41) using the 44th Street cross-sectional model.**

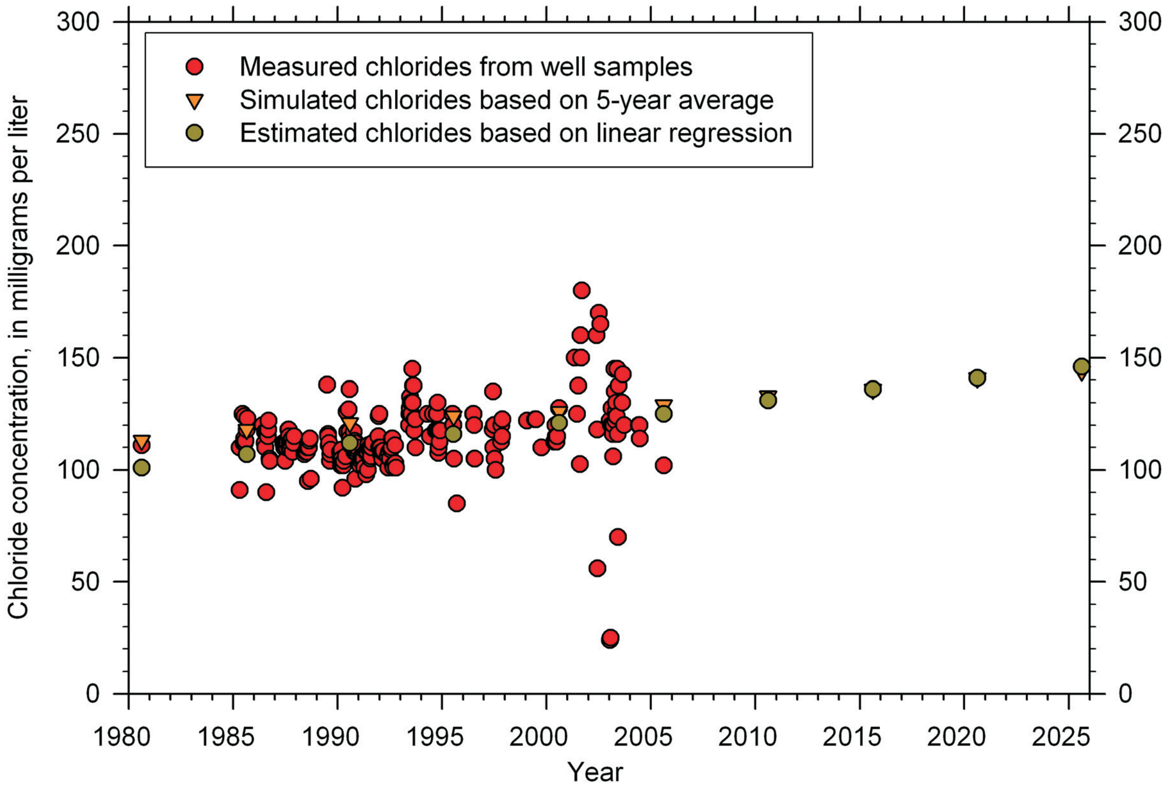


Figure 44. Measured, simulated, and estimated chloride concentrations in the Manokin aquifer production well A (WO Ah 34) using the Gorman Avenue cross-sectional model.

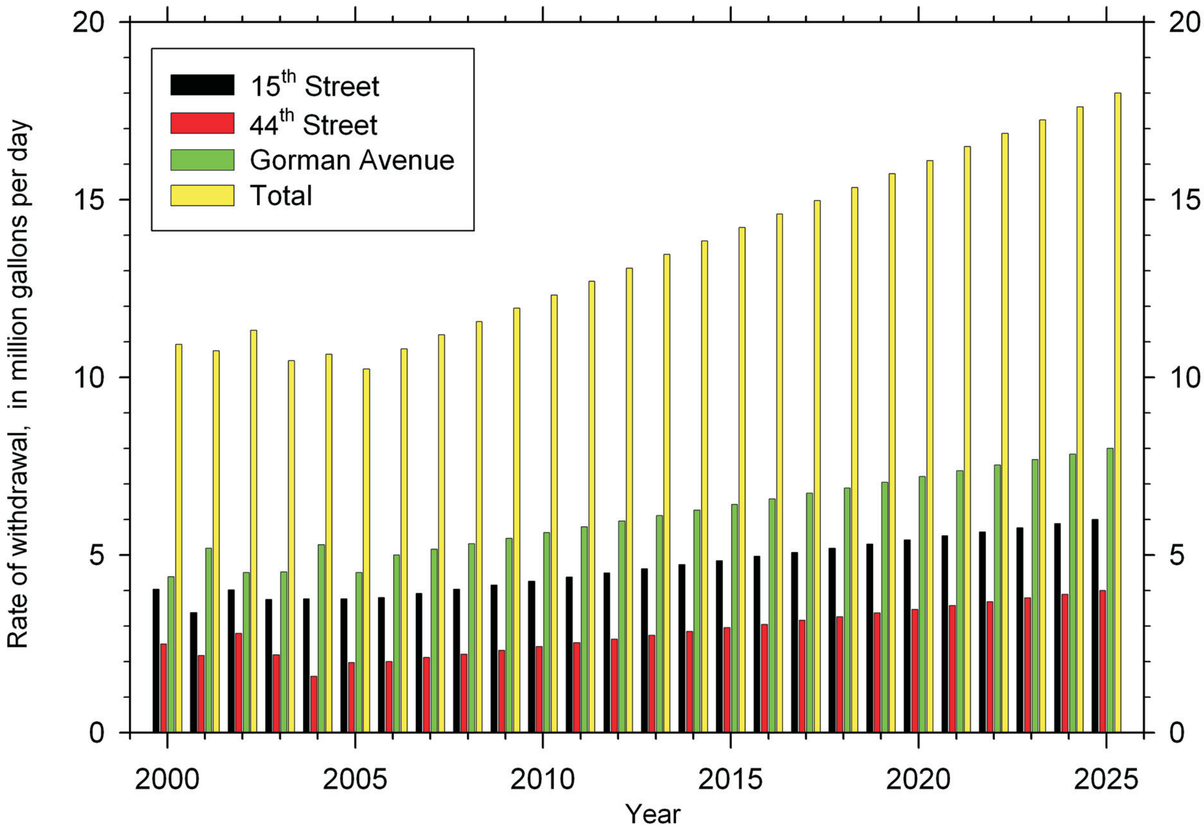


Figure 45. Actual (2000-2005) and estimated (2006-2025) average daily withdrawal rates during the month of maximum withdrawals from the 15th Street, 44th Street, and Gorman Avenue well fields in Ocean City.

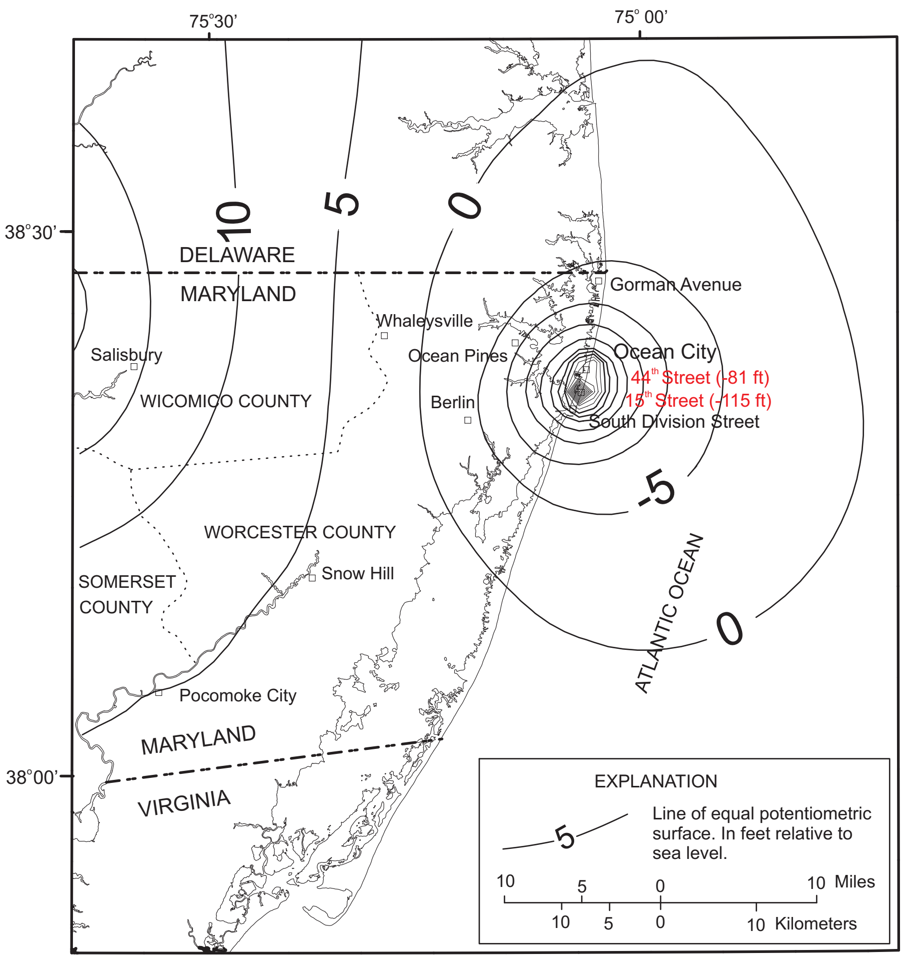


Figure 46. Simulated August 2025 potentiometric surface of the Ocean City aquifer.

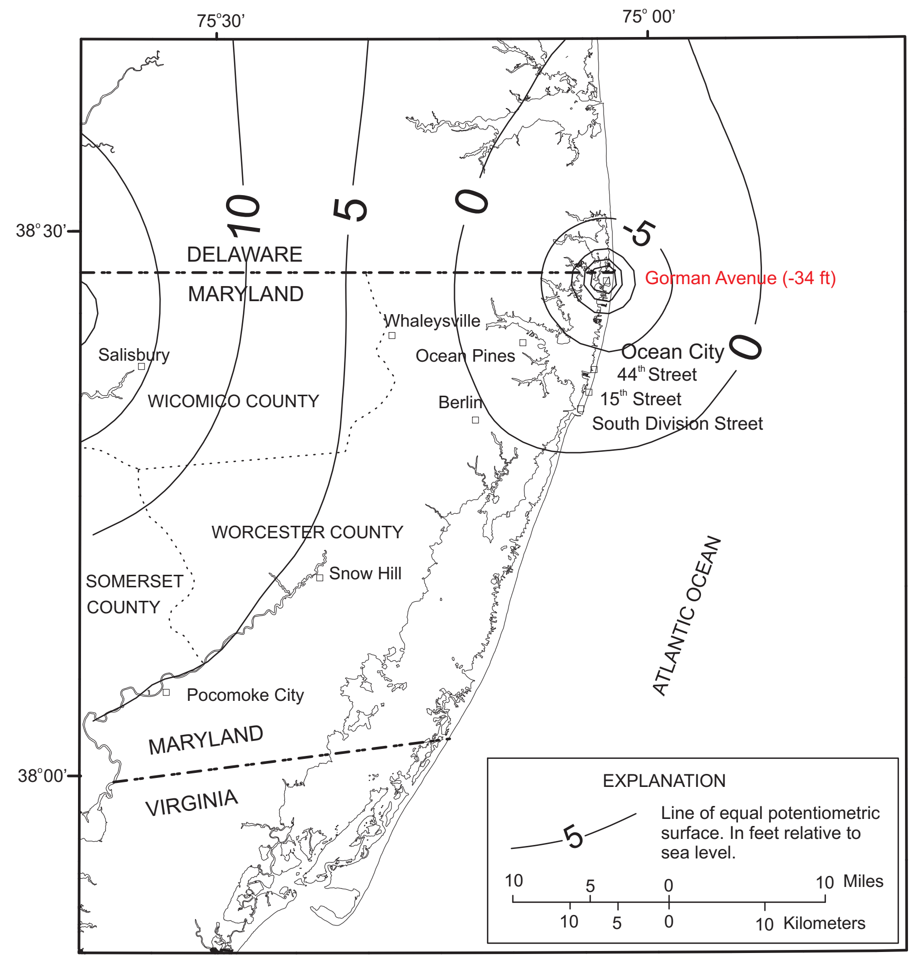


Figure 47. Simulated August 2025 potentiometric surface of the Manokin aquifer.

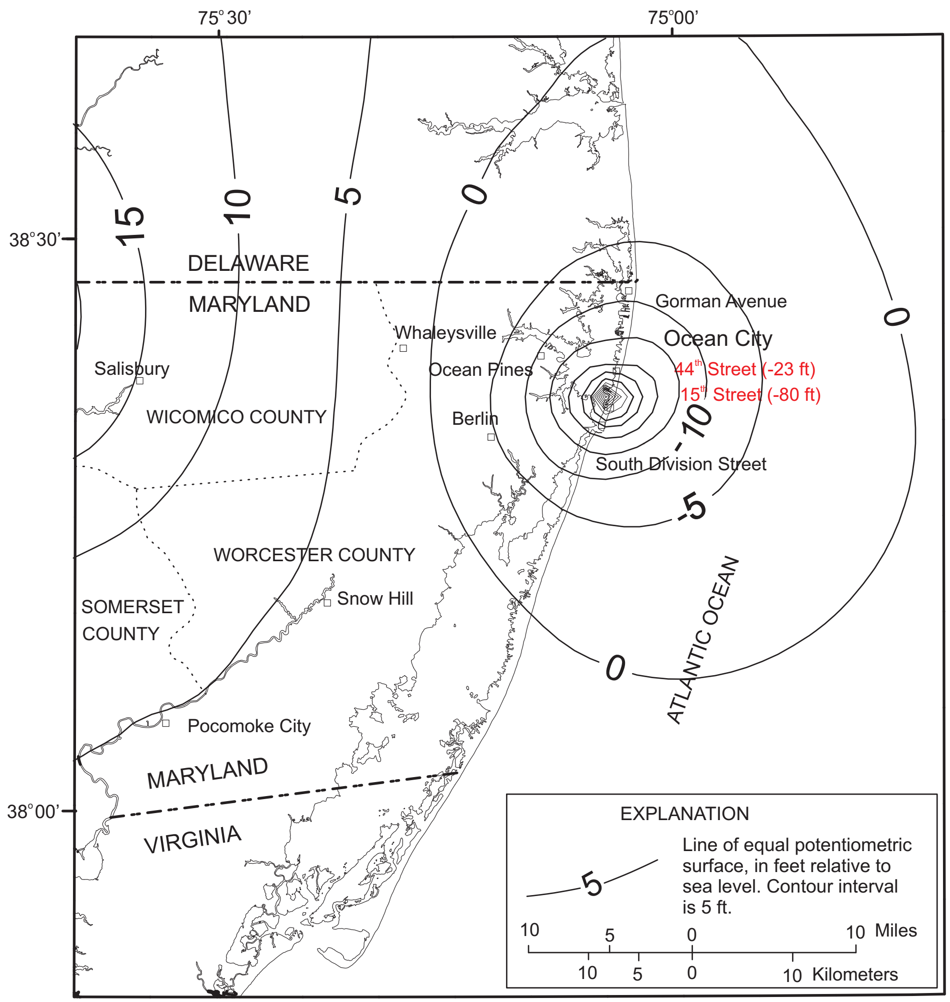


Figure 48. Simulated December 2025 potentiometric surface of the Ocean City aquifer.

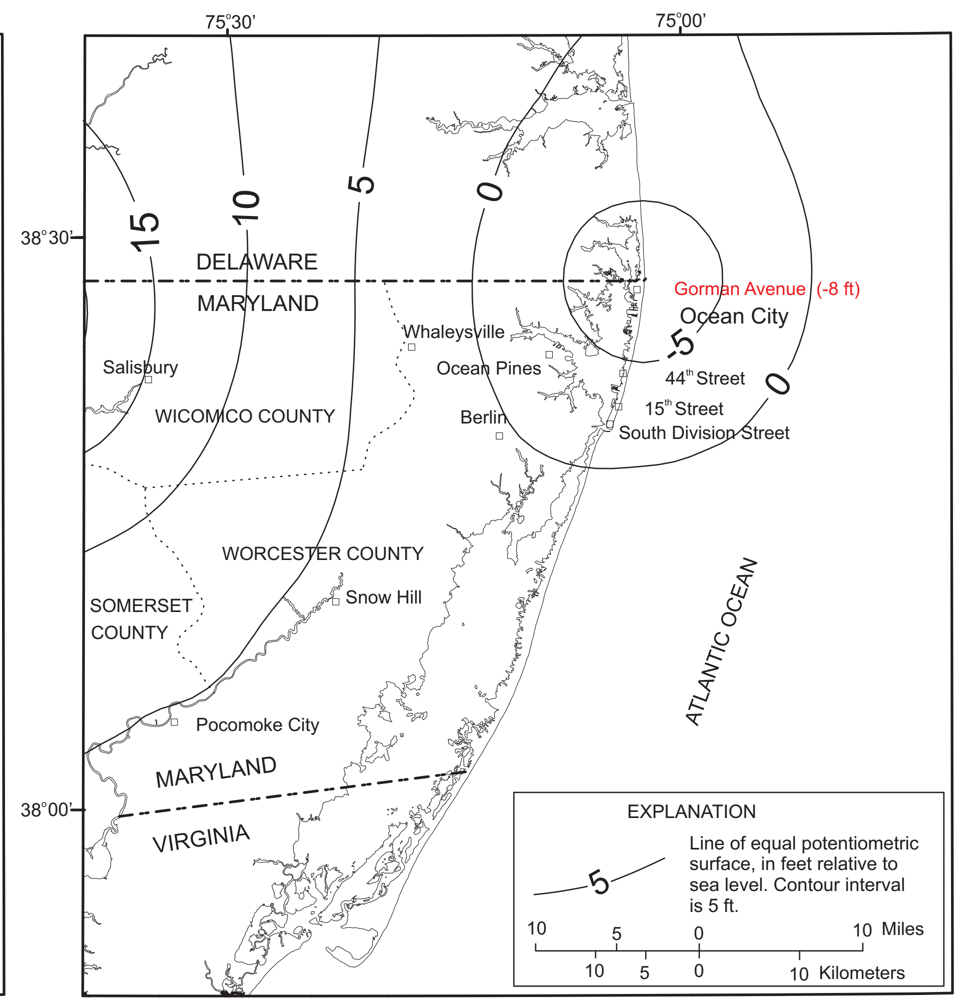


Figure 49. Simulated December 2025 potentiometric surface of the Manokin aquifer.

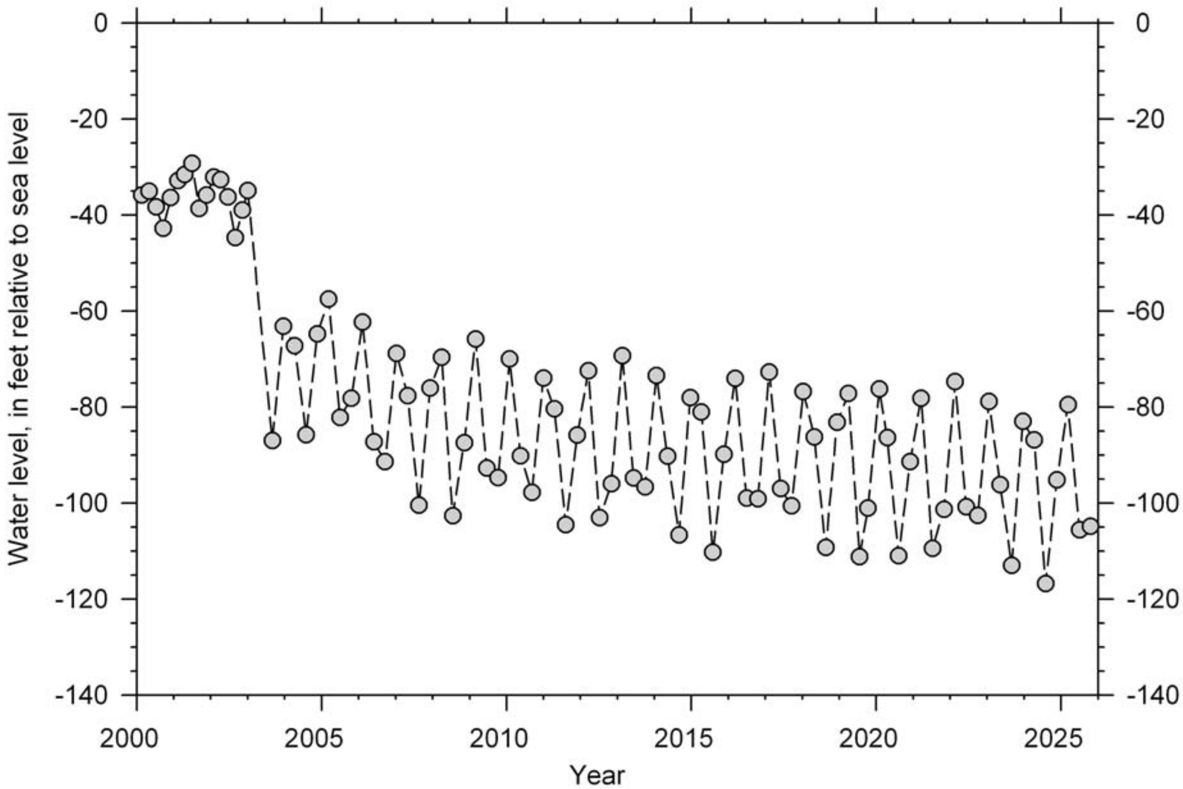
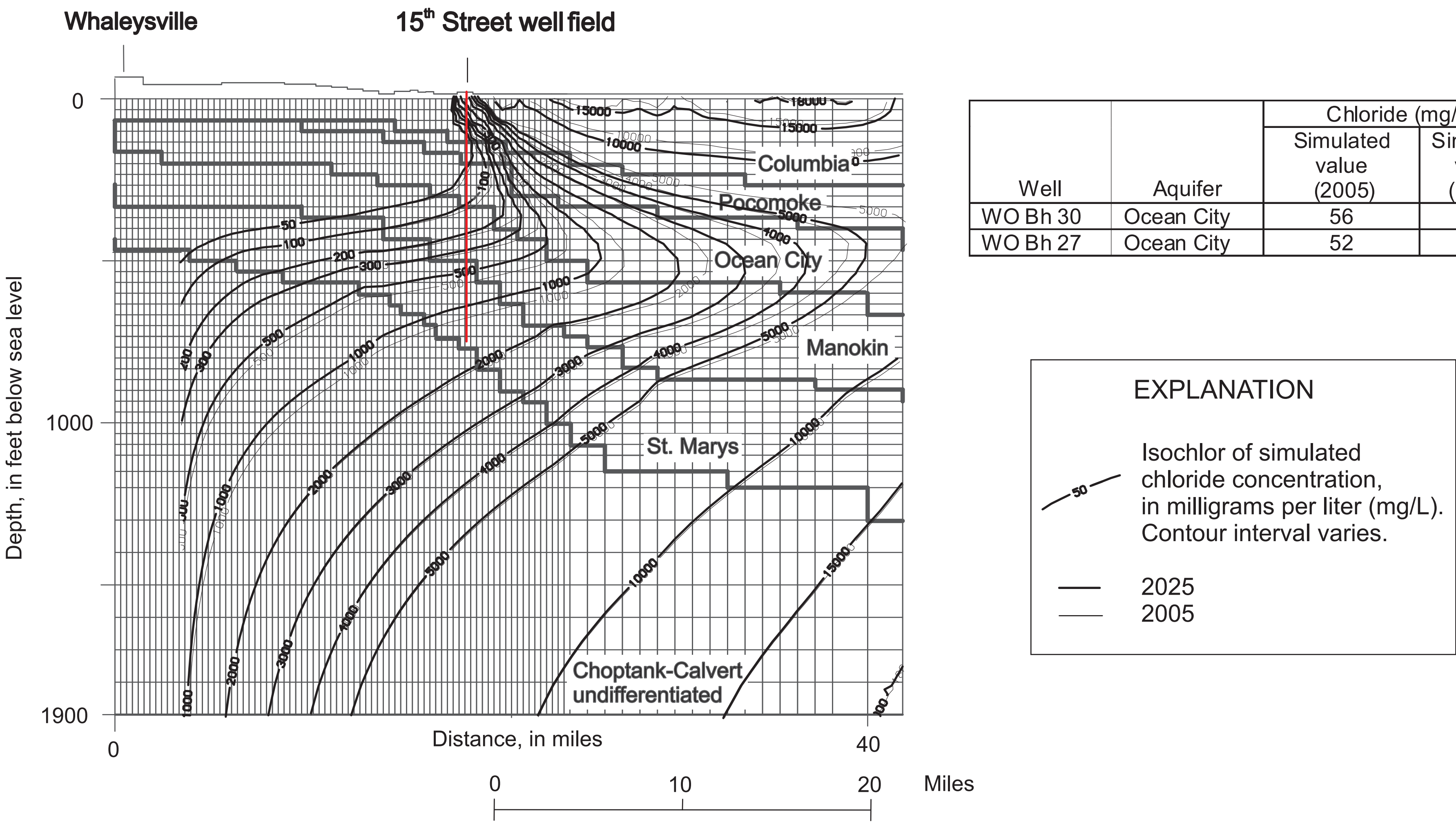


Figure 50. Simulated water levels in the Ocean City aquifer observation well WO Bh 98 at the 15th Street well field using the projected maximum withdrawal of 6 million gallons per day in 2025.



Well	Aquifer	Chloride (mg/L) Simulated value (2005)	Simulated value (2025)
WO Bh 30	Ocean City	56	60
WO Bh 27	Ocean City	52	55

Figure 51. Simulated 2005 and 2025 chloride concentrations at the 15th Street cross-sectional model and in the Ocean City aquifer production wells WO Bh 27 and WO Bh 30.

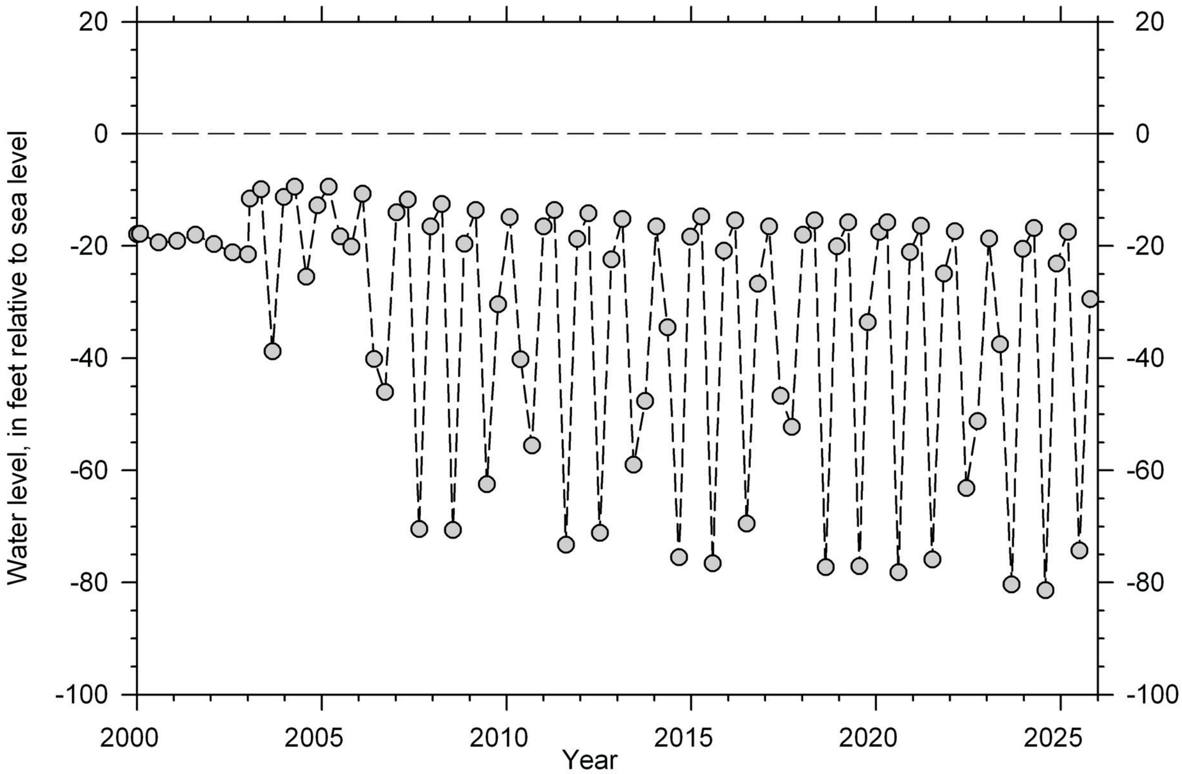
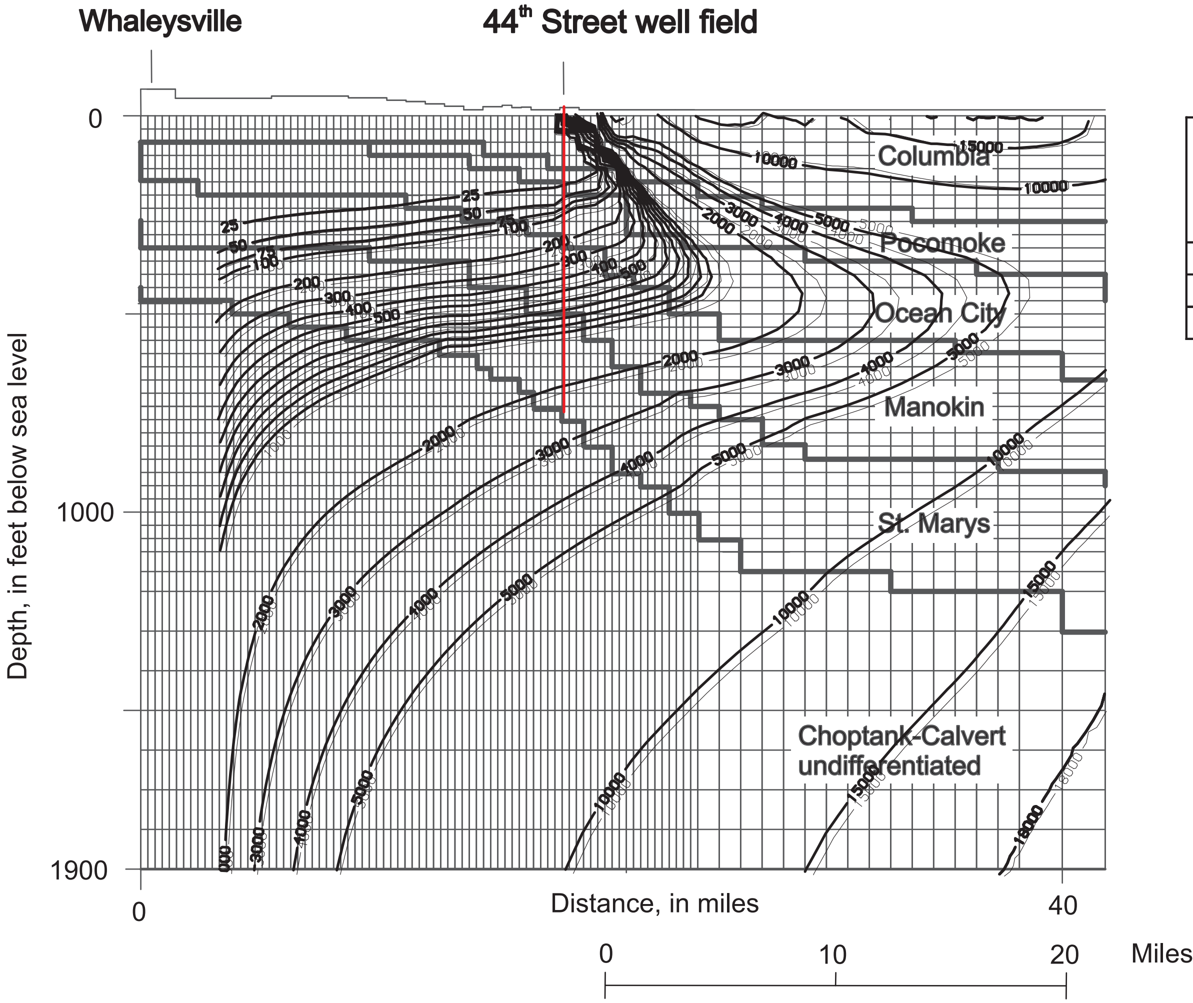


Figure 52. Simulated water levels in the Ocean City aquifer observation well WO Bh 31 at the 44th Street well field using the projected maximum withdrawal of 4 million gallons per day in 2025.



Well	Aquifer	Chloride (mg/L) Simulated value (2005)	Chloride (mg/L) Simulated value (2025)
WO Bh 41	Ocean City	124	153
WO Bh 29	Ocean City	130	150
WO Bh 28	Ocean City	217	245

EXPLANATION

Isochlor of simulated chloride concentration, in milligrams per liter (mg/L). Contour interval varies.

2025

2005

Figure 53. Simulated 2005 and 2025 chloride concentrations at the 44th Street cross-sectional model and in the Ocean City aquifer production wells WO Bh 28, WO Bh 29, and WO Bh 41.

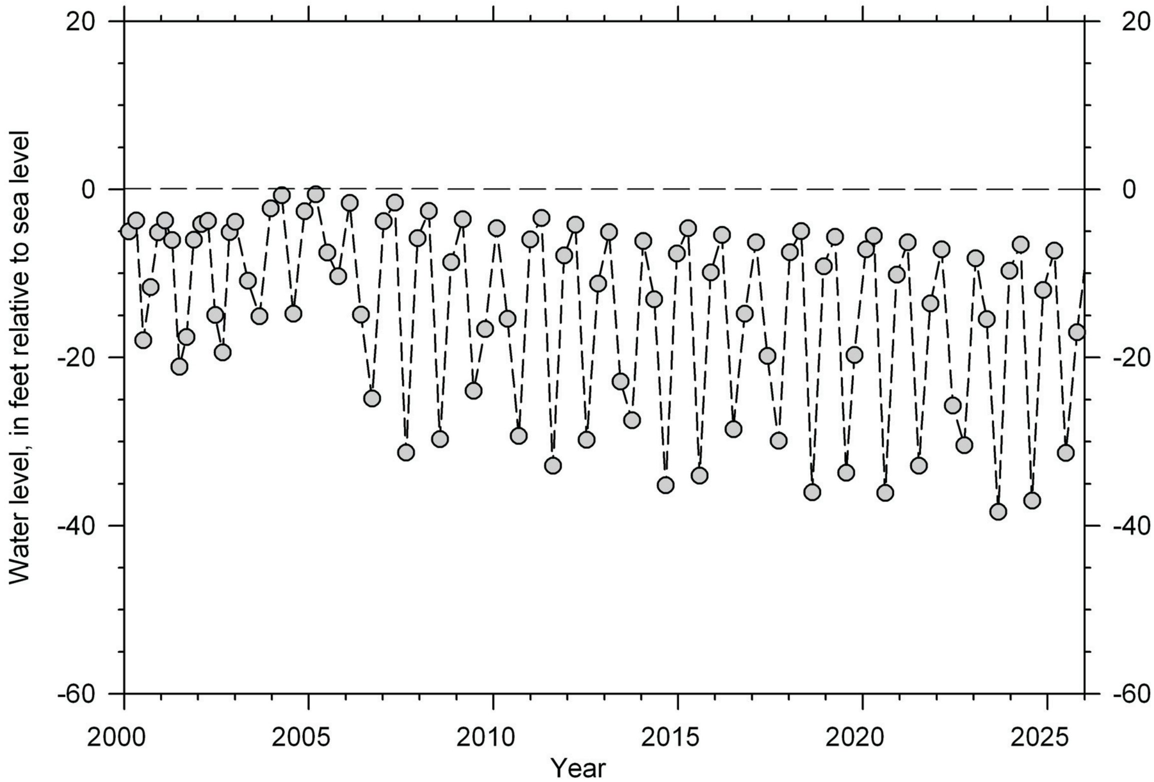
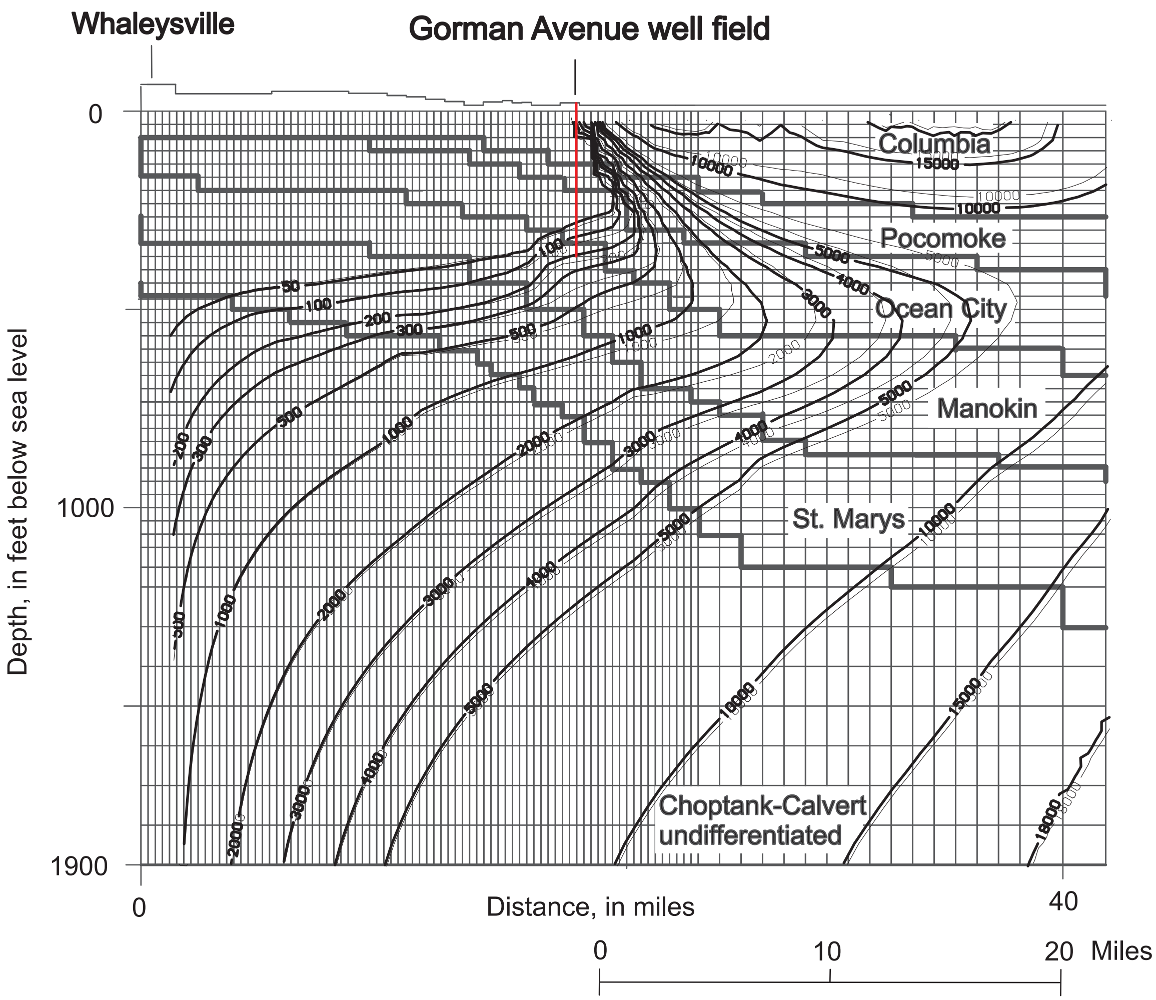


Figure 54. Simulated water levels in the Manokin aquifer observation well (WO Ah 6) at the Gorman Avenue well field using the projected maximum withdrawal of 8 million gallons per day in 2025.



Well	Aquifer	Chloride (mg/L) Simulated value (2005)	Chloride (mg/L) Simulated value (2025)
WO Ah 38	Manokin	122	148
WO Ah 33	Manokin	129	144
WO Ah 34	Manokin	129	144

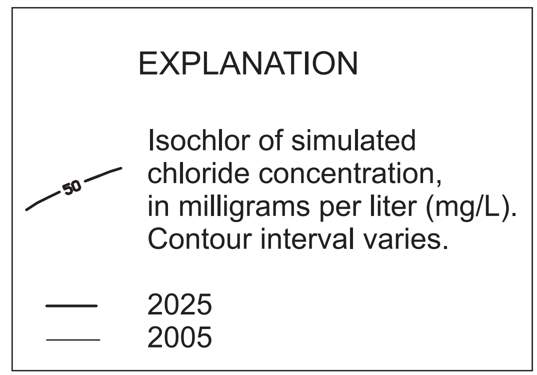


Figure 55. Simulated 2005 and 2025 chloride concentrations at the Gorman Avenue cross-sectional model and in the Manokin aquifer production wells WO Ah 33, WO Ah 34, and WO Ah 38.

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

[Modified from Weigel and Achmad, 1982; Achmad and Wilson, 1993; ft, feet; mg/L, milligrams per liter; >, greater than]

Erathem	System	Subsystem	Series/stage	Group	Formation/ informal unit	Lithology	Aquifer/confining bed and hydrologic properties	Approximate thickness of unit (ft)
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
			Pleistocene	COLUMBIA	Sinepuxent	Dark gray, poorly sorted fine to medium sand; more clayey near base.	Columbia aquifer. An unconfined to semi-confined water-table aquifer and leaky confining unit. Water is mostly fresh; some brackish-water intrusion from surface.	80-120
	TERTIARY	NEOGENE	? Pliocene		Beaverdam Sand	Light blue-gray to white and pale orange, fine to coarse and gravelly feldspathic sand.		
					Confining bed		Upper confining bed	15-20
				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.	30-80
			? Upper Miocene		Confining bed		Upper part of lower confining bed	20-40
					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.	80-150
					Confining bed		Basal part of lower confining bed	50-100
					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.	Manokin aquifer and associated confining units. Contains brackish water in some areas; chlorides range from less than 50 to 1,000 mg/L.	90-200
			? Middle Miocene		St. Mary's	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.	160-200
					Choptank	Light olive gray, fine to coarse sands; shelly, lignite bearing.	Choptank aquifer. Water is brackish. Chlorides range over 2,700 mg/L.	330
			? 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
		PALEOGENE	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
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
	Jurassic (?) and/or Triassic (?)				--	Sandstones and shales.	Confining unit	>460
Precambrian (?) and Paleozoic					--	Igneous and metamorphic rocks.	Confining unit	?

Table 2. Ocean City production well designations, aquifer pumped, well design capacity, and 2005 well capacity.

[USGS, U.S. Geological Survey; gpm, gallons per minute.
Bolded numbers indicate significant reduction of 2005 capacity below design capacity.]

Ocean City well designation	Street location	Aquifer pumped	USGS well number	Date drilled	Design capacity (gpm)	2005 capacity (gpm)
15th Street Water Plant						
A Well*	Worcester Avenue	Ocean City	WO Cg 32	5/10/55	663	**430**
B Well*	Worcester Avenue	Ocean City	WO Cg 33	5/21/55	663	757
C Well*	South Division Street	Ocean City	WO Cg 34	3/27/67	869	**385**
D Well*	South Division Street	Manokin	WO Cg 75	4/9/84	1,000	1,033
E Well	North Division Street	Ocean City	WO Cg 89	1/20/99	800	995
A Well	15th Street	Ocean City	WO Bh 26	8/15/57	776	**540**
B Well‡	14th Street	Ocean City	WO Bh 27	2/19/60	715	708
C Well‡	St. Louis Avenue	Ocean City	WO Bh 30	3/24/67	726	**693**
D Well	15th Street	Manokin	WO Bh 88	5/30/84	1,016	1,087
E Well	3rd Street	Ocean City	WO Bg 58	12/9/96	752	**700**
F Well	28th Street	Ocean City	WO Bh 101	7/16/98	525	750
44th Street Water Plant						
A Well‡	44th Street	Ocean City	WO Bh 28	3/19/63	703	**650**
B Well‡	45th Street	Ocean City	WO Bh 29	4/19/63	503	775
C Well‡	42nd Street	Ocean City	WO Bh 41	7/13/69	800	**605**
D Well	42nd Street	Ocean City	WO Bh 81	6/16/71	800	**740**
F Well †	South Convention Hall	Ocean City	WO Bh 39	3/27/69	830	**400**
G Well	33rd Street	Ocean City	WO Bh 100	1/1/97	720	720
Gorman Avenue Water Plant						
A Well‡	137th Street	Manokin	WO Ah 34	4/30/72	1,000	1,220
B Well‡	Gorman Avenue	Manokin	WO Ah 33	4/21/72	810	1,010
C Well‡	Fountain Road	Manokin	WO Ah 38	8/26/76	1,400	**860**
D Well‡	141st Street	Manokin	WO Ah 39	1/1/86	1,600	**1,210**
E Well	130th Street	Manokin	WO Ah 43	4/22/89	1,200	1,250
F Well	125th Street	Manokin	WO Ah 45	4/30/91	900	1,050
G Well	120th Street	Manokin	WO Ah 49	4/8/04	850	**700**

* Formerly South Division Street Water Plant
† Production well used for heating/cooling of convention center only
‡ Well is in SUTRA cross-sectional model

Table 3. Annual withdrawals from the South Division Street, 15th Street, 44th Street, and Gorman Avenue well fields, 1969-2005.

[Numbers are in gallons per year. Pumpages are rounded to nearest integer. Bolded numbers indicate maximum withdrawal from each well field.]

Year	South Division Street	15th Street	44th Street	Gorman Avenue	Total
1969	164,324,000	143,936,000	136,249,000	0	444,509,000
1970	142,604,000	239,047,000	191,820,000	0	573,471,000
1971	148,073,000	243,336,000	232,198,000	0	623,607,000
1972	319,484,000	132,446,000	271,874,000	0	723,804,000
1973	276,325,000	249,705,000	391,817,000	8,500,000	926,347,000
1974	236,889,000	235,414,000	416,922,000	119,899,000	1,009,124,000
1975	252,543,000	208,420,000	402,151,000	196,397,000	1,059,511,000
1976	291,670,000	247,497,000	425,892,000	292,584,000	1,257,643,000
1977	277,938,000	291,914,000	428,318,000	362,923,000	1,361,093,000
1978	279,931,000	263,424,000	574,684,000	318,682,000	1,436,721,000
1979	**354,338,000**	165,343,000	549,160,000	398,118,000	1,466,959,000
1980	194,104,000	263,926,000	446,965,000	407,913,000	1,312,908,000
1981	175,833,000	191,539,000	490,115,000	416,987,000	1,274,474,000
1982	263,264,000	325,214,000	372,927,000	348,098,000	1,309,503,000
1983	299,284,000	391,996,000	445,017,000	274,725,000	1,411,022,000
1984	171,094,000	194,722,000	802,136,000	369,235,000	1,537,187,000
1985	288,594,000	160,541,000	778,613,000	408,972,000	1,636,720,000
1986	171,888,000	373,530,000	833,143,000	345,470,000	1,724,031,000
1987	228,534,000	240,650,000	834,810,000	488,530,000	1,792,524,000
1988	197,498,000	278,164,000	**957,830,000**	449,330,000	1,882,822,000
1989	135,760,000	193,150,000	815,090,000	796,120,000	1,940,120,000
1990	130,210,000	150,420,000	425,260,000	1,357,930,000	2,063,820,000
1991	106,840,000	106,150,000	461,420,000	1,359,230,000	2,033,640,000
1992	79,930,000	38,990,000	325,340,000	**1,490,080,000**	1,934,340,000
1993	84,830,000	65,120,000	545,220,000	1,378,620,000	2,073,790,000
1994	42,450,000	86,490,000	716,280,000	1,278,840,000	2,124,060,000
1995	92,450,000	206,580,000	589,230,000	1,239,180,000	**2,127,440,000**
1996	2,160,000	931,210,000	343,260,000	756,880,000	2,033,510,000
1997	*	441,420,000	444,900,000	1,011,630,000	1,965,260,000
1998	*	348,260,000	282,870,000	1,238,900,000	1,870,030,000
1999	*	1,055,910,000	236,910,000	599,750,000	1,892,570,000
2000	*	**1,216,980,000**	287,950,000	469,750,000	1,974,680,000
2001	*	926,270,000	264,030,000	664,180,000	1,854,480,000
2002	*	1,106,280,000	344,850,000	448,060,000	1,899,190,000
2003	*	694,380,000	211,380,000	821,980,000	1,735,790,000
2004	*	1,048,490,000	167,940,000	511,220,000	1,727,650,000
2005	*	1,070,540,000	178,690,000	462,350,000	1,711,580,000

* Withdrawals from the South Division Street well field were included with withdrawals from the 15th Street well field beginning in 1997

Table 4. Average daily rates during the month of maximum withdrawals from well fields in Ocean City, 1969-2005.

[Numbers are in gallons per day. Well field pumpages are rounded to nearest decimal; total pumpages are rounded to the nearest integer. Bolded figures indicate maximum withdrawal from each well field.]

Year	South Division Street	15th Street	44th Street	Gorman Avenue	Total
1969	923774.2	1257096.8	1059032.3	0.0	3,239,903
1970	1059612.9	1603871.0	1578064.5	0.0	4,241,548
1971	1089580.6	1499354.8	1745483.9	0.0	4,305,968
1972	1510354.8	1423225.8	1850645.2	0.0	4,784,226
1973	1475236.0	1912333.3	1943999.7	274193.5	5,605,763
1974	1528354.8	1798064.5	2482580.6	1257566.7	7,066,567
1975	1487000.0	1388064.5	2632903.2	1384000.0	6,891,968
1976	1590001.2	1851935.5	2608064.5	2051000.0	8,101,001
1977	1571580.6	1947419.4	3052903.2	2101064.5	8,672,968
1978	1761161.3	1740000.0	3260000.0	2311290.3	9,072,452
1979	1631903.2	1735483.9	3310645.2	3465483.9	10,143,516
1980	1087161.3	1646774.2	2724193.5	3139000.0	8,597,129
1981	1497496.5	1326451.6	2399677.4	3167935.5	8,391,561
1982	1451354.8	1949032.3	2022666.3	3064129.0	8,487,182
1983	1917677.4	2133225.8	2806774.2	2418129.0	9,275,806
1984	1948032.3	2106129.0	2786774.2	3307806.5	10,148,742
1985	1590064.5	2189354.8	3135806.5	3387871.0	10,303,097
1986	1586774.2	2341935.5	3543548.4	3171612.9	10,643,871
1987	**1989354.8**	2614516.1	3433871.0	3586129.0	11,623,871
1988	1921290.3	2296451.6	3794332.8	3561612.9	11,573,688
1989	1097419.4	1844516.1	3352333.8	5666129.0	11,960,398
1990	1167096.8	1766451.6	2847741.9	6330000.0	12,111,290
1991	1114838.7	1191612.9	3059666.9	6269032.3	11,635,151
1992	1049354.8	482580.6	2947096.8	**6841935.5**	11,320,968
1993	1195161.3	904838.7	3974516.1	6420000.0	12,494,516
1994	941290.3	1230967.7	**4083871.0**	6231612.9	12,487,742
1995	1320967.7	2793000.0	3823548.4	6132903.2	**14,070,419**
1996	58709.7	4053871.0	3279677.4	5725161.3	13,117,419
1997	*	2810333.3	3940322.6	5700000.0	12,450,656
1998	*	3179354.8	2978709.7	5092903.2	11,250,968
1999	*	**4221612.9**	2348064.5	4934193.5	11,503,871
2000	*	4043548.4	2487096.8	4388064.5	10,918,710
2001	*	3382258.1	2172258.1	5192903.2	10,747,419
2002	*	4015806.5	2789677.4	4505806.5	11,311,290
2003	*	3749354.8	2194193.5	4524193.5	10,698,065
2004	*	3617741.9	1592903.2	5288064.5	10,498,710
2005	*	3762258.1	1965806.5	4499677.4	10,227,742

* Withdrawals from the South Division Street well field were included with withdrawals from the 15th Street well field beginning in 1997

Table 5. Average daily rates of the annual average pumpage from ground-water users other than the Town of Ocean City for 1995 and 2005.

[Source: Judith Wheeler, U.S. Geological Survey, written commun., 2005.
0, inactive in 1995 or 2005; pumpage rounded to nearest integer]

User	Aquifer pumped							
	Columbia		Pocomoke		Ocean City		Manokin	
	Rate of withdrawal (in thousand gallons per day)							
	Year		Year		Year		Year	
	1995	2005	1995	2005	1995	2005	1995	2005
Showell Farms, Inc.							41	41
Pocomoke State Park					11	11		
Ocean Pines Association					24	24		
Davis Ice, Inc.	44	43						
Pocomoke City			641	514				
City of Berlin	325	418						
Ralph Mason, Inc.	0	0						
City of Snow Hill							339	274
Savage Ice, Inc.					563	2,549		
Mason Canning Co.	0	0						
Maryland Marine Utilities	819	1,116						
Snow Hill Farms, Inc.	661	785						
Bishop Hill Farms, Inc.	12	19						
Holly Farms, Inc.							0	0
Chesapeake Foods, Inc.			799	818				
Shockley Fish Hatchery	0	0						
Pine Shore Golf Course	98	248						
Ocean City Golf Course	293	19						
Quality Inn							10	4
Ross Wells, Beatrice Food	13	20						
Ocean Downs Race Track	24	14						
Purdue Farms, Inc.	6	3						
Campbell Soup	0	0						
Mystic Harbor					110	147		
Newark Sanitary Comm.					18	19		
General Motor Inn	14	8						
1995 Total	2,309		1,440		726		390	
2005 Total		2,693		1,332		2,750		319
Total for all aquifers 1995	4,865							
Total for all aquifers 2005	7,094							

Table 6. Minimum, average, and maximum rates of monthly withdrawals from all Ocean City well fields, 1970-2005.

[in million gallons per day]

Year	Minimum	Average	Maximum
1970	0.38	1.56	4.24
1975	1.14	2.89	6.89
1980	1.43	3.58	8.60
1981	1.10	3.47	8.39
1982	1.37	3.57	8.49
1983	1.52	3.85	9.28
1984	1.37	4.19	10.15
1985	1.88	4.47	10.30
1986	1.93	4.70	10.64
1987	1.88	4.89	11.62
1988	2.30	5.13	11.57
1989	2.24	5.29	11.96
1990	3.00	5.63	12.11
1991	2.17	5.55	11.64
1992	2.31	5.27	11.32
1993	2.46	5.66	12.49
1994	2.56	5.80	12.49
1995	2.63	5.80	14.07
1996	2.19	5.54	13.12
1997	0.00	5.09	12.45
1998	2.08	5.10	11.25
1999	1.93	5.16	11.50
2000	2.52	5.38	10.92
2001	2.38	5.06	10.75
2002	2.29	5.18	11.31
2003	2.07	4.73	10.70
2004	2.13	4.72	10.50
2005	2.21	4.73	10.23

Table 7. Aquifer and confining-bed properties used in the flow model.

[ft, feet; ft/day, feet per day]

Aquifer/confining bed	Layer	Approximate thickness (ft)	Conductivity (ft/day)	Storage coefficient
Columbia aquifer	1	80 – 120	30 – 80	0.15
Upper confining bed	2	15 – 20	5×10^{-7} – 10^{-5}	0.0001
Pocomoke aquifer	3	30 – 80	40 – 60	0.00012
Upper part of lower confining bed	4	20 – 40	1×10^{-7} – 3×10^{-7}	0.0001
Ocean City aquifer	5	80 – 150	40 – 100	0.00009
Basal part of lower confining bed	6	50 – 100	3×10^{-6} – 6×10^{-4}	0.0001
Manokin aquifer	7	90 – 200	100 – 500	0.00012
St. Marys confining bed	8	160 – 200	2×10^{-9}	0.00002
Choptank and Calvert Formations (undifferentiated)	9	960	5	0.0001

Table 8. Comparison of simulated and measured water levels using least squares analysis for the entire simulation time for each aquifer.

[Appendix E shows the comparison for 2005; ft, feet]

Aquifer	Mean error (ft)	Mean absolute error (ft)	Standard error of the estimate (ft)	Root mean square (ft)	Number of points (n)
Columbia	-2.3	2.9	0.08	3.9	1,960
Pocomoke	-2.0	5.4	0.4	6.0	196
Ocean City	-5.6	15.6	0.5	24.3	1,960
Manokin	-0.4	8.0	0.2	10.3	2,548
St. Marys	3.2	3.2	0.1	3.6	196
All aquifers	-2.7	9.1	0.18	14.8	6,860

Mean Error = $1/n \sum_{i=1}^{n} (X_{calc} - X_{obs})_i$

Mean Absolute Error = $1/n \left(\sum_{i=1}^{n} \left| X_{calc} - X_{obs} \right|_i \right)$

Standard Error of the Estimate = $\sqrt{} \{[\sum_{i=1}^{n} (X_{calc} - X_{obs})_i^{\,2}] - [\sum_{i=1}^{n} (X_{calc} - X_{obs})_i]^2\}$

Root Mean Square = $1/n \sqrt{} [\sum_{i=1}^{n} (X_{calc} - X_{obs})_i^2]$

$\sqrt{}$ = square root

X_{calc} = simulated water level

X_{obs} = measured water level

Table 9. Deepest water levels during summer pumpages at the Ocean City well fields from 1995 to 2025 in the Manokin aquifer at Gorman Avenue and in the Ocean City aquifer at the South Division Street, 15th Street, and 44th Street well fields.

[Summer pumpage, average daily rates during month of maximum withdrawal. Withdrawals from the South Division Street well field were included with withdrawals from the 15th Street well field after 1996. ft, feet; mgd, million gallons per day]

Year	Well field	Deepest water level (ft relative to sea level)	Summer pumpage (mgd)
1995	Gorman Avenue	-17	6.13
	44th Street	-29	3.82
	15th Street	-19	2.79
	South Division Street	-4	1.32
2000	Gorman Avenue	-10	4.39
	44th Street	-15	2.49
	15th Street	-67	4.04
2005	Gorman Avenue	-19	4.50
	44th Street	-28	1.97
	15th Street	-87	3.76
2010	Gorman Avenue	-29	5.63
	44th Street	-72	2.42
	15th Street	-103	4.26
2015	Gorman Avenue	-31	6.42
	44th Street	-75	2.95
	15th Street	-107	4.84
2020	Gorman Avenue	-33	7.21
	44th Street	-78	3.47
	15th Street	-110	5.42
2025	Gorman Avenue	-34	8.00
	44th Street	-81	4.00
	15th Street	-115	6.00

Table 10. Aquifer and fluid properties used in the cross-sectional models.

[Source: Achmad and Wilson, 1993.
K, hydraulic conductivity; m^2, meters squared]

Layer	Hydrologic unit	Permeability (m^2)	Anisotropy ($k_{vertical}/k_{lateral}$)	Porosity (percent)
1	Columbia	$9.0 – 27.0 \times 10^{-12}$	10^{-4}	0.30
2	Pocomoke	$7.2 – 28.8 \times 10^{-12}$	10^{-4}	0.30
3	Ocean City	$9.0 – 27.0 \times 10^{-12}$	10^{-4}	0.30
4	Manokin	$9.0 – 36.1 \times 10^{-12}$	10^{-4}	0.30
5	St. Mary's	1.4×10^{-19}	1.0	0.30
6	Choptank/Calvert (undifferentiated)	$0.6 – 1.7 \times 10^{-12}$	1.0	0.30

	Value
Thickness of cross section	1.0 m
Matrix compressibility	7.7×10^{-7} kiloPascal^{-1}
Longitudinal dispersivity	100.0 m
Transverse dispersivity	1.0 m
Diffusivity	1.0×10^{-9} m^2/s
Fluid viscosity at 68 degrees Fahrenheit	1.0×10^{-3} kg/ms
Fluid compressibility	4.4×10^{-7} kiloPascal^{-1}
Base chloride concentration	0 mg/L
Base temperature	68 degrees Fahrenheit
Fresh-water density	998.2 kg/m^3
Maximum ocean-water chloride concentration	19,000 mg/L
Ocean-water density	1,025 kg/m^3
Coefficient of fluid density change with concentration	1.4105 (unitless)

Table 11. Measured, simulated, and estimated chloride concentrations in production wells at the three Ocean City well fields for 1980-2005.

[mg/L, milligrams per liter; measured, analysis of well sample; simulated, based on 5-year average; estimated, linear regression]

15th Street well field

Production well B (WO Bh 27)				Production well C (WO Bh 30)			
Date sampled	Chloride concentration (mg/L)			Date sampled	Chloride concentration (mg/L)		
	Measured	Simulated	Estimated		Measured	Simulated	Estimated
8/7/1980	32.5	38	30	8/21/1980	36.5	41	33
8/12/1985	44	42	32	8/1/1985	39	48	35
8/12/1991	32	46	34	8/14/1991	37	50	37
8/7/1995	33	48	35	10/25/1995	35	54	38
5/23/2000	40	52	37	6/14/2000	146	55	40
8/8/2005	46	52	39	8/15/2005	55	56	42

44th Street well field

Production well A (WO Bh 28)				Production well B (WO Bh 29)				Production well C (WO Bh 41)			
Date sampled	Chloride concentration (mg/L)			Date sampled	Chloride concentration (mg/L)			Date sampled	Chloride concentration (mg/L)		
	Measured	Simulated	Estimated		Measured	Simulated	Estimated		Measured	Simulated	Estimated
6/7/1980	135	182	165	8/21/1980	71	104	75	7/7/1980	80	100	72
8/14/1985	175	195	175	8/1/1985	92	104	84	8/12/1985	109	113	82
8/3/1990	185	201	182	8/12/1990	93	110	93	8/14/1990	115	116	92
8/9/1995	195	206	193	5/10/1995	113	116	103	8/21/1995	100	119	102
8/9/2000	208	212	203	8/2/2000	120	122	112	8/28/2000	115	121	110
8/1/2005	210	217	212	8/22/2005	134	130	121	8/15/2005	123	124	120

Gorman Avenue well field

Production well A (WO Ah 34)				Production well B (WO Ah 33)				Production well C (WO Ah 38)			
Date sampled	Chloride concentration (mg/L)			Date sampled	Chloride concentration (mg/L)			Date sampled	Chloride concentration (mg/L)		
	Measured	Simulated	Estimated		Measured	Simulated	Estimated		Measured	Simulated	Estimated
8/15/1980	111	113	101	8/15/1980	89	108	76	8/15/1980	75	104	68
8/22/1985	118	118	107	8/12/1985	100	120	82	9/17/1985	74	110	75
8/3/1990	114	121	112	8/14/1990	82	121	88	7/23/1990	71	113	83
7/19/1995	120	124	116	9/18/1995	105	121	94	8/7/1995	105	115	91
8/9/2000	127.5	126	121	7/5/2000	100	123	100	8/30/2000	115	118	99
8/10/2005	102	129	125	8/1/2005	116	125	108	8/22/2005	116	122	118

Table 12. Comparison of the earliest measured chloride concentrations with simulated 1900 flow conditions.

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

Well designation	Aquifer	Screen depth below land surface (ft)	Year measured	Measured chloride concentration (mg/L)	Simulated chloride concentration (mg/L)
15th Street well field					
WO Bh 8	Pocomoke	151 - 176	1951	20	23
WO Bh 1	Ocean City	272 - 285	1951	30	59
WO Bh 102	Manokin (base)	528 - 538	2004	889	865
44th Street well field					
WO Bh 84	Columbia	84 - 89	1973	39	19
WO Bh 85	Pocomoke	190 - 195	1973	46	49
WO Bh 28	Ocean City	248 - 294	1985	103	183
WO Bh 89	Manokin	388 - 423	1989	520	496
WO Bh 89	Manokin(base)	495 - 510	1987	1,030	980
WO Bh 90	Choptank	691 - 736	1989	2,900	2,904
Gorman Avenue well field					
WO Ah 36	Manokin	420 - 430	1975	170	210
WO Ah 6	Manokin	464 - 474	1969	300	370
WO Ah 6	Choptank	708 - 718	1969	2,700	1,995
Offshore test hole*					
Test hole no. 6008	Columbia	68-98	1976	15,352	14,400
	Columbia	98-128	1976	13,927	11,400
	Columbia	128-158	1976	8,871	8,600
	Columbia	158-188	1976	4,625	5,200
	Pocomoke	228-259	1976	231	3,900
	Pocomoke	273-304	1976	1,594	1,420
	Ocean City	335-366	1976	896	880

* Sample depth below sea floor. Test hole no. 6008 data from F. A. Kohout, U.S. Geological Survey, written commun., 1980.

Table 13. Maximum, average, and minimum daily rates of withdrawal from the 15th Street, 44th Street, and Gorman Avenue well fields used in the 2005-2025 flow model simulations.

[in million gallons per day]

Year	Maximum withdrawals			Average withdrawals			Minimum withdrawals		
	15th Street	44th Street	Gorman Avenue	15th Street	44th Street	Gorman Avenue	15th Street	44th Street	Gorman Avenue
2005	3.76	1.97	4.50	2.99	0.48	1.26	2.21	0.00	0.00
2006	3.80	2.00	5.00	3.08	1.00	2.50	2.35	0.00	0.00
2007	3.92	2.11	5.16	3.14	1.05	2.58	2.37	0.00	0.00
2008	4.03	2.21	5.32	3.21	1.11	2.66	2.39	0.00	0.00
2009	4.15	2.32	5.47	3.27	1.16	2.74	2.40	0.00	0.00
2010	4.26	2.42	5.63	3.34	1.21	2.82	2.42	0.00	0.00
2011	4.38	2.53	5.79	3.41	1.26	2.89	2.44	0.00	0.00
2012	4.49	2.63	5.95	3.47	1.32	2.97	2.45	0.00	0.00
2013	4.61	2.74	6.11	3.54	1.37	3.05	2.47	0.00	0.00
2014	4.73	2.84	6.26	3.61	1.42	3.13	2.48	0.00	0.00
2015	4.84	2.95	6.42	3.67	1.47	3.21	2.50	0.00	0.00
2016	4.96	3.05	6.58	3.74	1.53	3.29	2.52	0.00	0.00
2017	5.07	3.16	6.74	3.80	1.58	3.37	2.53	0.00	0.00
2018	5.19	3.26	6.89	3.87	1.63	3.45	2.55	0.00	0.00
2019	5.31	3.37	7.05	3.94	1.68	3.53	2.57	0.00	0.00
2020	5.42	3.47	7.21	4.00	1.74	3.61	2.58	0.00	0.00
2021	5.54	3.58	7.37	4.07	1.79	3.68	2.60	0.00	0.00
2022	5.65	3.68	7.53	4.13	1.84	3.76	2.61	0.00	0.00
2023	5.77	3.79	7.68	4.20	1.89	3.84	2.63	0.00	0.00
2024	5.88	3.89	7.84	4.27	1.95	3.92	2.65	0.00	0.00
2025	6.00	4.00	8.00	4.33	2.00	4.00	2.66	0.00	0.00

Table 14. Simulated summer and winter water levels in the 15th Street, 44th Street, and Gorman Avenue well fields in 2005 and 2025.

[mgd, million gallons per day; ft, feet]

Well field	Aquifer	Pumping rate (mgd)		Simulated cell-averaged water level (ft below sea level)				80-percent management level in 2025 (ft below sea level)	Estimated available drawdown in 2025 summer (ft)
		2005	2025	2005 Summer	2005 Winter	2025 Summer	2025 Winter		
15th Street	Ocean City	3.76	6.00	-87	-55	-115	-80	-190	75
44th Street	Ocean City	1.97	4.00	-28	-12	-81	-23	-200	119
Gorman Avenue	Manokin	4.50	8.00	-19	-3	-34	-8	-340	306

Table 15. Simulated chloride concentrations in production wells at the 15th Street, 44th Street, and Gorman Avenue well fields in 2005 and 2025.

[USGS, U.S. Geological Survey; ft, feet; mg/L, milligrams per liter]

Well field	Production well (USGS well number)	Screen depth (ft below sea level)	Aquifer	Chloride concentration (mg/L)	
				2005	2025
15th Street	B (WO Bh 27)	228-283	Ocean City	52	55
	C (WO Bh 30)	226-292	Ocean City	56	60
44th Street	A (WO Bh 28)	242-288	Ocean City	217	245
	B (WO Bh 29)	242-288	Ocean City	130	157
	C (WO Bh 41)	253-313	Ocean City	124	153
Gorman Avenue	A (WO Ah 34)	345-445	Manokin	129	144
	B (WO Ah 33)	342-446	Manokin	129	144
	C (WO Ah 38)	326-426	Manokin	122	148

Martin O'Malley
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Deputy Secretary

A message to Maryland's citizens

The Maryland Department of Natural Resources (DNR) seeks to balance the preservation and enhancement of the living and physical resources of the state with prudent extraction and utilization policies that benefit the citizens of Maryland. This publication provides information that will increase your understanding of how DNR strives to reach that goal through the earth science assessments conducted by the Maryland Geological Survey.

Martin O'Malley
Governor

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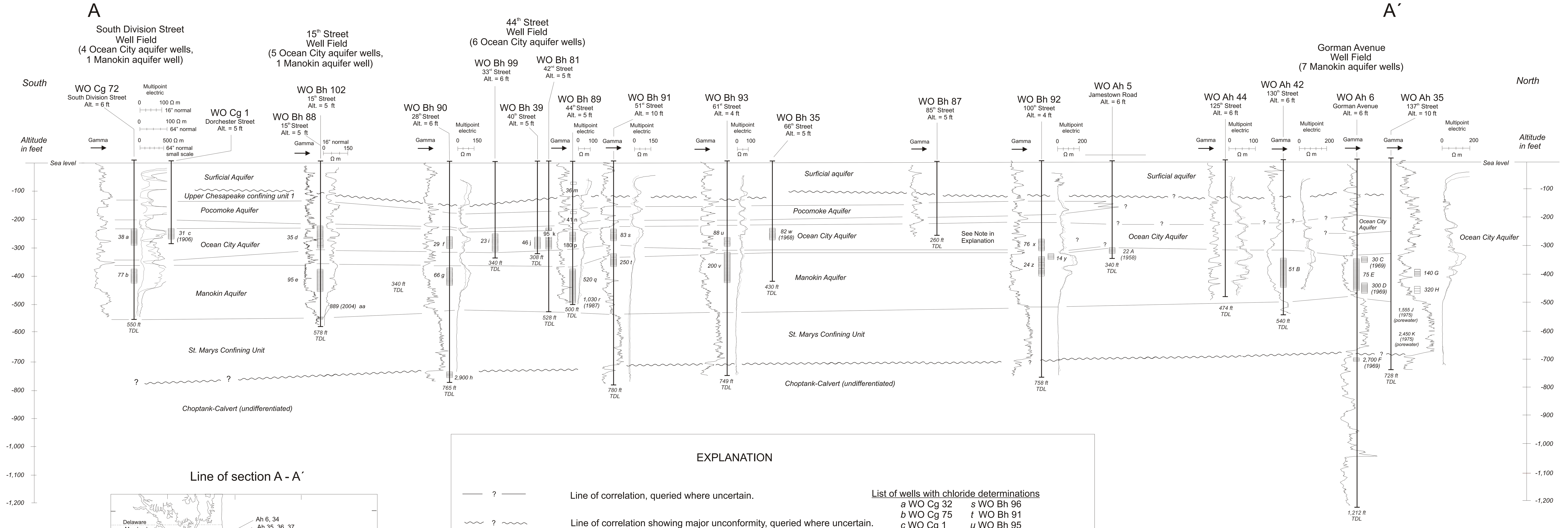
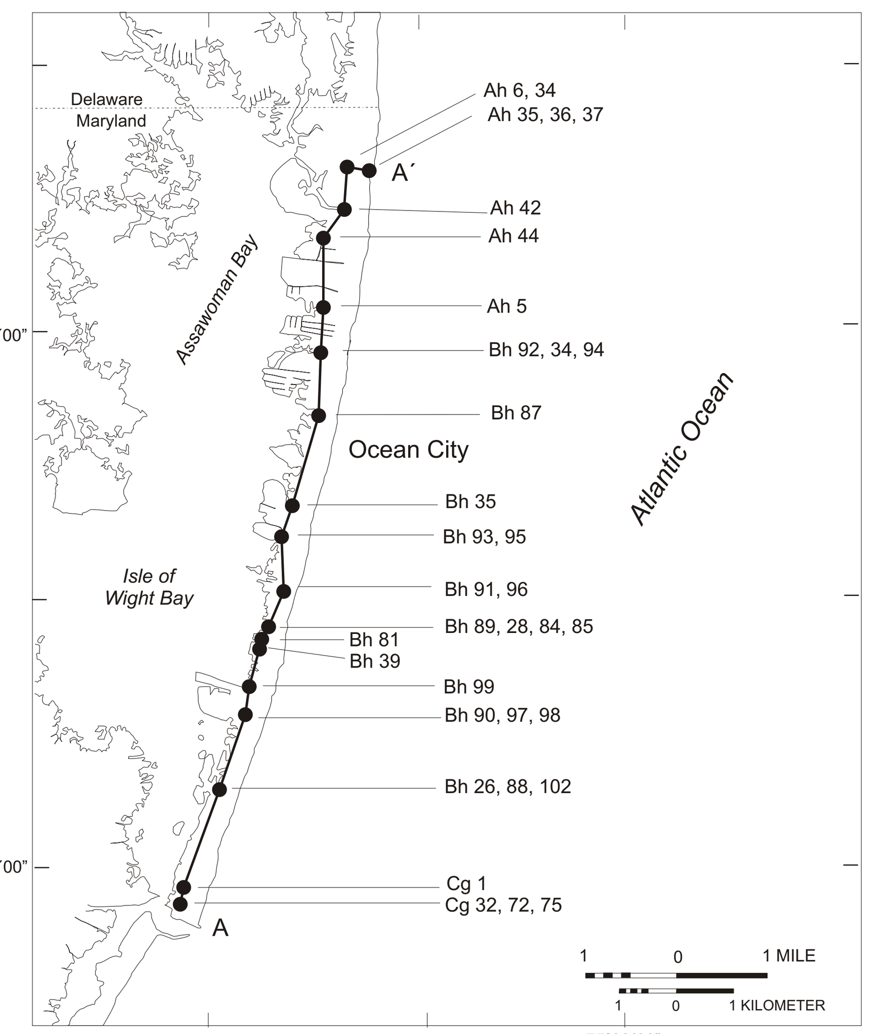


Aquifer and confining bed	Series	System
Surficial aquifer	Pleistocene	Quaternary
Upper Chesapeake confining unit 1	Pliocene	Tertiary
Pocomoke aquifer		
Upper Chesapeake confining unit 2	Upper Miocene	
Ocean City aquifer		
Upper Chesapeake confining unit 3		
Manokin aquifer		
St. Marys confining unit	Middle Miocene	
Choptank and Calvert (undifferentiated)	Lower Miocene	

(Holocene units not differentiated)
Modified from Achmad and Wilson (1993)

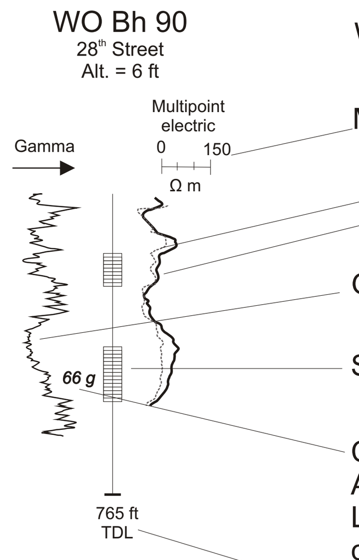
Line of section A - A´



EXPLANATION

Line of correlation, queried where uncertain.

Line of correlation showing major unconformity, queried where uncertain.



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 93
w WO Bh 35
x WO Bh 94
y WO Bh 34
z WO Bh 92
aa WO Bh 102

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

DMA, 2006