New Jersey Geological Survey
Geological Survey Report GSR 41

GROUND-WATER FLOW AND QUALITY IN THE ATLANTIC CITY 800-FOOT SAND, NEW JERSEY

N.J. Department of Environmental Protection - Division of Science, Research and Technology

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

The mission of the New Jersey Department of Environmental Protection is to assist the residents of New Jersey in preserving, sustaining, protecting and enhancing the environment to ensure the integration of high environmental quality, public health and economic vitality.

NEW JERSEY GEOLOGICAL SURVEY

The mission of the New Jersey Geological Survey is to map, research, interpret and provide scientific information regarding the state's geology and ground-water resources. This information supports the regulatory and planning functions of DEP and other governmental agencies and provides the business community and public with the information necessary to address environmental concerns and make economic decisions.

Cover illustration: Night drilling at an observation well off the Atlantic City shoreline. Drilling was conducted around the clock and completed in 1985.

New Jersey Geological Survey
Geological Survey Report GSR 41

GROUND-WATER FLOW AND QUALITY IN THE ATLANTIC CITY 800-FOOT SAND, NEW JERSEY

by

Steven D. McAuley, Julia L. Barringer,
Gary N. Paulachok, Jeffrey S.Clark, and Otto S. Zapecza
U.S. Geological Survey
West Trenton, New Jersey

Prepared by the United States Geological Survey
in cooperation with the
New Jersey Department of Environmental Protection
Division of Science, Research and Technology
Geological Survey

New Jersey Department of Environmental Protection
Division of Science, Research and Technology
Geological Survey
P.O. Box 427
Trenton, NJ 08625
2001

Printed on recycled paper

New Jersey Geological Survey Reports (ISSN 0741-7357) are published by the New Jersey Geological Survey, P.O. Box 427, Trenton, NJ 08625. This report may be reproduced in whole or part provided that suitable reference to the source of the copied material is provided.

Additional copies of this and other reports may be obtained from:

Maps and Publications Sales Office
P.O. Box 438
Trenton, NJ 08625-0438

A price list is available on request.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

ILLUSTRATIONS--Continued

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Hydraulic conductivity, transmissivity, and flow	
foot per day (ft/d)	0.3048	meter per day
square foot per day (ft^2/d)	0.09290	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
gallon per day (gal/d)	0.06308	liter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	Temperature	
degree Celsius (°C)	°F = 1.8 x °C + 32	degree Fahrenheit

GROUND-WATER FLOW AND QUALITY IN THE ATLANTIC CITY 800-FOOT SAND, NEW JERSEY

By Steven D. McAuley, Julia L. Barringer, Gary N. Paulachok,
Jeffrey S. Clark, and Otto S. Zapecza

ABSTRACT

The regional, confined Atlantic City 800-foot sand is the principal source of water supply for coastal communities of southern New Jersey. In response to extensive use of the aquifer—nearly 21 million gallons per day in 1986—water levels have declined to about 100 feet below sea level near Atlantic City and remain below sea level throughout the coastal areas of southern New Jersey, raising concerns about the potential for saltwater intrusion into well fields.

Water levels in the Atlantic City 800-foot sand have declined in response to pumping from the aquifer since the 1890's. Water levels in the first wells drilled into the Atlantic City 800-foot sand were above land surface, and water flowed continuously from the wells. By 1986, water levels were below sea level throughout most of the coastal areas. Under current conditions, wells near the coast derive most of their supply from lateral flow contributed from the unconfined part of the aquifer northwest of the updip limit of the confining unit that overlies the Atlantic City 800-foot sand. Ground water also flows laterally from offshore areas and leaks vertically through the overlying and underlying confining units into the Atlantic City 800-foot sand. The decline in water levels upsets the historical equilibrium between freshwater and ancient saltwater in offshore parts of the aquifer and permits the lateral movement of saltwater toward pumping centers. The rate of movement is accelerated as the decline in water levels increases. The chloride concentration of aquifer water 5.3 miles offshore of Atlantic City was measured as 77 mg/L (milligrams per liter) in 1985 at a U.S. Geological Survey observation well. Salty water has also moved toward wells in Cape May County. The confined, regional nature of the Atlantic City 800-foot sand permits water levels in Cape May County to decline in response to pumping in Atlantic County and vice versa. Historically, chloride concentrations as great as 1,510 mg/L have been reported for water in a former supply well in southern Cape May County. These data indicate that salty water has moved inland in Cape May County. Analysis of the chloride-concentration data indicates that ground water with a chloride concentration of 250 mg/L is within 4 miles of supply wells in Stone Harbor, Cape May County, and is about 10 miles offshore of supply wells near Atlantic City.

Results of numerical simulations of ground-water flow were analyzed to determine the effects of four water-supply alternatives on water levels, the flow budget, and potential saltwater movement toward pumping centers during 1986-2040. In the supply alternatives, pumpage is (1) held constant at 1986 rates of pumpage; (2) increased by 35 percent at 1986 locations; (3) increased by 35 percent, but with relocation of some supply wells further inland; and (4) increased by 35 percent but with some of the increase derived from inland wells tapping the Kirkwood-Cohansey aquifer system rather than the Atlantic City 800-foot sand. Inland relocation of supply wells closer to the updip limit of the overlying confining unit results in the smallest decline in water levels and the smallest rate of ground-water flow between the offshore location of salty water and coastal supply wells. Increased pumpage from coastal supply wells results in the greatest water-level declines and the greatest increase in the rate of ground-water flow from offshore to coastal wells.

Flow of undesirable salty ground water from offshore locations remains nearly the same as for current (1986) conditions when pumping rates do not change, and the flow-rate increase is smallest for the relocated pumpage (fourth) alternative. In comparing the two conditions of a 35-percent increase in pumpage, the flow from undesirable salty water positions is lessened and flow from the unconfined aquifer is increased when some of the pumping centers are relocated farther inland. Ground water from the 250-mg/L isochlor position does not reach supply wells during any simulated conditions predicted for 1986-2040. The analysis of the simulation, however, includes only advective freshwater flow from an estimated 250-mg/L isochlor position and does not include density effects. A chloride concentration data-collection network could be designed to monitor for saltwater intrusion and serve as an early warning system for the communities of southern Cape May County and the coastal communities near Atlantic City. Data from existing offshore wells could continue to serve as an early warning system for the Atlantic City area; however, observation wells south of Stone Harbor, in the Wildwood area, would be useful as an early warning system for southern Cape May County.

INTRODUCTION

Ground water from the Atlantic City 800-foot sand of the Kirkwood Formation is the principal source of supply for the coastal communities of Atlantic, Cape May, and Ocean Counties, N.J. The coastal communities have experienced substantial economic development and population growth as demand for seaside resorts on the northeastern seaboard has increased, especially since gambling was legalized in Atlantic City in 1977. Most withdrawals from the aquifer were for use by coastal communities; however, inland communities in Atlantic, Burlington, Cape May, and Ocean Counties have also experienced increased development and withdrawals from the Atlantic City 800-foot sand of the Kirkwood Formation may be a viable source of water because this deep, confined aquifer is largely protected from contamination introduced at or near land surface. During 1956-80, ground-water withdrawals from the Atlantic City 800-foot sand of the Kirkwood Formation, commonly referred to as the "Atlantic City 800-foot sand" (Vowinkel, 1984, p. 24), nearly doubled.

In response to large ground-water withdrawals, water levels in the Atlantic City 800-foot sand declined to more than 60 ft below sea level by fall 1983 (Eckel and Walker, 1986, p. 47). The water use is seasonal, and summer water levels have been as low as 110 ft below sea level in 1986 (Clark and Paulachok, 1989, p. 28). The water-level decline throughout much of the region near Atlantic City, N.J., has increased concerns about water-supply shortages and ground-water contamination from saltwater intrusion. The "New Jersey Statewide Water Supply Master Plan" (New Jersey Department of Environmental Protection, 1981) indicates that a steady increase in ground-water withdrawals, as well as contamination of fresh ground-water supplies from saltwater, will be likely consequences of increased economic development and population growth in the area near Atlantic City.

Water-level declines in response to ground-water withdrawals result in migration of saltwater toward the coast and into the freshwater zone of the Atlantic City 800-foot sand. Measurements of chloride concentrations can be used as indicators of saltwater intrusion. Chloride concentrations that exceed the national secondary drinking-water standard (U.S. Environmental Protection Agency, 1977), which indicate contamination by saline water, have been measured in water from the Atlantic City 800-foot sand in wells in southern Cape May County (Gill, 1962, p. 103). Chloride concentrations of well water from the chloride monitoring network in the Atlantic City 800-foot sand in the coastal communities of Atlantic, Cape May, and Ocean Counties did not exceed drinking-water standards in 1986 (Bauersfeld and others, 1988, p. 318-338); however, the potential for saltwater intrusion was not clearly understood because the flow system had not been well-defined and because chloride concentrations in water from offshore parts of the Atlantic City 800-foot sand were unknown.

To provide information needed to plan for and effectively manage the ground-water resources of the Atlantic City 800-foot sand in New Jersey, the U.S. Geological Survey (USGS), in cooperation with the New Jersey Department of Environmental Protection, New Jersey Geological Survey, conducted an investigation of ground-water flow and the potential for saltwater intrusion in the Atlantic City 800-foot sand under 1986 conditions and for selected water-supply alternatives.

Purpose and Scope

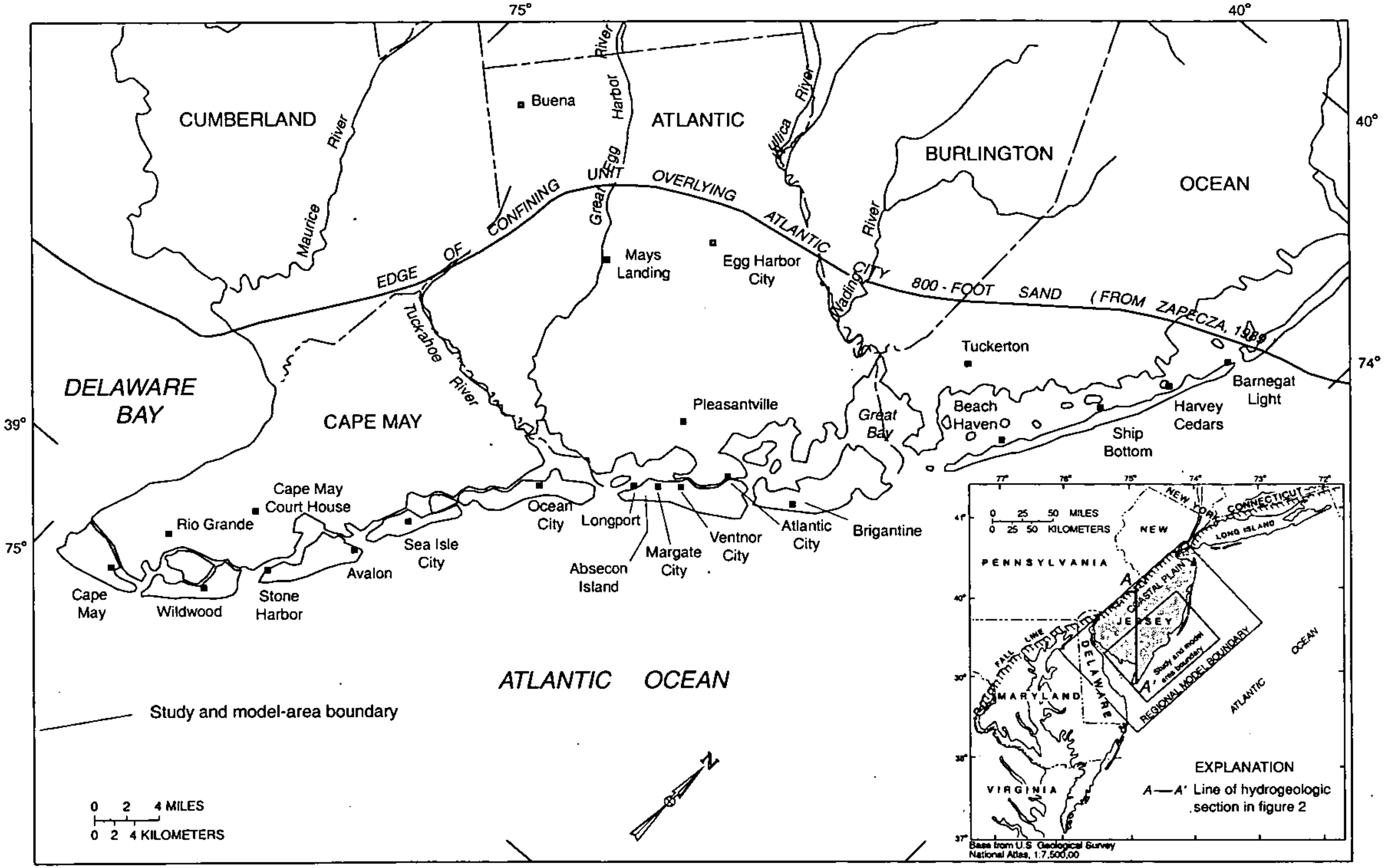
This report presents the results of an investigation of ground-water flow in the Atlantic City 800-foot sand that included (1) an analysis of the response of the flow system to ground-water withdrawals and (2) an evaluation of the potential for saltwater intrusion both under 1986 conditions and under conditions anticipated in the future. The results can assist water-resource managers in planning for water use and preserving the quality of the ground-water resource. An understanding of the flow system is achieved through analysis of hydrologic data and development of a conceptual model of the ground-water flow system. The concepts of the flow system are further analyzed and flow-system responses to water use are described, especially with regard to the potential for saltwater intrusion, by use of a computer-model simulation of flow conditions. The New Jersey Regional Aquifer-System Analysis Program (Martin, 1998), a large regional model of ground-water flow in the entire New Jersey Coastal Plain, was used to provide ground-water flow rates as boundary conditions for a model of flow in the Atlantic City 800-foot sand. Ground-water flow conditions are described before development of the water supply, in response to water use in April 1986 and September 1986, and for water use predicted in 2040.

Extent and thickness of aquifers and confining units are described on the basis of hydrologic data previously collected. Hydraulic properties of the hydrogeologic zones, such as hydraulic conductivity and storage properties, are discussed in terms of water-level responses to ground-water discharge during aquifer tests and flow-model simulations. Water-use and water-level data are used to describe regional responses in the flow system to water use, directions of ground-water flow, and trends in water levels over time. Chloride concentrations are used to show the extent of saltwater intrusion and the areal limits of the body of freshwater. Ground-water velocities computed from flow-model simulations are used as a basis for discussing movement of salty water toward pumping centers. Flow budgets from flow-model simulations are used to describe sources of water to pumping centers.

Description of Study Area

The study area is in the Coastal Plain Physiographic Province of New Jersey. The study focuses on the area where fine-grained sediments overlie and hydraulically confine the water-bearing sediments of the Atlantic City 800-foot sand (fig. 1). The area includes parts of Atlantic, Burlington, Cumberland, Cape May, and Ocean Counties. Data were also collected from two observation wells 1.9 mi and 5.3 mi offshore and southeast of Atlantic City. The simulation of ground-water flow extends to offshore areas and is truncated at a distance where the effect of ground-water withdrawals on the flow system is probably negligible.

The topography of the coastal-communities area consists of broad, low-relief areas underlain by sand, silt, gravel, and clay. Land-surface elevations are at or very near sea level.



EXPLANATION

A—A' Line of hydrogeologic section in figure 2

Base from U.S. Geological Survey National Atlas, 1:7,500,00

Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 1. Location of study area, New Jersey.

Much commercial and residential growth in and around the coastal communities resulted from the attraction of southeastern New Jersey as a resort area within the densely populated Northeast Corridor of the United States. The 1980 population of the three counties that lie wholly or partly within the study area (Atlantic, Cape May, and Ocean) was 290,818 (New Jersey Department of Labor, 1985). Population has increased dramatically during the previous 50 years, and it is expected to continue to increase, although at a lower rate, during 1990-2040 (New Jersey Department of Labor, 1985; URS Consultants, 1988). The population during the summer (resort-use) months is about four times that of the population during the winter (non-resort-use) months, although the establishment of legalized gambling in Atlantic City in 1977 is anticipated to result in increased rates of population growth during nonsummer months.

The topography of the inland-communities area also forms broad areas of low relief. The land surface slopes generally southeastward toward the coast, and land-surface altitudes range from 150 ft in westernmost parts of the study area to sea level along the bays. The inland areas are within a short commute of the coast; in addition, inland areas provide many natural resources desired by business, industry, and agriculture. The year-round population of inland communities also is expected to increase at a greater rate during 1990-2040 than during years prior to 1980 (New Jersey Department of Labor, 1985; URS Consultants, 1988). The New Jersey Department of Environmental Protection (NJDEP) estimates that ground-water withdrawals from the Atlantic City 800-foot sand may increase by 35 percent from 1986 to 2040 (Robert Kecskes, New Jersey Department of Environmental Protection, written commun., 1989).

Acknowledgments

The authors acknowledge hydrogeologists of the New Jersey Geological Survey (specifically, Lloyd Mulliken for supplying well logs and well information, and members of the well drilling program for installing observation wells for the study) and resource managers of the Water Supply Planning Element of the New Jersey Department of Environmental Protection for their extensive cooperation, advice, and assistance. Also, water purveyors, well owners, and concerned citizens of Atlantic, Cape May, and southern Ocean Counties provided much assistance and information that greatly benefited this study effort.

GROUND-WATER FLOW AND QUALITY

Data on aquifer and confining-unit extent and thickness, water-bearing properties, water levels, water use, and water quality were compiled and analyzed to construct a conceptual model of ground-water flow and quality in the Atlantic City 800-foot sand. Ground-water flow directions and rates were analyzed for conditions before ground-water withdrawals and in response to seasonal periods of minimum withdrawals (April 1986) and maximum withdrawals (September 1986). The concepts of the ground-water flow system were used to develop a computer-model simulation of the flow system to permit more detailed analysis of directions and rates of ground-water flow. Ground-water-quality data were used to identify areas of fresh and saline water in the aquifer.

Extent and Thickness of Aquifers and Confining Units

The Atlantic City 800-foot sand is one of several aquifers within the New Jersey Coastal Plain. The characteristics of the ground-water system of the Coastal Plain are related directly to the geology. Water-bearing properties are a function of the lithology, thickness, and lateral extent of the various geologic formations.

The hydrogeologic framework described in this report is based primarily on that developed for the USGS Northern Atlantic Coastal Plain Regional Aquifer System Analysis (RASA) project (Zapecza, 1989). Results of surface and borehole geophysical investigations in the study area by the New Jersey Geological Survey (Mullikin and others, 1989), onshore and offshore exploratory drilling by the USGS, and paleontological and sedimentological interpretations of core material by the USGS (Owens and others, 1988) have supported and enhanced this description of the hydrogeologic framework. Detailed information on the well and borehole geophysical data used to construct hydrogeologic sections and structure-contour and isopach maps in this report can be found in Zapecza (1989). Well-construction data for wells used in this report are included in appendix 1.

The New Jersey Coastal Plain is a seaward-dipping wedge of unconsolidated sediments ranging from Cretaceous to Quaternary in age. These sediments consist mostly of clay, silt, sand, and gravel of continental, coastal, or marine origin. The Coastal Plain sediments thicken seaward from a featheredge at the Fall Line to greater than 6,500 ft at the southern tip of Cape May County. This sedimentary wedge forms a complex ground-water system in which the sands and gravels function as aquifers and the silts and clays function as confining units (fig. 2). The geologic and hydrogeologic units in the Coastal Plain of New Jersey are listed in table 1.

The aquifers that overlie the Atlantic City 800-foot sand in the study area, as represented in this analysis, include, from the water table down, the Holly Beach water-bearing zone (referred to as Holly Beach WBZ), the Kirkwood-Cohansey aquifer system, and the Rio Grande water-bearing zone. The stratigraphic relations among aquifers that overlie and underlie the Atlantic City 800-foot sand are shown in figure 3. The aquifers tend to thicken toward southeastern parts of the study area and become thinner or are truncated toward the northwest and northeast.

The Holly Beach WBZ, as designated informally by Martin (1998, p. H34), represents part of the unconfined Holly Beach WBZ described by Gill (1962, p. 41) present only on the peninsular part of Cape May County, where it is underlain by the estuarine clay facies of the Cape May Formation mapped by Gill (1962, fig. 8); it does not extend offshore or into Delaware. Zapecza (1989, table 1) includes the Holly Beach WBZ as part of the undifferentiated sand and gravel sediments of Quaternary age. Throughout the rest of the study area, the estuarine clay facies is considered to be absent, and the sediments of the Holly Beach WBZ and any other surficial sediments are considered to be part of the Kirkwood-Cohansey aquifer system. The saturated sediments of the Holly Beach WBZ range from 30 to 70 ft in thickness, and the altitude of the top of the saturated sediments ranges from about 15 ft above sea level to near sea level. The Holly Beach WBZ was not investigated as part of this study but was included in computer-model analysis to evaluate effects of the water table on water levels in the confined part of the Atlantic City 800-foot sand.

The Kirkwood-Cohansey aquifer system is an important source of water supply for inland areas. On the barrier islands and along the coast, the aquifer system is susceptible to saltwater intrusion and commonly contains brackish or salty water. The Kirkwood-Cohansey aquifer system is an unconfined (water-table) aquifer except where overlain by Quaternary deposits in Cape May County (Gill, 1962). The Atlantic City 800-foot sand is recharged by lateral flow from the Kirkwood-Cohansey aquifer system in areas updip from the extent of the confining unit and by vertical leakage from the Kirkwood-Cohansey aquifer system through the confining unit. The Atlantic City 800-foot sand truncates as an aquifer at the updip edge of the overlying confining unit. The Kirkwood-Cohansey aquifer system and the Atlantic City 800-foot sand are considered to function as one unconfined system beyond the extent of the confining unit above the minor Rio Grande water-bearing zone (Zapecza, 1989, p. B18). The unconfined aquifer thickens downdip from less than 50 ft at the Kirkwood Formation outcrop to more than 400 ft near the edge of the confining unit overlying the Atlantic City 800-foot sand.

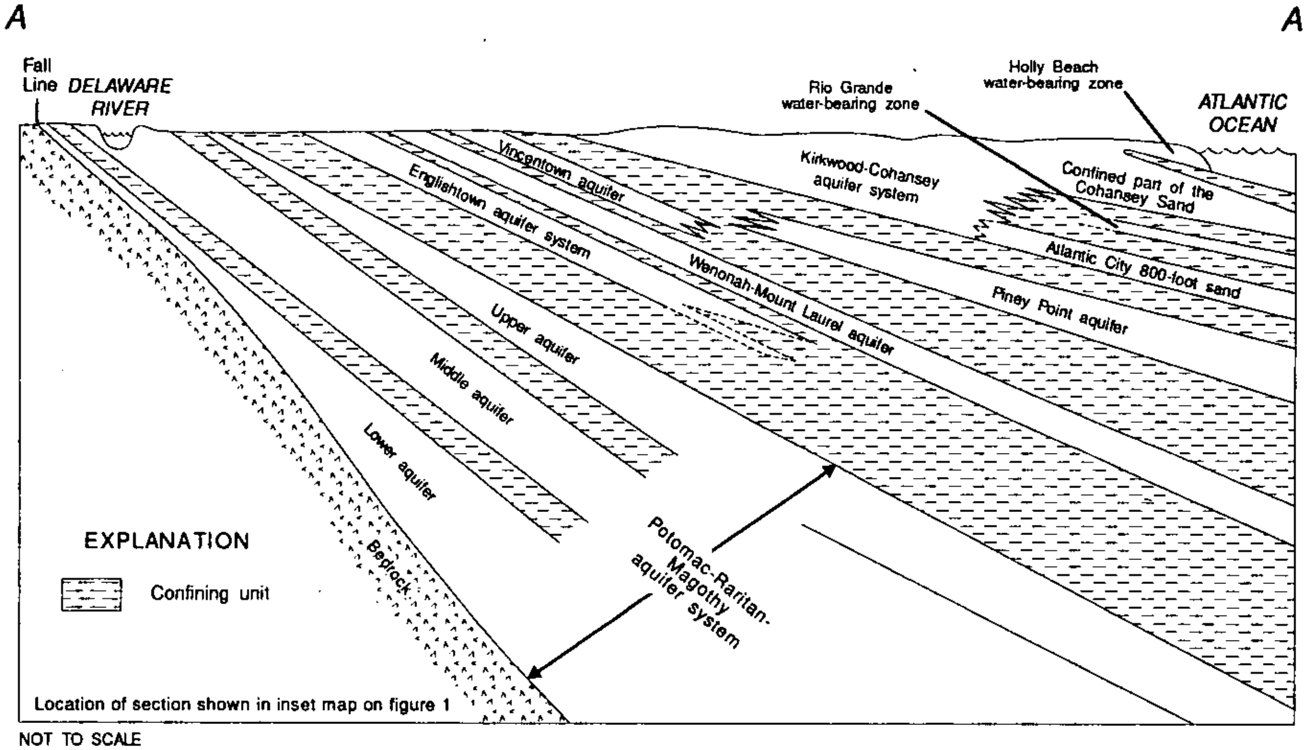


Figure 2. Diagrammatic hydrogeologic section *A-A'* through the New Jersey Coastal Plain. (Modified from Zapecza and others, 1987)

The thickness and extent of the confining unit that overlies the Atlantic City 800-foot sand are shown in figure 4. Confining-unit thickness increases downdip from less than 100 ft near Mays Landing, Atlantic County, to more than 300 ft beneath the Atlantic City area. The confining unit is thickest along the barrier beaches of Cape May County, where thicknesses of 400 to 450 ft are common. However, sandy zones within the confining unit are common in the Cape May area. The confining unit thins toward the line approximating its westernmost limit in the subsurface. The unit cannot be identified in geophysical logs of wells less than 5 mi updip from the limit shown on the map (fig. 4). The confining unit thins toward the west and appears to truncate. On the basis of borehole geophysical data, the confining unit grades laterally from a thick deposit of clay and silt in coastal areas to sand toward the west (fig. 3).

The Rio Grande water-bearing zone (Gill, 1962), equivalent to the 550-foot horizon of Woolman (1891, p. 224), lies within the confining unit that overlies the Atlantic City 800-foot sand. The Rio Grande water-bearing zone is seldom used as a source of water outside southern Cape May County and thus is of minor importance as a water-supply source.

The Atlantic City 800-foot sand is a major water-bearing unit that lies within the lower part of the Kirkwood Formation. It is the principal confined aquifer supplying water along the barrier beaches from Stone Harbor in Cape May County to Harvey Cedars in Ocean County and as far west as Egg Harbor City in Atlantic County. The Atlantic City 800-foot sand is composed of gray, medium- to coarse-grained quartz sand with a considerable amount of interspersed fragmented shell material. The altitude of the top of the Atlantic City 800-foot sand and its approximate extent are shown in figure 5. The approximate updip limit of the Atlantic City

Table 1. Geologic and hydrogeologic units in the Coastal Plain of New Jersey
[Modified from Zapecza, 1989, table 2]

SYSTEM	SERIES	GEOLOGIC UNIT	LITHOLOGY	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Quaternary	Holocene	Alluvial deposits	Sand, silt, and black mud.	Undifferentiated	Surficial material, commonly hydraulically connected to underlying aquifers. Locally some units may act as confining units. Thicker sands are capable of yielding large quantities of water.
		Beach sand and gravel	Sand, quartz, light-colored, medium- to coarse-grained, pebbly.		
	Pleistocene	Cape May Formation	Sand, quartz, light-colored, heterogeneous, clayey, pebbly.	Holly Beach water-bearing zone	
Tertiary	Miocene	Pennsauken Formation		Kirkwood-Cohansey aquifer system	A major aquifer system. Ground water occurs generally under water-table conditions. In Cape May County, the Cohansey Sand is under artesian conditions.
		Bridgeton Formation			
		Beacon Hill Gravel	Gravel, quartz, light-colored, sandy.		
		Cohansey Sand	Sand, quartz, light-colored, medium- to coarse-grained, pebbly; local clay beds.		
		Kirkwood Formation	Sand, quartz, gray and tan, very fine to medium-grained, micaceous, and dark-colored diatomaceous clay.	Confining unit	Thick diatomaceous clay bed occurs along coast and for a short distance inland. A thin water-bearing sand is present in the middle of this unit.
				Rio Grande water-bearing zone	
				Confining unit	
				Atlantic City 800-foot sand	A major aquifer along the coast.
				Composite confining unit	Poorly permeable sediments.
	Oligocene	Piney Point Formation	Sand, quartz and glauconite, fine- to coarse-grained.	Piney Point aquifer	Yields moderate quantities of water.
	Eocene	Shark River Formation			
		Manasquan Formation	Clay, silty and sandy, glauconitic, green, gray and brown, contains fine-grained quartz.		Poorly permeable sediments.
	Paleocene	Vincentown Formation	Sand, quartz, gray and green, fine- to coarse-grained, glauconitic, and brown clayey, very fossiliferous, glauconite and quartz calcarenite.	Vincentown aquifer	Yields small to moderate quantities of water in and near its outcrop area.
		Hornerstown Sand	Sand, clayey, glauconitic, dark-green, fine- to coarse-grained.		Poorly permeable sediments.
Cretaceous	Upper Cretaceous	Tinton Sand	Sand, quartz, glauconitic, brown and gray, fine- to coarse-grained, clayey, micaceous.		
		Red Bank Sand		Red Bank Sand	Yields small quantities of water in and near its outcrop area.
		Navesink Formation	Sand, clayey, silty, glauconitic, green and black, medium- to coarse-grained.		Poorly permeable sediments.
		Mount Laurel Sand	Sand, quartz, brown and gray, fine- to coarse-grained, slightly glauconitic.	Wenonah-Mount Laurel aquifer	A major aquifer.
		Wenonah Formation	Sand, very fine- to fine-grained, gray and brown, silty, slightly glauconitic.	Marshalltown-Wenonah confining unit	A leaky confining unit.
		Marshalltown Formation	Clay, silty, dark-greenish-gray; contains glauconitic quartz sand.		
		Englishtown Formation	Sand, quartz, tan and gray, fine- to medium-grained; local clay beds.	Englishtown aquifer system	A major aquifer. Two sand units in Monmouth and Ocean Counties.
		Woodbury Clay	Clay, gray and black, and micaceous silt.	Merchantville-Woodbury confining unit	A major confining unit. Locally the Merchantville Formation may contain a thin water-bearing sand.
		Merchantville Formation	Clay, glauconitic, micaceous, gray and black; locally, very fine grained quartz and glauconitic sand are present.		
		Magothy Formation	Sand, quartz, light-gray, fine- to coarse grained. Local beds of dark-gray lignitic clay. Includes Old Bridge Sand Member.	Potomac-Raritan-Magothy aquifer system: Upper aquifer	A major aquifer system. In the northern Coastal Plain, the upper aquifer is equivalent to the Old Bridge aquifer and the middle aquifer is equivalent to the Farrington aquifer. In the Delaware River Valley, three aquifers are recognized. In the deeper subsurface, units below the upper aquifer are undifferentiated.
				Confining unit	
		Raritan Formation	Sand, quartz, light-gray, fine- to coarse-grained, pebbly, arkosic; contains red, white, and variegated clay. Includes Farrington Sand Member.	Middle aquifer	
				Confining unit	
	Lower Cretaceous	Potomac Group	Alternating clay, silt, sand, and gravel.	Lower aquifer	
Pre-Cretaceous		Bedrock	Precambrian and lower Paleozoic crystalline rocks, schist and gneiss; locally, Triassic sandstone and shale and Jurassic diabase are present.	Bedrock confining unit	No wells obtain water from these consolidated rocks except along Fall Line.

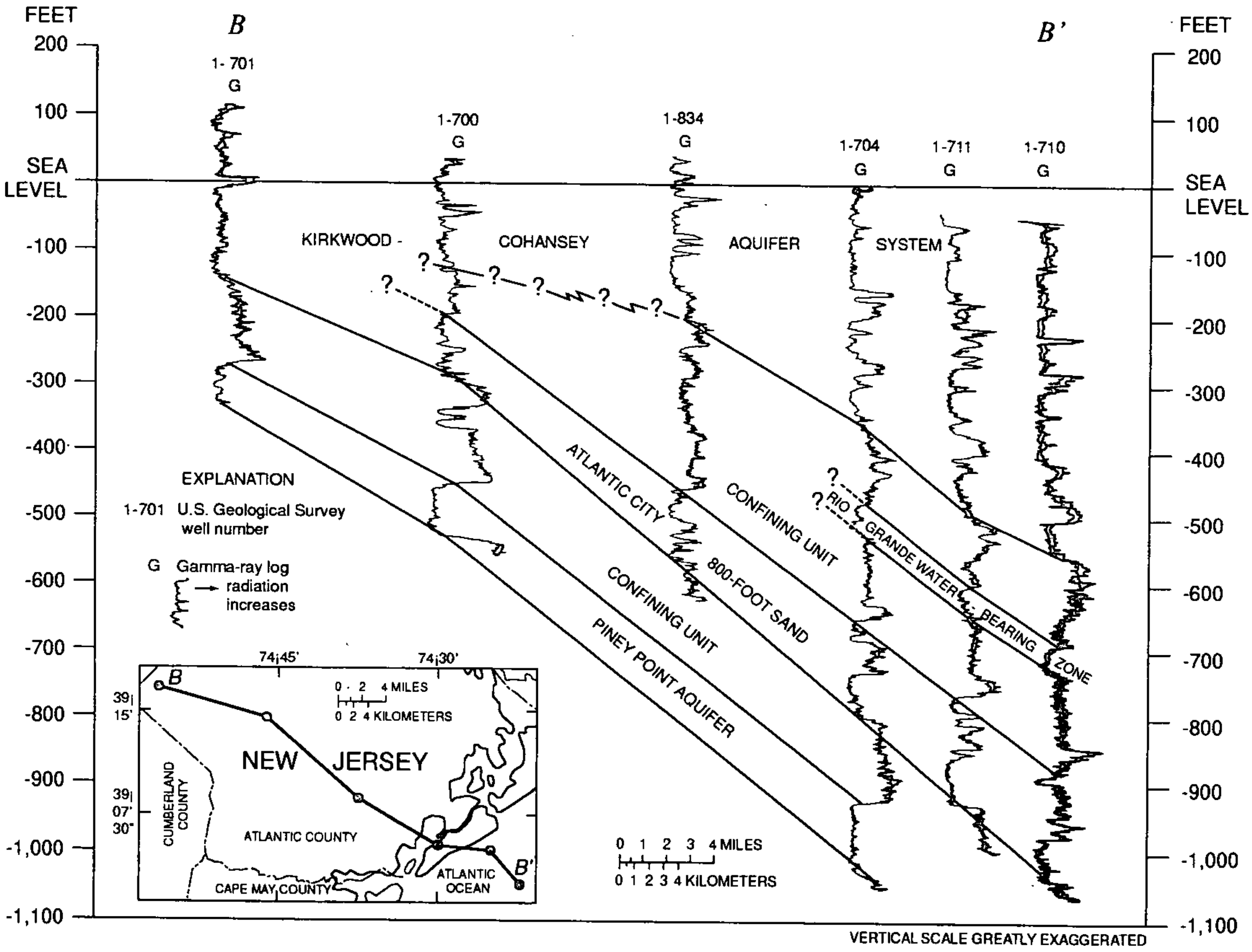
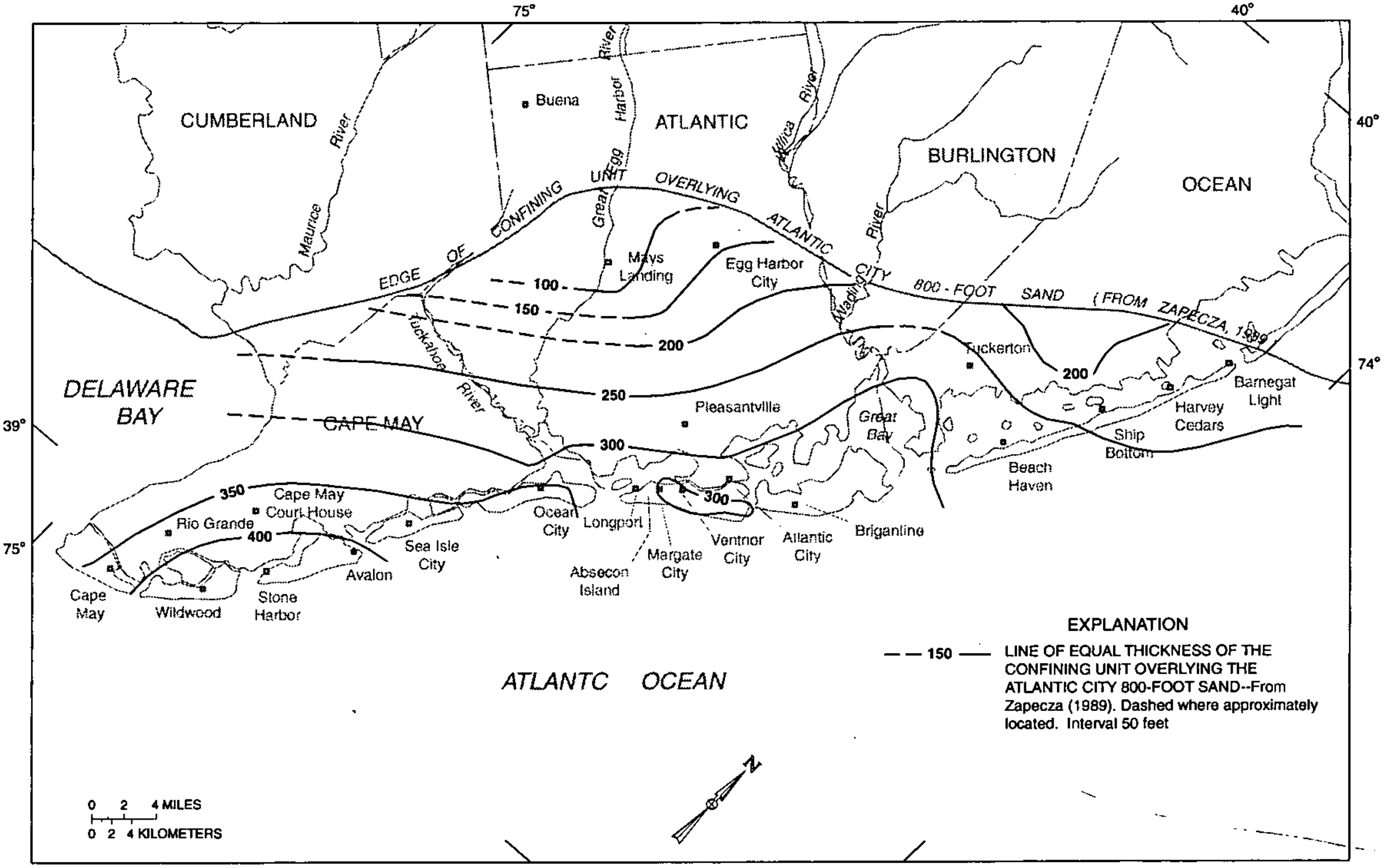
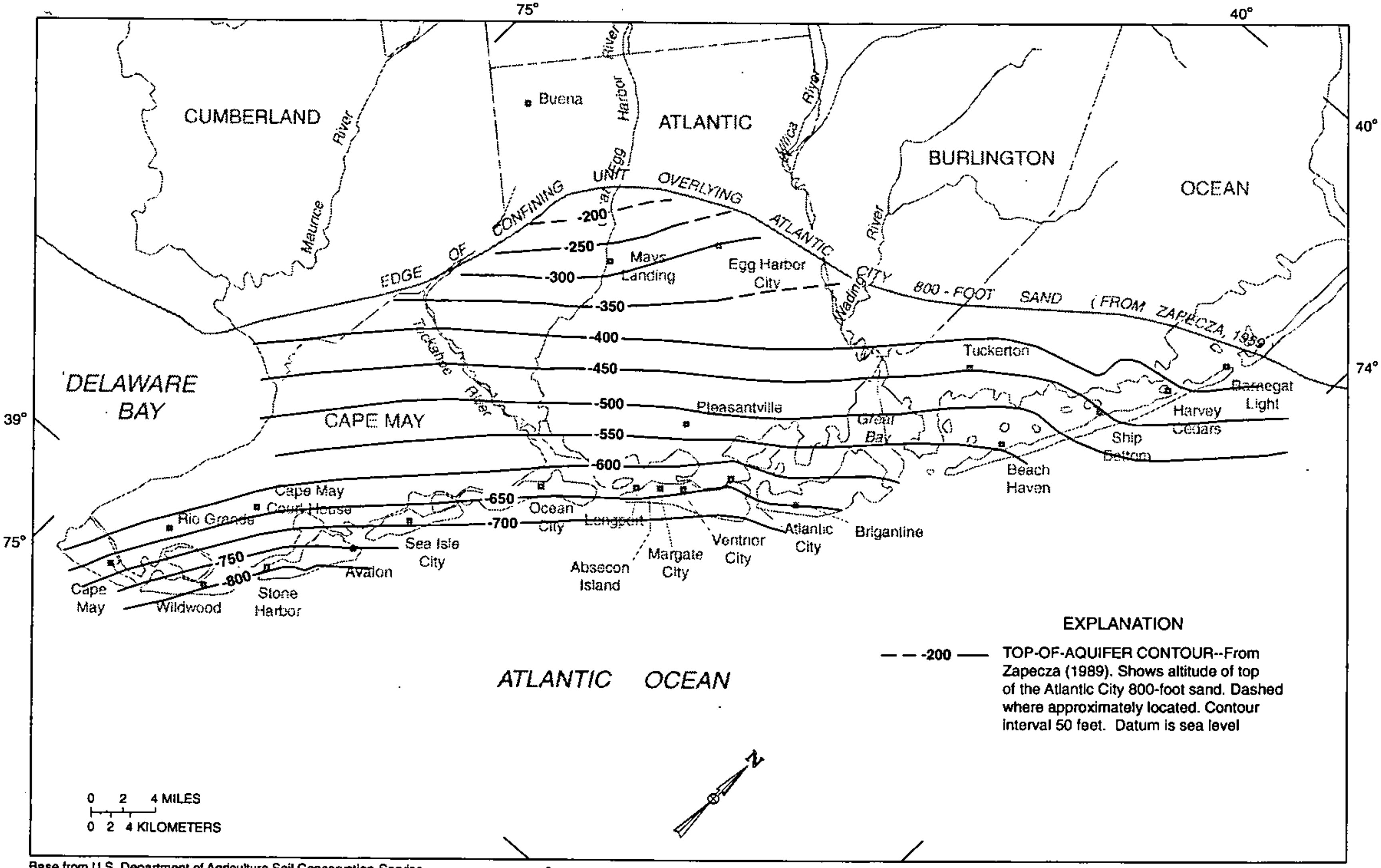


Figure 3. Hydrogeologic section *B-B'* through the New Jersey Coastal Plain.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 4. Thickness of the confining unit overlying the Atlantic City 800-foot sand, New Jersey.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 5. Altitude of the top of the Atlantic City 800-foot sand, New Jersey.

800-foot sand is based on the approximate updip limit of the overlying confining unit. The Atlantic City 800-foot sand is recognizable in the subsurface only where it is overlain by the thick, massive clay unit southeast of the line approximating the confining unit's extent. In areas northwest of the confining-unit limit, the Kirkwood Formation is composed primarily of fine- to medium-grained sand that is hydraulically connected to the overlying Cohansey Sand and younger deposits, forming a relatively thick unconfined aquifer.

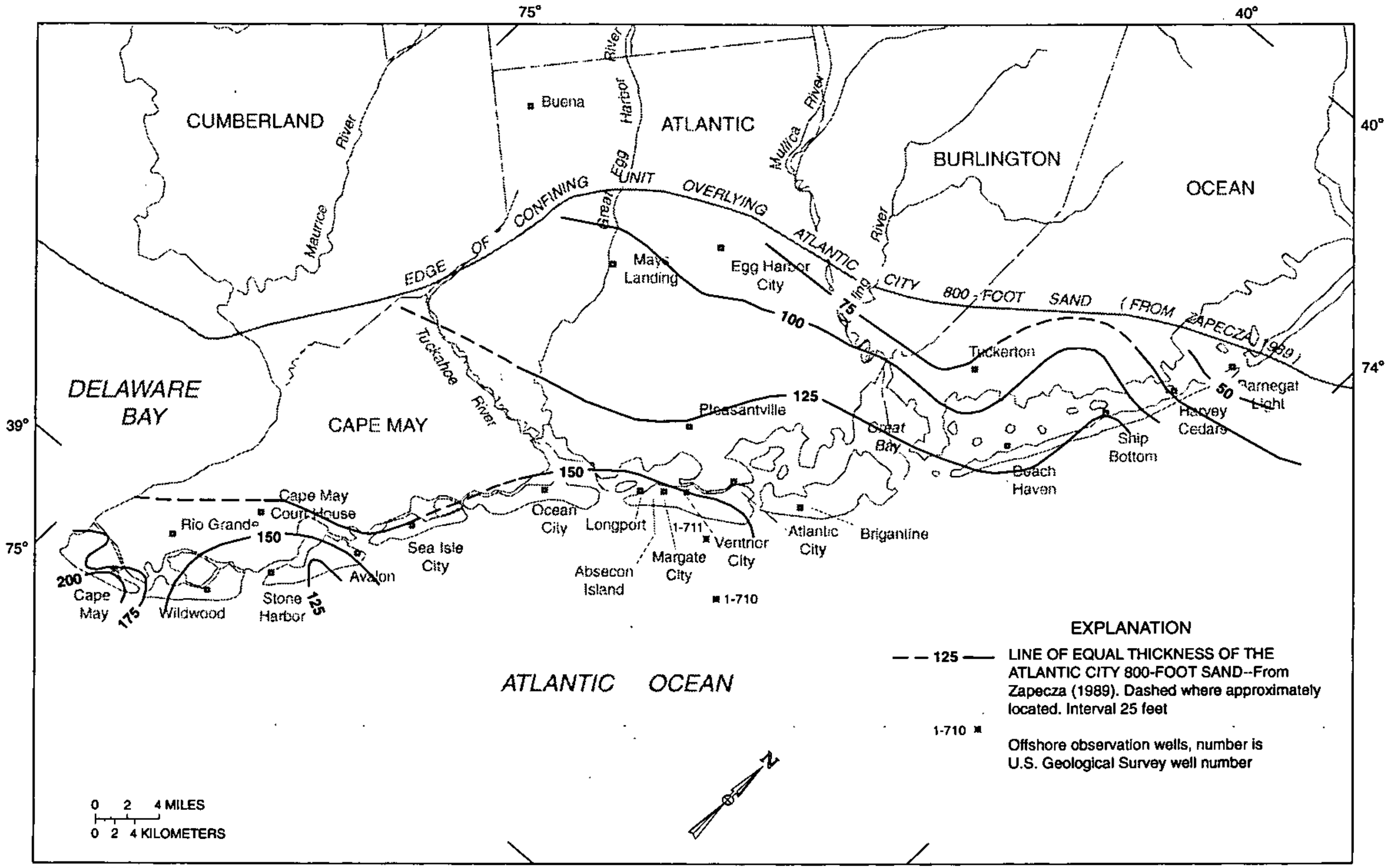
The relation of the Atlantic City 800-foot sand to the overlying and underlying confining units and to the adjacent unconfined Kirkwood-Cohansey aquifer system is shown in figure 2. Borehole geophysics, recent paleontological and sedimentological analysis of Kirkwood Formation sediments (Owens and others, 1988), and recent stratigraphic work on the Kirkwood Formation (Mullikin and others, 1989) indicate that the Atlantic City 800-foot sand continues beyond the western edge of the overlying confining unit and becomes part of the larger unconfined system to the west. This is a significant finding because a lateral connection would indicate that most of the recharge to the confined Atlantic City 800-foot sand is from unconfined areas to the west and northwest.

The Atlantic City 800-foot sand generally thickens downdip (fig. 6). The aquifer also thickens toward the south, from approximately 40 ft at Barnegat Light, Ocean County, to greater than 200 ft at Cape May City, Cape May County. Aquifer thickness near Atlantic City is about 150 ft (Zapecza, 1989, pl. 5).

A 10- to 30-ft-thick clay bed within the Atlantic City 800-foot sand is recognized on geophysical logs from Ocean City, Cape May County, to Beach Haven, Ocean County. Most of the water-supply wells along the coast are screened below this thin clay bed. According to unpublished results of an aquifer test conducted in 1980 at Atlantic City, Atlantic County, significant downward leakage can occur from the upper sandy zone of the aquifer (C.L. Tilley and A.J. Straus, U.S. Geological Survey, written commun., 1980).

Meisler and others (1984, p. 6) show that the sediments that form hydrogeologic units under the New Jersey Coastal Plain extend beneath the Atlantic Ocean to the Continental Slope. These sediments are described by generalized geologic ages but not by specific aquifer designation. The quality of water in the Atlantic City 800-foot sand in areas offshore of Atlantic City is important to the determination of the extent of freshwater available for communities along the southern coast of New Jersey. During 1985, the USGS drilled from platforms raised above the Atlantic Ocean in order to complete two monitoring wells into the Atlantic City 800-foot sand offshore. The wells are 1.9 mi and 5.3 mi offshore of Atlantic City. Analyses of geophysical logs and drillers' logs indicate that the sediments of the Atlantic City 800-foot sand extend offshore, although the thickness of the sediments decreases to 130 ft at the well 5.3 mi offshore. Other tests and analyses at the sites demonstrated that the sediments constitute a viable confined freshwater aquifer at both 1.9 mi and 5.3 mi offshore. The results of this investigation and previous research of Meisler and others (1984) indicate that the Atlantic City 800-foot sand freshwater aquifer extends several miles southeast and southwest offshore of the southern coast of New Jersey, although the extent is not mapped because of the paucity of data.

The confining unit underlying the Atlantic City 800-foot sand is composed primarily of silt- and clay-sized sediments of the lower part of the Kirkwood Formation. This confining unit is regionally extensive in the Atlantic City area and effectively isolates the underlying Piney Point aquifer from the major aquifers within the Kirkwood Formation and Cohansey Sand. The confining unit is easily recognized by its characteristic gamma signature on gamma-ray logs. Hydrogeologic section B-B′ (fig. 3) shows the lateral persistence of the signature in the subsurface, corresponding to the basal confining unit underlying the Atlantic City 800-foot sand in downdip areas and the basal confining unit underlying the unconfined Kirkwood-Cohansey



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 6. Thickness of the Atlantic City 800-foot sand, New Jersey.

aquifer system in updip areas. This confining unit forms the upper part of the composite confining unit described by Zapecza (1989, p. B14) and listed in table 1. The thickness of the confining unit averages about 100 ft in the Atlantic City area.

The Piney Point aquifer underlies the basal confining unit of the Kirkwood Formation. The Piney Point aquifer has been developed for public water supply in extreme northern parts of the study area near Barnegat Light in Ocean County and Buena Borough in western Atlantic County. The aquifer is extensive in the Atlantic City area; however, in the vicinity of Atlantic City and south to the Cape May Peninsula, it is known to contain brackish and salty water.

The Piney Point aquifer as defined in this report represents the moderately permeable glauconitic sand and shell beds that lie directly below the basal clay of the Kirkwood Formation and that are laterally continuous with the Piney Point aquifer of the Delaware and Maryland Coastal Plain, although researchers have not agreed on the name designation (Zapecza, 1989; Olsson and others, 1980, p. 550; Enright, 1969, p. 19). The lateral persistence of this hydrogeologic unit in the subsurface is shown in section B-B′ (fig. 3). The thickness of the Piney Point aquifer ranges from less than 40 ft to more than 200 ft in Cumberland County (Zapecza, 1989, p. B17).

The hydrogeologic units below the Piney Point aquifer were not included in this investigation. The confining unit beneath the Piney Point aquifer is considered to have insignificant permeability and therefore is treated as an impermeable unit.

Hydraulic Properties

The Atlantic City 800-foot sand has the ability to yield an abundant quantity of ground water. Hydraulic conductivities computed by Gill (1962, p. 47), Anderson and Appel (1969, p. 48), and Martin (1998, p. H26-H28) range from 38 to 320 ft/d; the mean is 84 ft/d. Computed transmissivities from analysis of aquifer tests range from 860 to 19,900 ft^2/d; the mean is 6,300 ft^2/d. Single-well aquifer tests were done to determine hydraulic properties at observation wells used to monitor water-level trends during the Atlantic City area study. Computed hydraulic conductivities at these wells range from 9 to 88 ft/d, and the mean is 51 ft/d. Transmissivities range from 1,200 to 8,300 ft^2/d, and the mean is about 5,600 ft^2/d.

During 1985, an aquifer test was done that allowed the calculation of hydraulic properties between pumping centers in Atlantic City and the well 1.9 mi offshore of Atlantic City (well 1-711). Analysis of the 8-day test was complicated, however, by the areal distribution of multiple wells pumping at a total rate of about 2,400 gal/min, by the effects of tide on water levels, and by the effect of uncontrolled pumpage distant from the test wells. Transmissivity of the Atlantic City 800-foot sand between Atlantic City and well 1-711 was estimated to be about 2,600 ft^2/d (unpublished data on file at the U.S. Geological Survey New Jersey District office). The hydraulic conductivity was estimated to be 17 ft/d. The reduced hydraulic conductivity offshore coincides with the determination from lithologic data, examined during drilling, that permeability decreases in an offshore direction in the Atlantic City 800-foot sand. The trend of decreased permeability with increased distance offshore from well 1-711, 1.9 mi offshore of Atlantic City, and from selected wells on the coast, is corroborated by comparatively low transmissivity, 1,700 ft^2/d, and hydraulic conductivity, 9 ft/d, computed from a single-well test at well 1-710. The transmissivity and the hydraulic conductivity were based on the results of the 5 days of pumping at an average rate of 46 gal/min (unpublished data on file at the U.S. Geological Survey New Jersey District office).

Storage coefficients from analysis of aquifer tests in previous investigations range from 2.1×10^{-5} to 6.0×10^{-4}. All storage coefficients were computed by use of analytical methods on results of aquifer tests and were reported by Gill (1962, p. 47), Anderson and Appel (1969, p. 48), and Martin (1998, p. H28).

The confining unit overlying the Atlantic City 800-foot sand is leaky. Leakage through the overlying confining unit has been computed from vertical hydraulic conductivity as determined from laboratory tests of cores extracted from boreholes during well-drilling operations in 1984-88. Hydraulic conductivities of the clay cores were determined by permeability tests using a constant-volume variable-head apparatus (Enrique Manuel, Woodward-Clyde Consultants, written commun., 1985 and 1988). Hydraulic conductivity ranges from 7.2×10^{-6} to 7.7×10^{-3} ft/d. The vertical hydraulic conductivity of the confining units decreases with distance offshore. Confining-unit cores from well 1-834 in Margate, N.J., were found to have hydraulic conductivity that ranges from 3.5×10^{-3} to 7.7×10^{-3} ft/d. Hydraulic conductivity of confining-unit cores from well 1-710, 5.3 mi offshore of Atlantic City, ranges from 7.2×10^{-6} to 2.4×10^{-5} ft/d.

The Atlantic City 800-foot sand is recharged from the unconfined aquifer in areas updip from the edge of the overlying confining unit. Hydraulic conductivity of the unconfined aquifer is generally greater than that of the Atlantic City 800-foot sand and is reported to range from 90 to 250 ft/d, on the basis of aquifer-test analysis (Gill, 1962, p. 47; Rhodehamel, 1973, p. 55). Hydraulic conductivities determined from laboratory permeability tests of confining-unit cores range from 5.2×10^{-6} to 1.9×10^{-5} ft/d for the clayey confining unit underlying the Atlantic City 800-foot sand (Enrique Manuel, written commun., 1985 and 1988). Porosity, also determined from cores of confining-unit material above and below the Atlantic City 800-foot sand, range from 0.42 to 0.61.

Predevelopment Ground-Water Flow

Flow directions and hydraulic gradients in the prepumping flow system were interpreted from historical water levels. Rates of flow into and out of the prepumping flow system were accounted for in a flow budget. An understanding of the prepumping system is a prerequisite for understanding the recent system and changes that have resulted from widespread pumping.

Water Levels and Flow Directions

The Kirkwood-Cohansey aquifer system is recharged as rainfall infiltrates through soil layers to the zone of saturation. The water table generally forms a subdued replica of the topography. Before pumping, the altitude of the water table ranged from 133 ft to sea level and was typically highest under highlands and lowest under lowlands, where the aquifer discharges to streams, wetlands, lakes, and the ocean (Zapecza and others, 1987, p. 116). The freshwater-saltwater interface is estimated to have been near the shore. The water table represents the Kirkwood-Cohansey water levels throughout all of the area shown in figure 1 except southern Cape May County, where the Kirkwood Formation materials and the Cohansey Sand are confined. In southern Cape May County, the unconfined aquifer is known as the Holly Beach WBZ (Gill, 1962, p. 37).

Depth to the water table ranges from 0 ft at surface-water bodies to 24.10 ft under highlands (Clark and Paulachok, 1989, p. 15). Water levels fluctuate seasonally as changes in storage take place in response to variations in recharge and discharge; however, seasonal water-level fluctuations are only about 5 ft in the Kirkwood-Cohansey aquifer system, and net change in storage is considered to be zero over long periods (Clark and Paulachok, 1989, p. 15-26). The effect of the water table on the Atlantic City 800-foot sand is to provide a constant source of recharge in updip areas, especially near the edge of the extent of the clayey unit that confines the Atlantic City 800-foot sand. Prepumping water levels in the Atlantic City 800-foot sand ranged from 50 to 9 ft above sea level, as shown in figure 7 (Zapecza and others, 1987, p. 114-115). Water levels in the Atlantic City 800-foot sand would likely fluctuate very little on a seasonal basis because seasonal and cyclic changes in recharge to the Atlantic City 800-foot sand are very small.

Recharge

Rates of recharge and discharge can be accounted for in a water budget. Under nonpumping conditions, if change in storage is assumed to be negligible, recharge must equal discharge. As mentioned previously, recharge to the aquifers is derived from precipitation. Average precipitation in the Coastal Plain of New Jersey has been estimated to be 45 in/yr (Rhodehamel, 1970, p. 6-7) from 1931-64 records of precipitation in southern New Jersey. An estimated 22.5 in/yr of precipitation is lost to evapotranspiration in southern New Jersey (Rhodehamel, 1970, p. 8-12). Of the remaining 22.5 in/yr of precipitation, 2.5 in/yr discharges to streams as direct overland runoff and as direct precipitation on surface-water bodies, and 20 in/yr infiltrates through the soil to recharge the ground-water system. The recharge enters the unconfined ground-water systems in upland areas, flows vertically downward, then flows laterally within the confined aquifer; ultimately, this water discharges upward through confining units into the ocean or bays at or near the interface between freshwater and saltwater or discharges as diffuse flow through leaky confining units into overlying aquifers or the ocean. The estimated regional deep flow component of the recharge to the unconfined flow system is about 3 in/yr from about 560 mi^2 of upland areas (Rhodehamel, 1970).

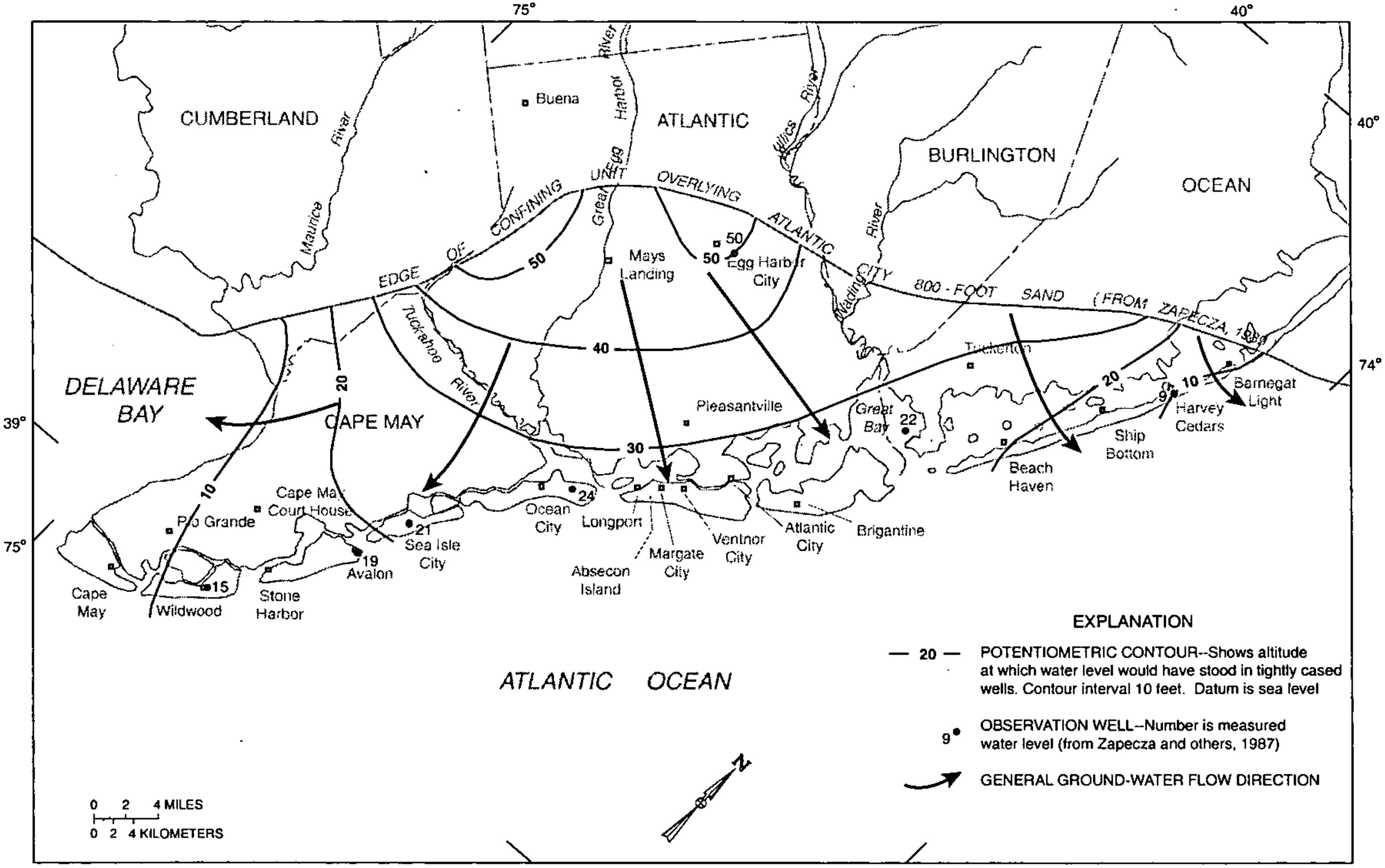
Recharge to the confined Atlantic City 800-foot sand during prepumping conditions was estimated for this study by use of Darcy's Law. The use of Darcy's Law requires the further assumptions that net changes in storage are negligible and that the aquifer system can be represented as isotropic and homogeneous. Recharge is computed as

$$Q_{DR} = \overline{KIA},$$

where Q_{DR} is deep recharge to the confined Atlantic City 800-foot sand,
$\overline{K}$ is average hydraulic conductivity of the confined aquifer,
$\overline{I}$ is average hydraulic gradient taken over the entire extent of the flow system, and
$\overline{A}$ is average cross-sectional area through which Q flows.

Average hydraulic conductivity ($\overline{K}$) of the Atlantic City 800-foot sand throughout its onshore extent is estimated to be 50 ft/d (Martin, 1998, p. H27).

The average hydraulic gradient ($\overline{I}$) is computed by dividing a change in hydraulic head, or water level, by the distance over which the change in water level occurs. The confined flow system extends from the edge of the overlying confining unit to the areas of discharge that include all flow through the confined part of the Atlantic City 800-foot sand. Prepumping water levels near the edge of the confining unit were reported to be as great as 50 ft above sea level. The discharge area includes the conceptualized freshwater-saltwater interface in the confined aquifer. At the interface, fresh ground water flows toward the ocean. Water levels at the interface are estimated to be at sea level. The change in water level over the entire extent of the deep flow system would then be about 50 ft. The distance over which the change in water levels takes place must be estimated because the distance from recharge areas to discharge areas depends on the direction of flow over which the distance measurement is made. Estimated distance to the freshwater-saltwater interface in the geologic media of Miocene age that contain the Atlantic City 800-foot sand is about 50 mi offshore of Atlantic City (Meisler and others, 1984, p. 6).



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 7. Prepumping potentiometric surface of the Atlantic City 800-foot sand, New Jersey. (Modified from Zapecza and others, 1987, fig. 9)

Estimated distance to the freshwater-saltwater interface is less than 1 mi, or near the shoreline, in areas offshore of Barnegat Light and near the mouth of the Maurice River in Cumberland County (D.A. Pope, U.S. Geological Survey, written commun., 1991). The freshwater-saltwater interface is assumed to be near the shore in these areas because the overlying confining unit is absent and a connection between the saltwater of the ocean or bay and the confined aquifer is likely. The average distance from shore to the freshwater-saltwater interface, 25 mi, is taken as the average of the two extreme distances. Distances on land along a conceptual direction of ground-water flow from upland recharge areas to the coast range from about 12 to 39 mi, so the average land distance is about 25 mi. The total distance over which the extremes in water levels exist is about 50 mi. The average hydraulic gradient is thus computed to be 0.0001894.

The average cross-sectional area ($\overline{A}$) through which deep recharge (Q) flows into the Atlantic City 800-foot sand is the product of the average thickness and the estimated width or length of the unit perpendicular to the flow direction. The average thickness is computed to be 125 ft, on the basis of the range of thickness given by Martin (1998, p. H34). The width, 72 mi, was estimated from maps in Zapecza (1989, pl. 22) showing the extent of the overlying confining unit. Thus, the average cross-sectional area ($\overline{A}$) is 47,520,000 ft^2.

The preceding computations indicate that, before pumping, recharge entered the deep confined Atlantic City 800-foot sand at a rate of 425,000 ft^3/d, or 3.55 Mgal/d. This rate is equivalent to 0.132 in/yr over the area contributing recharge to the deep flow system. This contributing area includes the uplands area of the New Jersey Coastal Plain, estimated to be 562 mi^2 (Rhodehamel, 1970, p. 18). This rate of recharge to the confined flow system (0.1 in/yr) is insignificant compared to the 20 in/yr estimated to recharge the confined and unconfined ground-water flow system, so an average of 20 in/yr is estimated to discharge to streams in the study area.

Postdevelopment Ground-Water Flow

Ground water is the primary source of water supply for the populations of the barrier islands of Ocean County, Atlantic County, and Cape May County in New Jersey. Water is pumped from the Atlantic City 800-foot sand in coastal communities between Harvey Cedars in Ocean County and Stone Harbor in Cape May County as well as at some inland sites (table 2). By 1986, in response to pumping, water levels in the Atlantic City 800-foot sand had declined to as much as 101 ft below sea level. The depressed water levels in the coastal wells completed in the Atlantic City 800-foot sand create a ground-water flow direction from the offshore location of saltwater toward supply wells. The chemical character of some ground-water samples is indicative of the water in the zone of diffusion between freshwater and saltwater in a coastal ground-water flow system.

Pumpage

In 1892, the first well at Atlantic City was drilled into the Atlantic City 800-foot sand to withdraw water for public supply. By 1896, 12 wells in Atlantic City and wells in Brigantine, Longport, Ocean City, and Wildwood had been drilled in the Atlantic City 800-foot sand. Several of these wells were reported to flow at land surface at rates between 100 and 180 gal/min and could be pumped at rates of as much as 400 gal/min. The water levels were reported to rise to between 9 and 14 ft above land surface (Woolman, 1895, p. 63-96). Since 1896, pumpage from the Atlantic City 800-foot sand has greatly increased, from an annual average of 2.7 Mgal/d in 1918 (when recordkeeping began) to 20.85 Mgal/d in 1986 (fig. 8).

Average annual pumpage shown in figure 8 was compiled from files of the New Jersey Department of Environmental Protection (NJDEP) and from Zapecza and others (1987). Pumpage during 1955-86 was compiled from reports of pumpage submitted quarterly to the

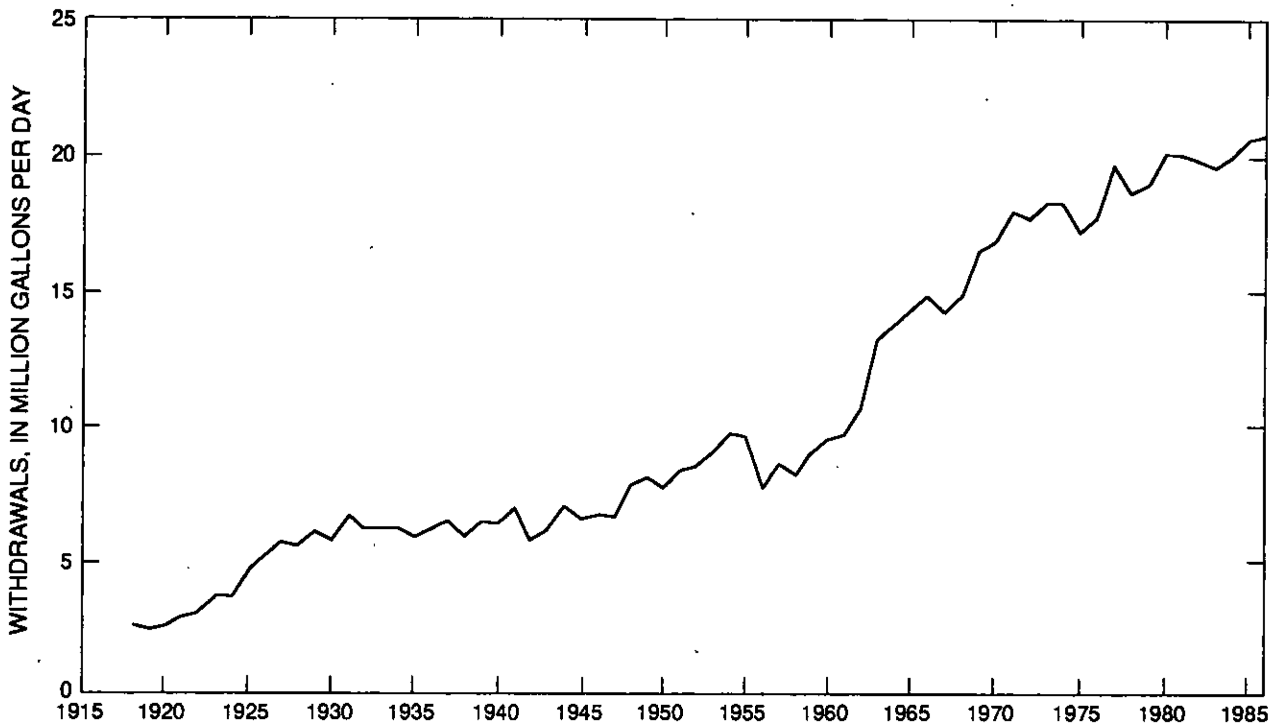


Figure 8. Average annual withdrawals from the Atlantic City 800-foot sand, New Jersey, during 1918-86.

NJDEP by water users who use 100,000 gal/d or more. Pumpage from before 1955 was estimated on the basis of the number of wells in operation each year and assumed average pumpage. Most pumpage from the Atlantic City 800-foot sand is for public supply.

In 1986, withdrawals from the Atlantic City 800-foot sand were about 9.7 Mgal/d from Atlantic County, 6.9 Mgal/d from Cape May County, and 4.3 Mgal/d from Ocean County (table 2). Ground-water withdrawals from the Rio Grande water-bearing zone, averaging about 1 Mgal/d during 1986, are included in the pumpage from the Atlantic City 800-foot sand; this pumpage, which is dispersed in Cape May County, does not seem to significantly affect water levels in the Atlantic City 800-foot sand in either Atlantic County or the coastal communities of Cape May County.

Withdrawals from the unconfined aquifer averaged 30.5 Mgal/d in 1986 in Atlantic and Cape May Counties. Pumping from the unconfined aquifer takes place in much of Atlantic County and Cape May County, for public supply, domestic supply, and agricultural use. The effects of pumping in the unconfined aquifer are considered to be of local extent and not likely to significantly affect water levels in or the flow budget of the Atlantic City 800-foot sand. Similarly, withdrawals from the Piney Point aquifer are at low rates (Zapecza and others, 1987, p. 100) and are not likely to significantly affect water levels in or the flow budget of the Atlantic City 800-foot sand.

Demand for public supply has large seasonal fluctuations because the economy of the barrier islands is affected greatly by the resort industry. Populations on the barrier islands in Atlantic County and nearby coastal communities were 50 percent greater during the summer than during winter in 1984 (URS Consultants, 1988).

Table 2. Average annual pumping rate and seasonal pumping rate during 1986 in the Atlantic City 800-foot sand, New Jersey

[Mgal/d, million gallons per day; WD, Water Department; WC, Water Company; MUA, Municipal Utility Authority]

U.S. Geological Survey well number	Owner[1]	Local name	Average 1986 withdrawal (Mgal/d)		
			Annual	January-April	May-September
1-20	BALLY'S	DENNIS	0.31	0.25	0.38
1-39	BRIGANTINE WD	NEW 4	2.14	1.45	2.94
1-117	EGG HARBOR WC	OW41 5	.45	.41	.50
1-121	SEAVIEW WATER COMPANY	1958 WELL	.02	.01	.02
1-227	HAMILTON TOWNSHIP MUA	HTMUA 5	.64	.51	.78
1-367	BOROUGH OF LONGPORT	LONGPORT 2	.14	.06	.25
1-368	BOROUGH OF LONGPORT	LONGPORT 1	.13	.06	.21
1-369	BOROUGH OF LONGPORT	LONGPORT 3	.14	.08	.24
1-370	CITY OF MARGATE	MCWD 6	.38	.27	.58
1-372	CITY OF MARGATE	MCWD 7	.38	.27	.58
1-375	CITY OF MARGATE	MCWD 4	.38	.27	.58
1-376	CITY OF MARGATE	MCWD 5	.38	.27	.58
1-568	ATLANTIC CITY MUA	ACWD 15	1.78	1.41	2.28
1-593	VENTNOR CITY	VCWD 10	1.02	.81	1.19
1-595	VENTNOR CITY	VCWD 5	.15	.11	.20
1-596	VENTNOR CITY	VCWD 4	.15	.12	.19
1-598	VENTNOR CITY	VCWD 9	.27	.24	.34
1-599	VENTNOR CITY	VCWD 7	.16	.09	.22
1-600	VENTNOR CITY	VCWD 8	.20	.17	.24
1-682	RESORTS INTERNATIONAL	1	.47	.40	.57
9-5	BOROUGH OF AVALON	AVALON WD 8-76	.89	.41	1.50
9-92	NEW JERSEY WATER COMPANY	NEPTUNUS 7	.31	.24	.38
9-100	MIDDLE TOWNSHIP DISTRICT	AVALON M WW 1	.02	.01	.03
9-106	NEW JERSEY WATER COMPANY	SHORE DIV 7	.22	.00	.54
9-108	NEW JERSEY WATER COMPANY	SHORE DIV 14	.79	.66	.94
9-109	NEW JERSEY WATER COMPANY	SHORE DIV 9	.22	.00	.52
9-110	NEW JERSEY WATER COMPANY	SHORE DIV 12	.21	.00	.49
9-116	NEW JERSEY WATER COMPANY	SHORE DIV 8	.12	.00	.29
9-117	NEW JERSEY WATER COMPANY	SHORE DIV 10	.06	.00	.15
9-122	NEW JERSEY WATER COMPANY	SHORE DIV 5	.13	.00	.31

Table 2. Average annual pumping rate and seasonal pumping rate during 1986 in the Atlantic City 800-foot sand, New Jersey--Continued

U.S. Geological Survey well number	Owner[1]	Local name	Average 1986 withdrawal (Mgal/d)		
			Annual	January-April	May-September
9-124	NEW JERSEY WATER COMPANY	SHORE DIV 13	1.07	1.07	1.06
9-125	NEW JERSEY WATER COMPANY	SHORE DIV 11	.49	.01	.72
9-131	CITY OF SEA ISLE CITY	SICWD 1	1.21	.75	1.90
9-132	BOROUGH OF STONE HARBOR	SHWD 4	.66	.26	1.02
9-136	ARAMINGO WATER COMPANY	CIWC 1	.03	.02	.06
9-144	ATLANTIC CITY ELEC	ACEC 5	0.15	0.19	0.11
9-148	ATLANTIC CITY ELEC	ACEC 3	.31	.36	.33
29-9	BEACH HAVEN BOROUGH	BHWD 8	.16	.12	.21
29-12	BEACH HAVEN BOROUGH	BHWD 7	.21	.10	.35
29-111	BOROUGH OF HARVEY CEDARS	HCWD 4	.33	.18	.41
29-455	TOWNSHIP OF LONG BEACH	LBWD 2	.11	.25	.08
29-457	TOWNSHIP OF LONG BEACH	TERRACE 3	.32	.00	.66
29-459	TOWNSHIP OF LONG BEACH	TERRACE 2	.11	.25	.08
29-461	TOWNSHIP OF LONG BEACH	BRANT BEACH 1	.11	.27	.04
29-462	LITTLE EGG HARBOR MUA	MYSTIC 3	1.06	.87	1.32
29-544	BOROUGH OF SHIP BOTTOM	SBWD 4	.35	.24	.51
29-557	STAFFORD MUA	STAFFORD 3	.06	.04	.10
29-559	BOROUGH OF SURF CITY	SCWD 3	.21	.10	.23
29-560	BOROUGH OF SURF CITY	SCWD 4	.19	.13	.28
29-561	BOROUGH OF SURF CITY	SCWD 5	.18	.12	.27
29-565	BOROUGH OF TUCKERTON	TMUA 4(OW1)	.08	.23	.01
29-590	BEACH HAVEN BOROUGH	BHWD 9	.25	.14	.35
29-1064	TOWNSHIP OF LONG BEACH	BRANT #3	.36	.03	.61
29-1092	BOROUGH OF TUCKERTON	S. GREEN ST-2	.18	.01	.30
	TOTAL		28.85	14.25	29.03

[1] Owner identifies the water user on the New Jersey Department of Environmental Protection (NJDEP) Bureau of Water Allocation permit; however, pumpage can occur from multiple wells under one well number and permit number. County location of well is indicated by digits preceding hyphen in U.S. Geological Survey well number, where 1 is Atlantic County, 9 is Cape May County, and 29 is Ocean County. Well locations are shown in figure 9. Well locations were determined from data on file at the owner's location, from files of the NJDEP Bureau of Water Allocation, and from water-use files of the U.S. Geological Survey office in West Trenton, N.J.

The average 1986 pumpage from the Atlantic City 800-foot sand was 20.85 Mgal/d, but pumpage varied seasonally, from 14.25 Mgal/d during January-April to 29.03 Mgal/d during May-September. The pumpage is distributed primarily along the barrier islands of Atlantic, Cape May, and Ocean Counties (table 2).

The period of annual minimum pumpage, or nonsummer season, for most of the resort communities extends from October through April. The period of annual minimum pumpage for 1986 was determined from average monthly pumpage rates during January through April. The "summer season" is a period of annual maximum pumpage that extends from May through September; for this report, the summer season pumpage was determined from average monthly pumpage during May-September 1986.

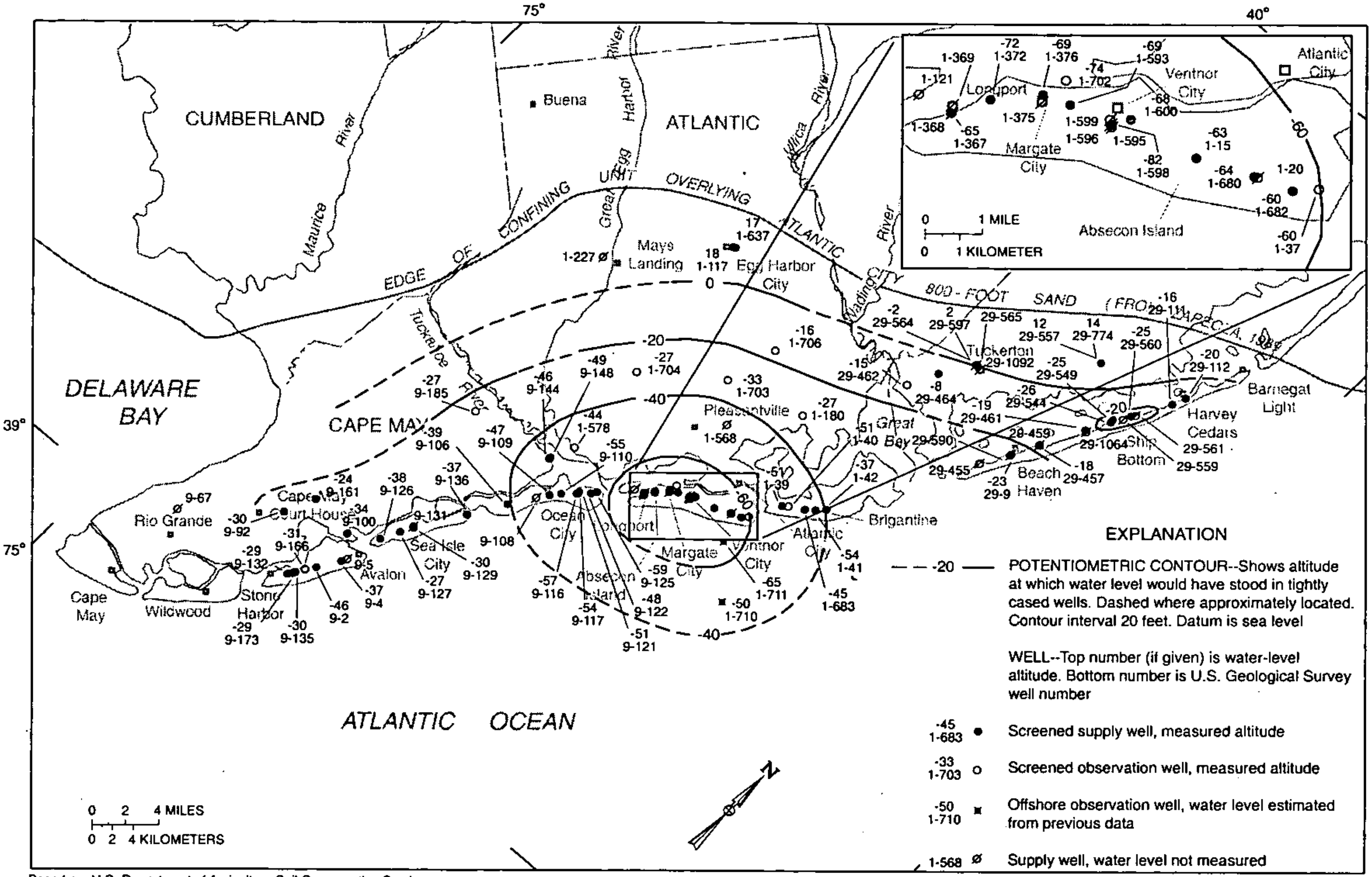
In Atlantic County there are three principal pumping centers: on Absecon Island, near Brigantine (on the barrier island immediately north of Absecon Island), and near Pleasantville. On Absecon Island, the pumping center includes pumpage in Atlantic City, Ventnor, Margate, and Longport. The pumping centers are areas of significant pumpage that are small enough that effects of pumping at any location within the pumping center cannot be separated or analyzed separately at the scale and scope of this regional investigation. Analysis of effects of pumping centers on the Atlantic City 800-foot sand permits a regional perspective on evaluation of the potential for saltwater intrusion. During January-April, 3.47 Mgal/d is pumped from the Absecon Island pumping center, and 6.35 Mgal/d is pumped during the summer season. In Brigantine, the nonsummer pumpage is 1.45 Mgal/d, and the summer-season pumpage is 2.94 Mgal/d. Near Pleasantville, the nonsummer pumpage is 1.41 Mgal/d, and the summer-season pumpage rate is 2.28 Mgal/d.

As is evident from the data in table 2, the annual maximum pumpage during the summer season for nearly all listed wells is at least 1.5 times the annual minimum pumpage during the nonsummer season. At the Ocean City, Avalon, and Stone Harbor supply wells, the summer-season pumpage is more than 3 times the nonsummer-season pumpage. The increased summer-season pumpage significantly affects the long-term trend in water levels and the potential for saltwater intrusion. The deep declines in water levels in response to summer-season pumpage in figure 10 illustrate the effects on water levels. The large water-level declines force water out of storage and permit the migration of saltwater toward pumping centers.

Water Levels and Flow Directions

The water table in the study area has not changed significantly in response to pumping. Water levels in the Kirkwood-Cohansey aquifer system in Atlantic County have declined slightly in some places in response to pumping (Clark and Paulachok, 1989, p. 15).

In contrast, water levels in the Atlantic City 800-foot sand have declined greatly in response to ground-water withdrawals. Water levels measured in April and September 1986 in 68 wells screened in the Atlantic City 800-foot sand were used to prepare maps of the potentiometric surface (Clark and Paulachok, 1989). The map of the potentiometric surface in April 1986 (fig. 9), which represents conditions at the end of a period of annual minimum pumping stress (January-April), shows an elongated regional cone of depression that extends from southern Ocean County to southern Cape May County and to more than 5.3 mi seaward of Atlantic City. The regional cone is centered on Margate and Ventnor, Atlantic County, where water levels declined from about 25 ft above sea level (fig. 7) to more than 70 ft below sea level. Water-level declines were greatest near coastal communities and were below sea level between Stone Harbor (29 ft below sea level) and just south of Barnegat Light (20 ft below sea level). Water levels near Ship Bottom, Ocean County, were more than 20 ft below sea level and formed a local cone of depression. The depicted regional cone of depression extends west to the edge of the confining



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 9. Potentiometric surface of and locations of pumped wells in the Atlantic City 800-foot sand, New Jersey, April 1986.

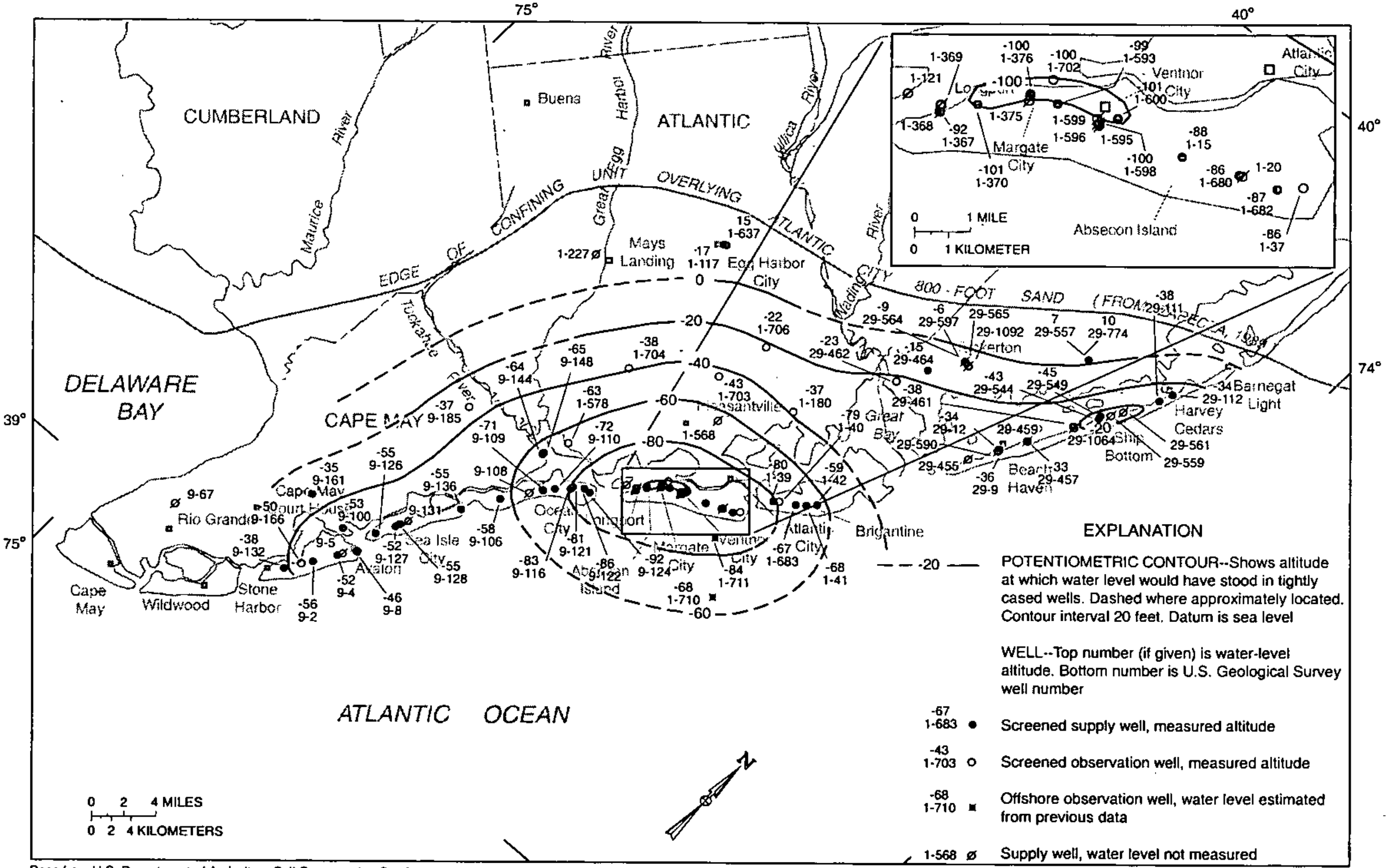
unit. Water levels were 18 ft above sea level near Egg Harbor City, where predevelopment water levels were more than 50 ft above sea level (fig. 7). The extent of the cone of depression offshore is not known, but the water level was 50 ft below sea level 5.3 mi offshore at well 1-710. To the west of Margate and Ventnor, gradients were about 5 ft/mi; to the north and east, 4 ft/mi; and to the south, 3.5 ft/mi. Gradients in the local cone of depression near Ship Bottom were about 12 ft/mi.

Flow directions in April 1986 had greatly changed compared to the prepumping period. Much of the flow was toward pumping centers on or near the barrier islands and coastal communities. In Atlantic County in 1986, flow of ground water was largely from the updip extent of the overlying confining unit toward the coast, but much of the flow was intercepted by wells near coastal communities; little ground water flowed east of the coastal area to eventually discharge to saltwater offshore, as was the case under prepumping conditions. The flow direction in the offshore area reversed from offshore to onshore, or from southeast to northwest. In Cape May County, ground water flowed from the northwest to the southwest and, to a lesser degree, to the southeast during the prepumping period; discharge areas were the Delaware Bay and the Atlantic Ocean. In April 1986, the flow direction was from northwestern Cape May County toward the coast, and also from both the Delaware Bay and the Atlantic Ocean toward the coast. In Ocean County, ground water flowed from the northwest offshore to the northeast during prepumping conditions. In April 1986, the flow direction was from the confining-unit edge southeast toward the coast and also from the ocean northwest to the coast. In all areas, the flow direction in offshore areas in April 1986 was from offshore toward the coastal pumping centers.

The map of the potentiometric surface in September 1986 (fig. 10) reflects conditions of annual maximum pumping stress on the Atlantic City 800-foot sand during May-September. The greatest declines between April and September occurred near coastal communities, and smaller declines occurred west of the coast. Although the shape of the cone of depression in September is similar to that in April, the regional cone was about 30 ft deeper in September near Margate and Ventnor. Near Stone Harbor and near Ship Bottom, water levels declined 19 ft between April and September. In the vicinity of Egg Harbor City, west of the coast, water levels declined only 2 ft, to 15 ft above sea level. The water level 5.3 mi east of Atlantic City at well 1-710 declined 18 ft. Hydraulic gradients increased to about 8 ft/mi to the west of Margate and Ventnor and to 5 ft/mi to the north, east, and south. Near Ship Bottom, gradients increased to about 16 ft/mi. Directions of ground-water flow in September 1986 were similar to those in April 1986, but gradients were higher.

Before the development of the Atlantic City 800-foot sand for water supply in the 1890's, ground-water levels were about 20 to 25 ft above sea level at Atlantic City (Thompson, 1928). By 1927, water levels in some wells in Atlantic City had declined to 75 to 80 ft below sea level because of increased withdrawals. A decrease in withdrawals after 1929 resulted in recovery of water levels to approximately 50 ft below sea level by 1934 (Barksdale and others, 1936). In 1949, when a water-level recorder was installed on well 1-37 in Atlantic City (fig. 11), the average water level in that well was approximately 60 ft below sea level. After 1949, water levels in well 1-37 generally declined, averaging about 80 ft below sea level in 1986, in response to increased withdrawals from the Atlantic City 800-foot sand and in the Atlantic City area.

Seasonal variations in ground-water withdrawals cause water-level fluctuations. Water levels declined as much as 30 ft in response to increased withdrawals during the summer months of 1949-86 in the Atlantic City area (fig. 11). This effect is most pronounced in coastal parts of the study area. During October-April, a reduction in withdrawals causes water levels to recover. Seasonal water-level fluctuations near Atlantic City can be seen onshore (fig. 11) and 1.9 mi offshore (fig. 12). Water-level declines of about 25 ft during May to September each year 1.9 mi offshore in response to summer-season pumpage onshore indicate that the permeability of the Atlantic City 800-foot sand does not greatly decrease within 1.9 mi of shore.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 10. Potentiometric surface of and locations of pumped wells in the Atlantic City 800-foot sand, New Jersey, September 1986.

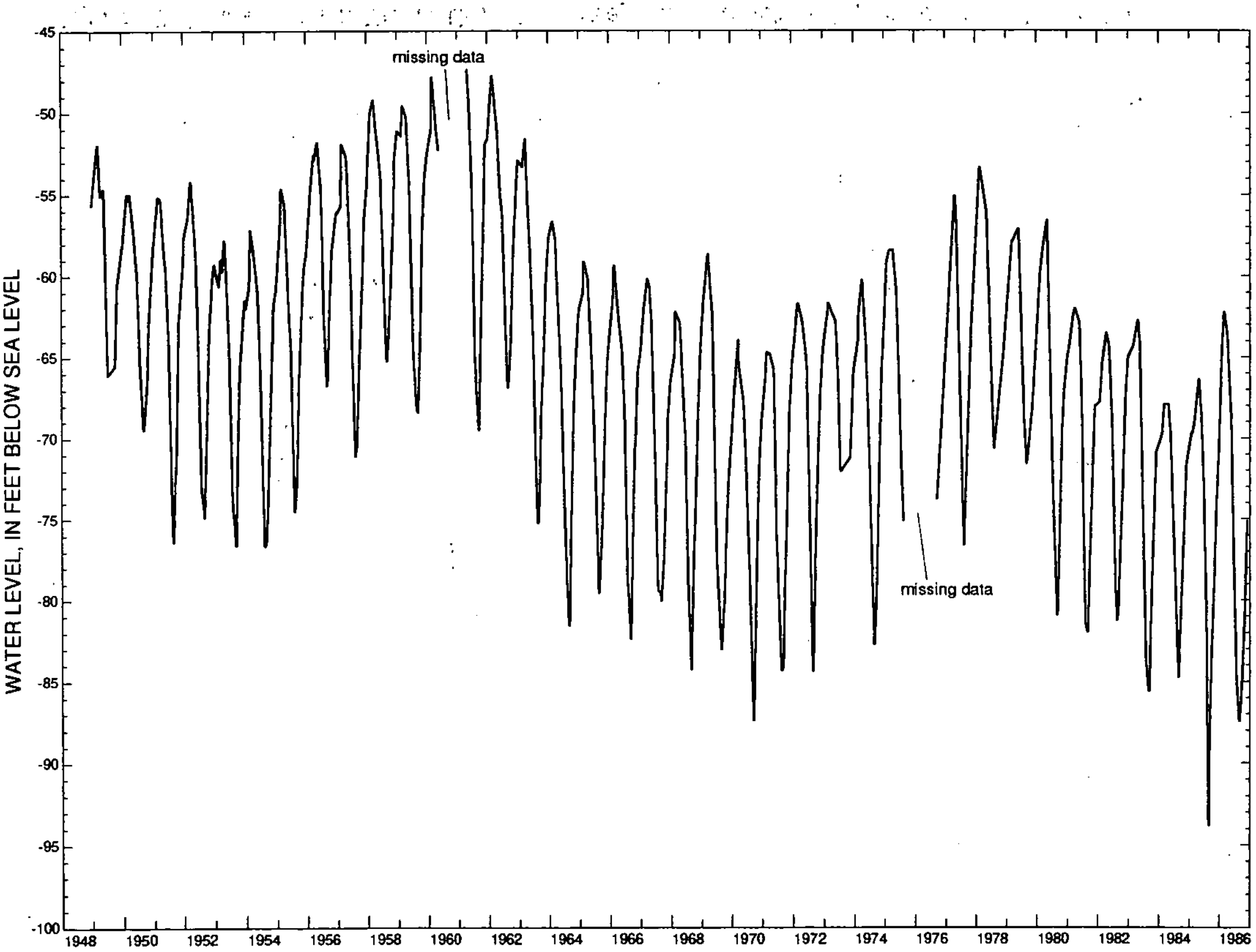


Figure 11. Daily mean water levels in well 1-37, Atlantic City area, New Jersey, 1949-86.

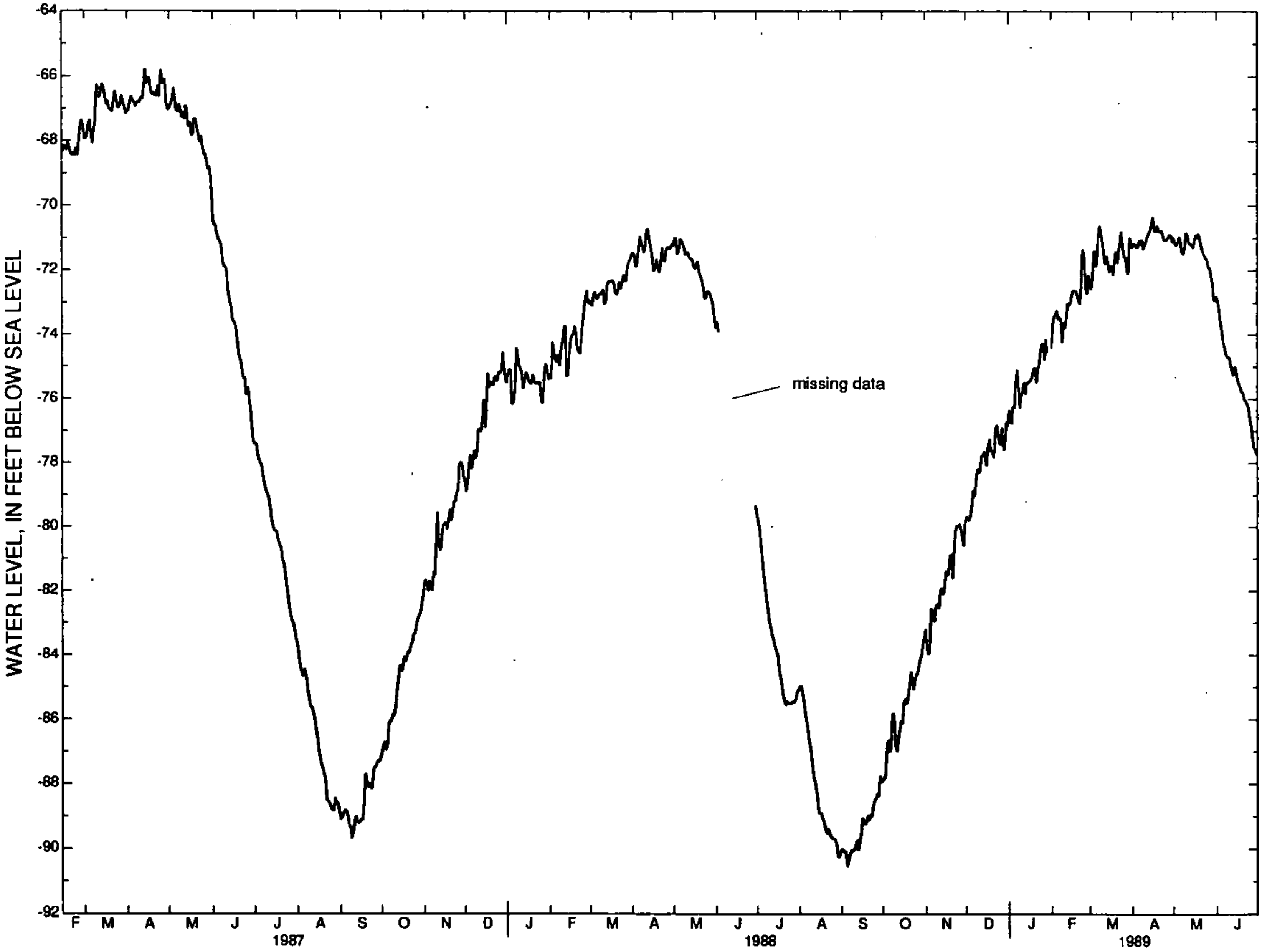


Figure 12. Water levels in Atlantic City, New Jersey, offshore well 1-711, February 1987-June 1989.

Water levels in the Atlantic City 800-foot sand also fluctuate in response to tidal loading and, to a smaller degree, to changes in barometric pressure. The amplitude of observed fluctuations caused by tidal loading is greatest in the marine wells offshore of Atlantic City (maximum observed amplitude about 5 ft; fig. 12), and the amplitude decreases inland with increasing distance from the shoreline.

Ground-Water Quality

To assess ground-water quality in the Atlantic City 800-foot sand, USGS personnel collected water samples from 66 wells tapping the aquifer during 1984-86 (fig. 13). Of these wells, 17 were along the coast of Ocean County, 24 were in Atlantic County, and 23 were along the Atlantic Coast of Cape May County. These wells included public-supply wells and privately owned wells supplying water for irrigation, industrial, commercial, and domestic use, as well as observation wells belonging to transportation authorities, State agencies, and the USGS. The two offshore observation wells also were sampled.

The data for the 66 wells tapping the Atlantic City 800-foot sand and water-quality analyses from previous studies are reported in Barton and others (1993) and are also discussed and interpreted in this report. Measurements of temperature, specific conductance, pH, alkalinity, and dissolved-oxygen concentration were made in the field. Determinations of major-ion, trace-element, nutrient, and phenol concentrations were made at the USGS National Water Quality Laboratory (NWQL) in Arvada, Colo. Water samples from 29 wells were analyzed for volatile organic compounds (VOC's).

The water-quality analyses by the NWQL were subject to the quality-assurance procedures in effect at the time of the analysis. The reliability of the analytical data was examined by means of quality-assurance checks described by Friedman and Erdmann (1982) and Hem (1985). A detailed discussion of the quality-assurance procedures can be found in Barton and others (1993).

Isotope analyses were done by Global Geochemistry Corporation[1]. For most samples, one or more replicate samples were analyzed. Some replicate samples were submitted as blind samples with fictitious sample numbers.

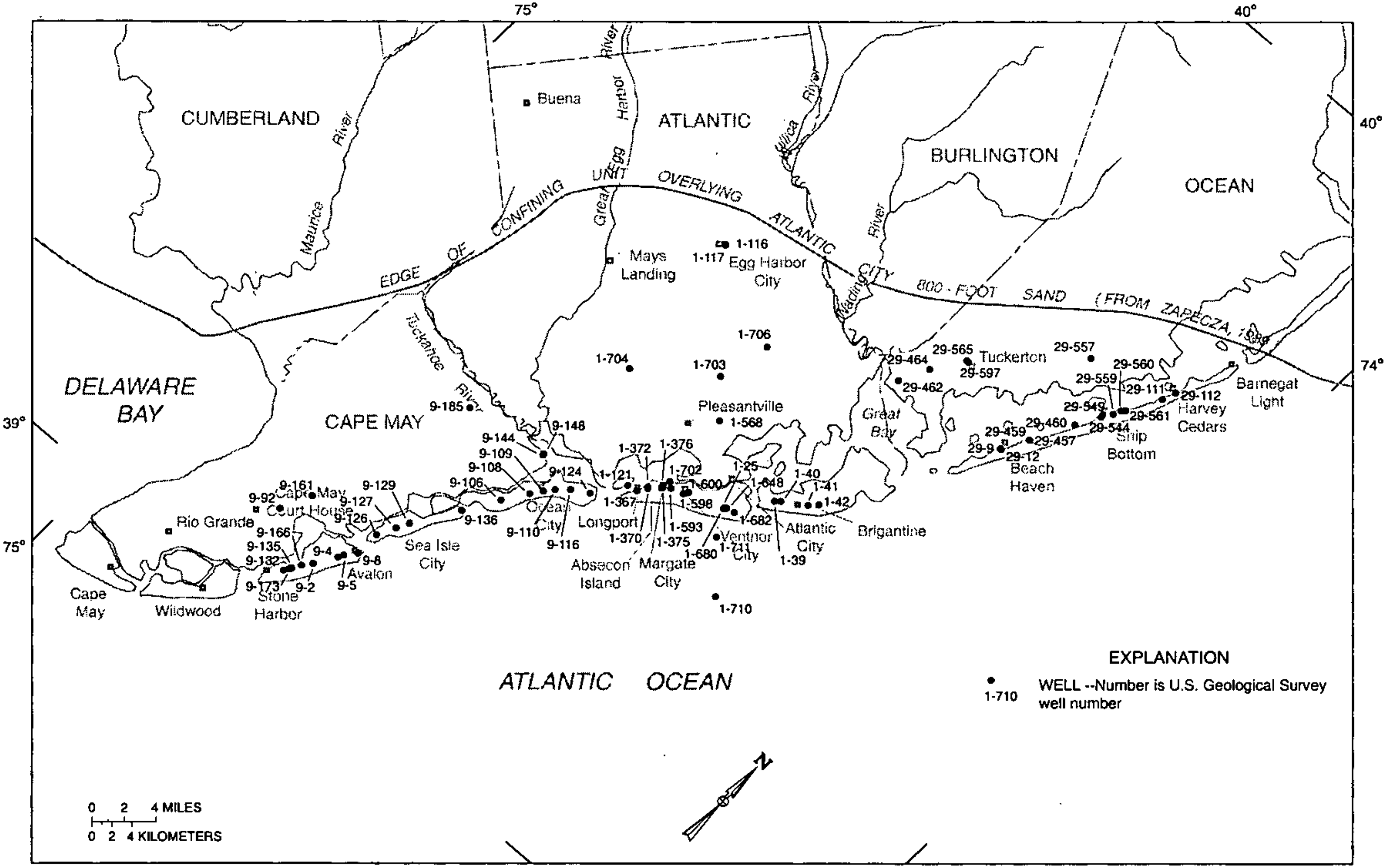
Chemical Evolution of Ground Water in the Atlantic City 800-Foot Sand

Ground water in the Atlantic City 800-foot sand appears to have evolved chemically in the downdip (southeast) direction. The 1984-86 data indicate that bicarbonate alkalinity and concentrations of sodium and chloride, and to a smaller extent, sulfate increase downdip, along principal directions of ground-water flow (fig. 14). Iron concentration decreases southeastward, whereas calcium and magnesium concentrations change only slightly. Although ground-water flow now is toward the cone of depression centered on Atlantic City, the predevelopment pattern of chemical evolution had apparently been little altered as of 1984-86, except for chloride concentrations.

The average age of water sampled from several wells supports the assumption that 1984-86 water quality in many locations reflects the prepumping chemical constitution of the water in the Atlantic City 800-foot sand. Four wells were sampled for radioactive isotopes in an attempt to estimate ages of ground water within the Atlantic City 800-foot sand. The age of the water was determined by measurements of carbon-14. (Faure (1986) presents a discussion of the standard

---

[1] The use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 13. Location of 66 wells tapping the Atlantic City 800-foot sand, New Jersey, sampled during 1984-86.

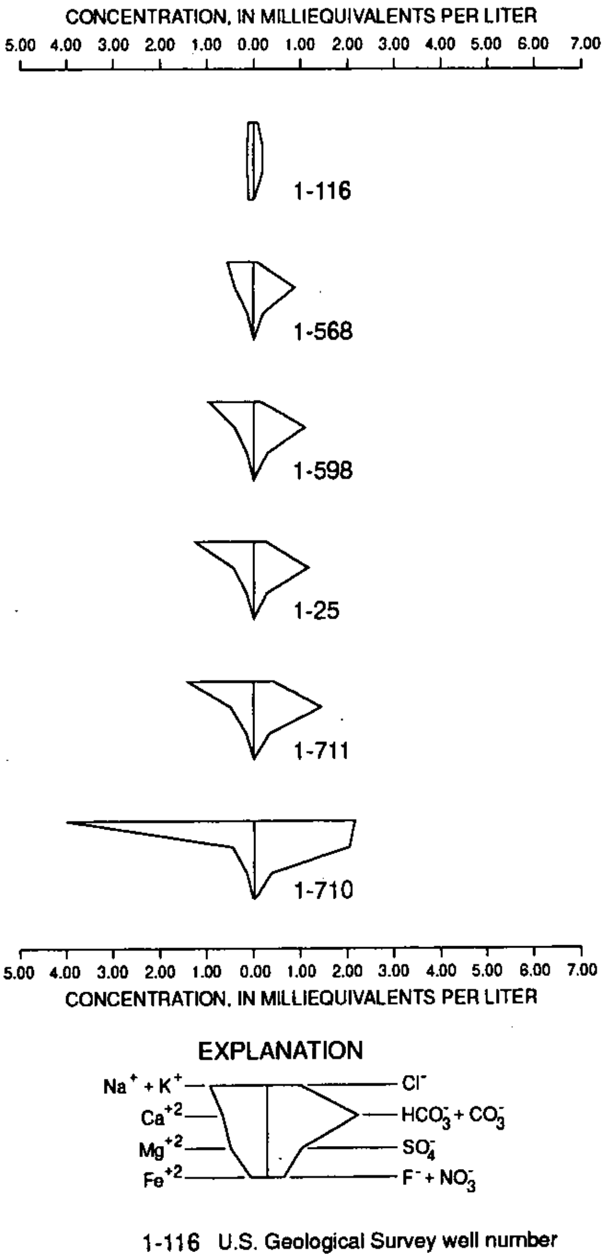


Figure 14. Stiff diagrams showing the evolution of ground water from the Atlantic City 800-foot sand, New Jersey, from inland, updip well 1-116 to offshore well 1-710. (Well locations are shown in fig. 13)

analytical methods used in these isotope measurements.) Carbon-14 (or radiocarbon) ages are given as years before present (BP). The well farthest inland (1-117) is near the updip limit of the confining unit overlying the Atlantic City 800-foot sand and is therefore close to the updip limit of the Atlantic City 800-foot sand. A downgradient well (1-568) is located about 1 mi inland from Absecon Bay. Also sampled were offshore wells 1-711 (1.9 mi offshore) and 1-1710 (5.3 mi offshore).

According to the radiocarbon age, water from the onshore well (1-117) at Egg Harbor City (2,070 years BP ±90) is younger than water from the onshore well at Pleasantville (1-568) (17,950 years BP ±590). This latter well taps water that is younger than the water from the two offshore wells, which yield water whose age is at least greater than 22,000 years BP and is possibly greater than 30,000 years BP.

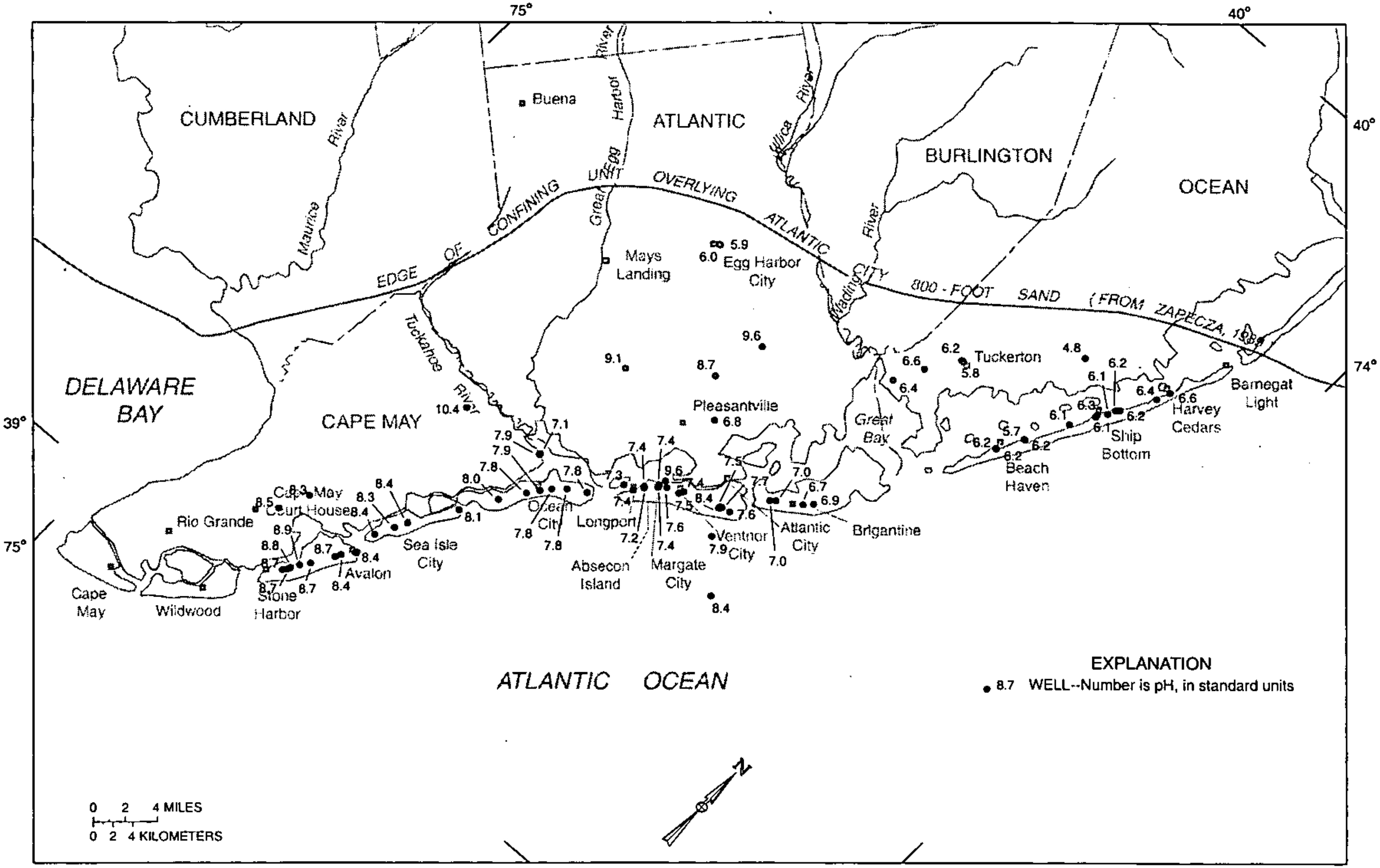
The pH of water from the Atlantic City 800-foot sand in 1984-86 (fig. 15) ranged from 4.8 to 10.4; however, the chemical character of water in the Atlantic City 800-foot sand in Ocean County and central Atlantic County resembled that of water from the unconfined system (Barringer and others, 1993). In general, wells in Ocean County yielded water that was substantially more acidic than the water in Cape May County. The pH of water from Ocean County wells ranged from 4.8 to 6.6, the pH of water from Atlantic County wells ranged from 5.9 to 9.6, and the pH of water from Cape May County wells ranged from 7.1 to 10.4. The most acidic water came from wells that tap the shallow, updip part of the aquifer in Ocean County.

The anomalously high pH values (9.0 or greater) of water from wells in Atlantic and Cape May Counties may have resulted from well-construction and water-sampling practices. The wells from which high-pH water was collected are test or observation wells, which are not pumped as often as are public-supply and domestic wells. Therefore, the cement grout surrounding the wells may have interacted with the ground water locally, causing a higher pH than would otherwise have been expected. The calcium concentrations in water samples from these wells (1-702, 1-704, 1-706, 9-185) also were elevated. In particular, the largest calcium concentration (27 mg/L) was in water from well 9-185.

Alkalinity (in milligrams per liter as calcium carbonate) in water from 65 wells in the Atlantic City 800-foot sand sampled during 1984-86 ranged from 1 to 120 mg/L. Median alkalinity was 64 mg/L. The spatial distribution of alkalinity concentrations was similar to the distribution of pH; the smallest alkalinity concentrations were in Ocean County, whereas the largest were in Cape May County. The alkalinities associated with the anomalously high pH values were above the median; the alkalinity concentration in water from well 9-185 (120 mg/L) was the largest in the data set.

The observed downdip increase in alkalinity can be explained by the following reaction. As water moves downgradient, shell material (calcium carbonate) within the Atlantic City 800-foot sand reacts with the acidic water from the Kirkwood-Cohansey aquifer system. Dissolution of calcium carbonate produces calcium and bicarbonate ions, increasing the alkalinity. The same reaction consumes hydrogen ions, and the pH of the water increases. In the Cape May Peninsula, mixing with saltwater also could contribute to increases in pH and in alkalinity (bicarbonate) in ground water. The seawater is likely to contain more bicarbonate ion than the fresh ground water with which it is mixing; and the pH of the seawater, which typically ranges from about 7.8 to 8.4 in the open ocean (Berner and Berner, 1987), may be slightly higher than that of the fresh ground water.

Concentrations of dissolved iron ranged from less than 3 µg/L (the minimum reporting level) to 3,300 µg/L; the median was 94 µg/L. Iron concentrations in updip wells in Atlantic County typically exceeded 100 µg/L, and concentrations exceeded 1,000 µg/L in Ocean County. Small dissolved-oxygen concentrations, ranging from 0.1 to 0.5 mg/L (Barton and others, 1993),



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 15. Distribution of pH of samples of ground water from the Atlantic City 800-foot sand, New Jersey, 1984-86.

indicate a tendency toward reducing conditions in the Atlantic City 800-foot sand. In a reducing environment, iron hydroxides can dissolve as ferric iron is reduced to soluble ferrous iron, resulting in large iron concentrations in ground water. Additionally, iron solubility increases in acidic waters (Krauskopf, 1967). Iron concentrations were found to vary inversely with pH. The largest concentrations of iron were found in ground water from Ocean County wells where pH was less than 7.0, whereas the smallest concentrations were in water from Cape May County wells where pH was greater than 7.0 (fig. 16). Iron can be removed from solution by the precipitation of the mineral siderite ($FeCO_3$) if the activity of carbonate species is sufficiently large. This reaction could explain why water from downgradient wells in Atlantic and Cape May Counties contains small concentrations of iron in parts of the aquifer system where the redox potential is likely to be low.

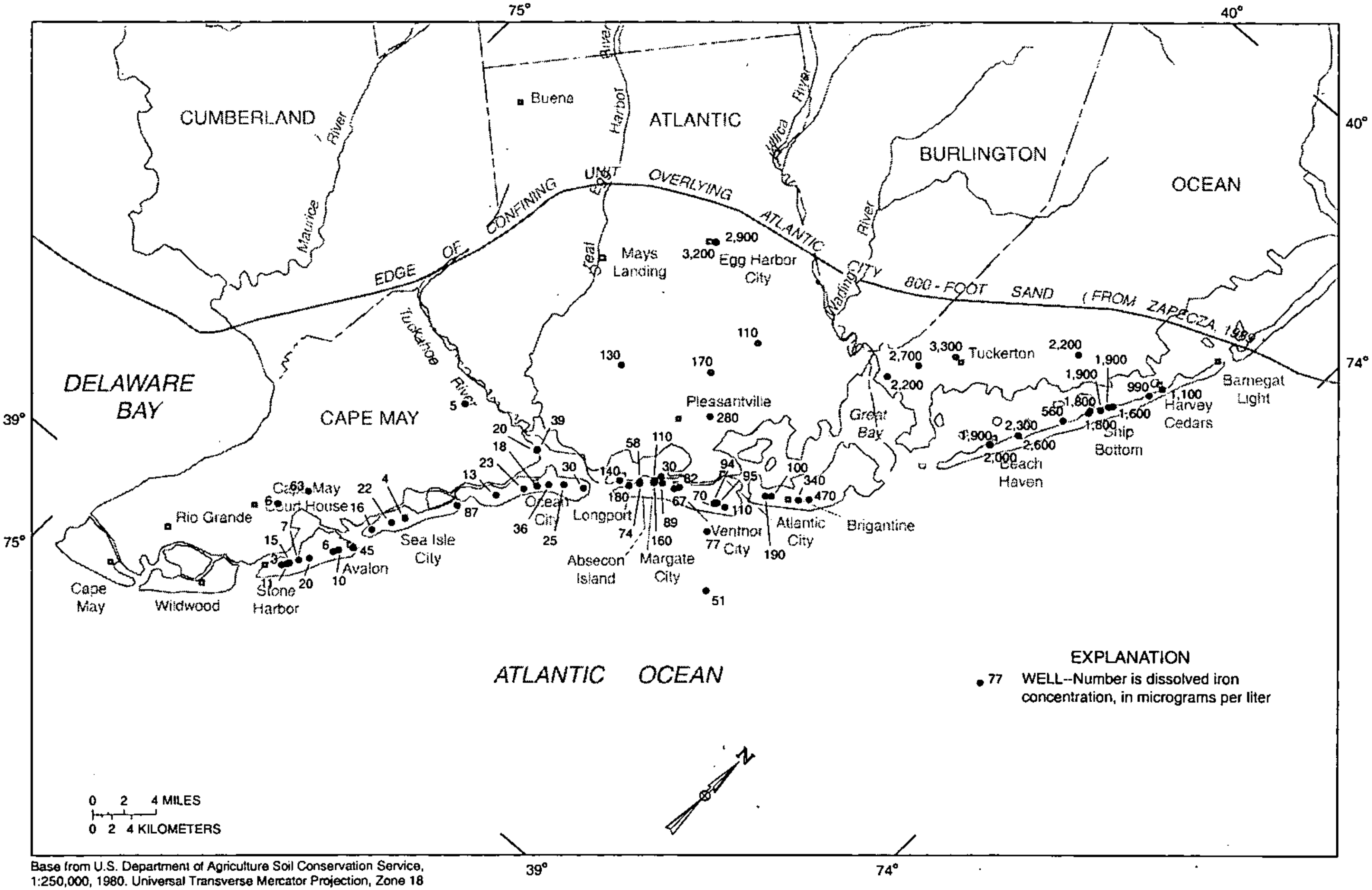
Concentrations of dissolved manganese tended to follow the same spatial distribution as dissolved-iron concentrations. The largest concentrations were in water from Ocean County wells, and the smallest concentrations (commonly below the minimum reporting level of 1 μg/L) were in water from Cape May County wells. The median dissolved-manganese concentration was 14 μg/L; a maximum concentration of 60 μg/L was reported in Barton and others (1993).

Analyses of water from 66 wells sampled during 1984-86 indicate that sulfate concentrations in the Atlantic City 800-ft sand ranged from 7.3 to 20 mg/L. The median concentration was 12 mg/L. The spatial pattern observed is less distinct for sulfate than it is for other chemical constituents. Sulfate concentrations in water from Ocean County wells ranged from 7.3 to 13 mg/L, and generally were slightly smaller than concentrations in water from Atlantic County wells, which ranged from 8.2 to 18 mg/L. Water from Cape May County wells had slightly larger sulfate concentrations (11 to 20 mg/L) than did water from wells in Ocean and Atlantic Counties.

Concentrations of sulfate increased slightly to the south and generally were larger than chloride concentrations, except in water from deep wells in Cape May County, where intrusion of chloride-rich water has caused an increase in chloride concentrations. The shallowest wells in Ocean and Atlantic Counties yielded water with a sulfate-to-chloride ratio typically between 2.0 and 4.0. Sulfate-to-chloride ratios greater than 4.0 are characteristic of water from several wells northwest of Atlantic City; several of these wells yielded water with anomalously high pH. In the Cape May Peninsula, at several wells where water was found to have larger chloride concentrations than sulfate concentrations, the sulfate-to-chloride ratio was typically greater than 0.40 but less than 0.90.

Spatial variability in the sulfate-to-chloride ratios appears to indicate differences in the reactivity and sources of the two anions. Chloride ion is presumably supplied by recharge from the unconfined part of the aquifer system, and additional chloride ion is introduced by intruding saltwater. There appears to be no source of chloride within the aquifer matrix. Sources of sulfate to ground water appear to be recharge from the unconfined part of the aquifer system, intruding saltwater, and the aquifer matrix. Minerals reported in lower Kirkwood Formation sediments from a core near Mays Landing include pyrite (Owens and others, 1988) in a stratigraphic horizon (approximately 250 to 350 ft deep) that is equivalent to the Atlantic City 800-foot sand. The pyrite is authigenic (Owens and others, 1988, p. 11, table 1); clearly, sulfate reduction took place at some time in the history of the sediments.

There is, however, no clear evidence that sulfate reduction currently is taking place within the aquifer. Although iron concentrations decrease substantially with distance downdip, sulfate concentrations do not. Stumm and Morgan (1981, p. 443, fig. 7.5) show that sulfate is a stable species, even under moderately reducing conditions, at pH of 7 or greater. Similarly, Krauskopf (1967, p. 252, fig. 9-4) shows that, at concentrations of dissolved iron of 10^{-6} M (molar), siderite ($FeCO_3$) is stable at pH's of approximately 6 to 9 under moderately reducing conditions and that



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 16. Concentrations of dissolved iron in samples of ground water from the Atlantic City 800-foot sand, New Jersey, 1984-86.

for pyrite (FeS_2) to precipitate, conditions would need to become yet more reducing. The relatively high pH's of water downdip apparently create conditions in which sulfate is a stable species; for example, a fairly strong linear relation between pH and sulfate can be seen in figure 17.

Concentrations of silica in ground-water samples collected from the Atlantic City 800-foot sand during 1984-86 generally were large; the range was from 15 to 54 mg/L, and the median was 27 mg/L. This contrasts with water from the unconfined Kirkwood-Cohansey aquifer system, where the median concentration of silica was 6.7 mg/L for water from 83 wells in Atlantic County (J.L. Barringer, U.S. Geological Survey, written commun., 1991). The higher silica concentrations in the Atlantic City 800-foot sand could result from the dissolution of diatomaceous materials, abundant in the overlying confining bed. Diatoms are composed of cryptocrystalline silica, which is more soluble than quartz (Hem, 1985, p. 70). Quartz sand dominates the sediments throughout the unconfined part of the aquifer system, but cryptocrystalline silica is not reported as a component of the unconfined aquifer materials. Alkaline conditions also promote dissolution of silica (Stumm and Morgan, 1981); pH's are higher in the Atlantic City 800-foot sand than in the unconfined part of the aquifer system. Therefore, silica concentrations in the unconfined system are relatively small, and contribute relatively little to the silica concentrations in the Atlantic City 800-foot sand.

Concentrations of sodium in water from 66 wells in the Atlantic City 800-foot sand sampled during 1984-86 ranged from 1.9 to 90 mg/L; the median was 21 mg/L. The concentrations reported for water from Ocean County wells sampled during this period were all less than 10 mg/L. Sodium concentrations in water from Cape May County wells sampled during the same period were all greater than 20 mg/L. Atlantic County wells sampled during the same 3-year period yielded water with spatially variable sodium concentrations, with some relatively small concentrations associated with locations northwest of Atlantic City. The concentrations shown in figure 18 indicate an area of concentrations greater than the median in the vicinity of Atlantic City. Overall, however, the spatial distribution of sodium in ground water is somewhat similar to the distribution of other chemical characteristics and constituents (such as pH and alkalinity concentrations) in that a downdip gradient is apparent (fig. 18).

Sodium concentrations (fig. 18) and chloride concentrations (fig. 19) in water from the Atlantic City 800-foot sand also increase southward and southeastward; however, chloride concentrations do not increase by the same factor as sodium concentrations. The increases in chloride concentrations in ground water from the Atlantic City 800-foot sand toward the tip of the Cape May Peninsula have been shown to be a sign of saltwater intrusion. Nonetheless, the changes in ground-water chemistry are not related solely to the increasing effect of saltwater on the freshwater in the aquifer. Equivalents of sodium commonly are about twice the equivalents of chloride in water from the Atlantic City 800-foot sand in Cape May County, and calcium equivalents commonly are about one-half the equivalents of bicarbonate. The cation-exchange capacity of exchangeable media such as clay minerals tends to increase with increased pH (Brady, 1974, p. 100). The apparent increase in sodium in solution, coupled with the decrease in calcium in solution, indicates that calcium is replacing sodium in clay minerals; this process of a divalent cation replacing a monovalent cation can occur when seawater is diluted by freshwater (Drever, 1988, p. 94), as in the case of ground water in the Cape May Peninsula. Therefore, exchange of calcium for sodium in clay minerals may explain, in part, the higher concentrations of sodium relative to chloride and the lower concentrations of calcium relative to bicarbonate in water from Cape May County. Back (1966, p. 40) points out that the process of cation exchange leads to a continuous increase in bicarbonate ion, because removal of calcium from solution prevents the water from coming to equilibrium with calcium carbonate.

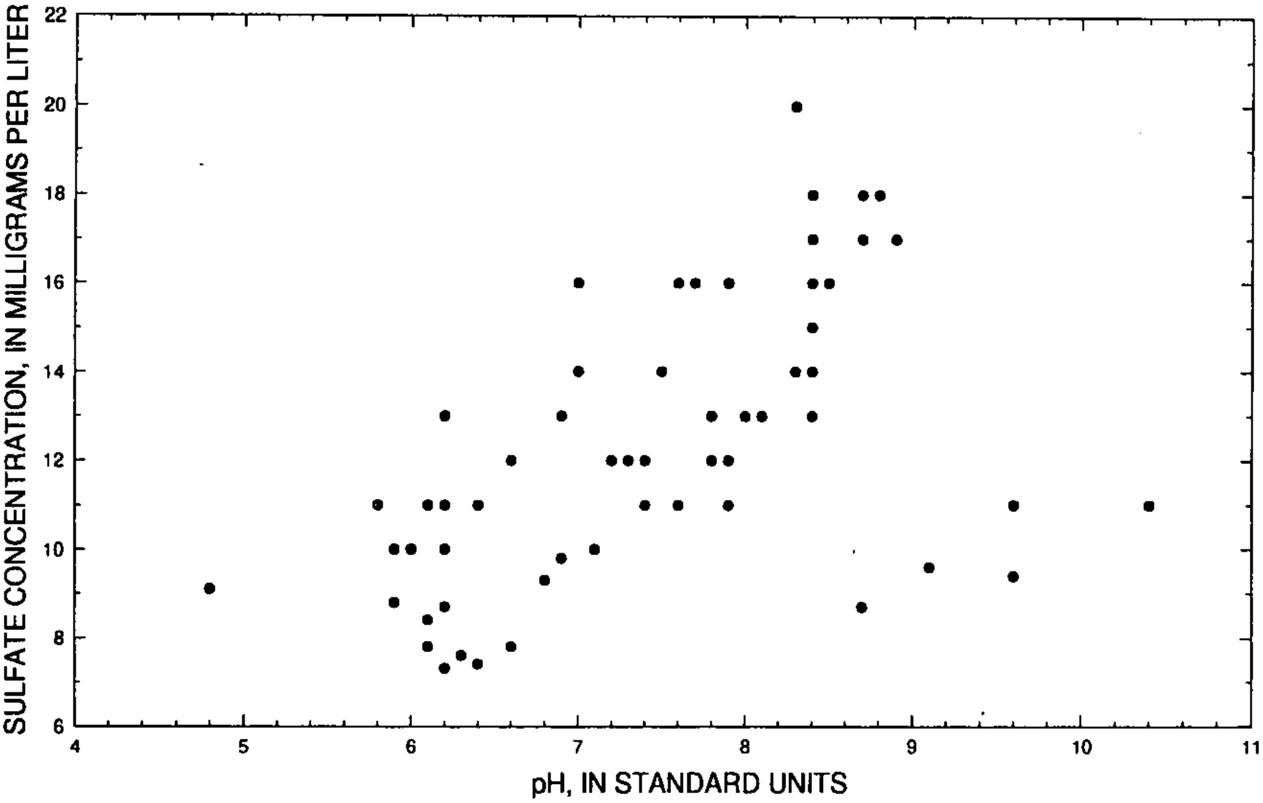
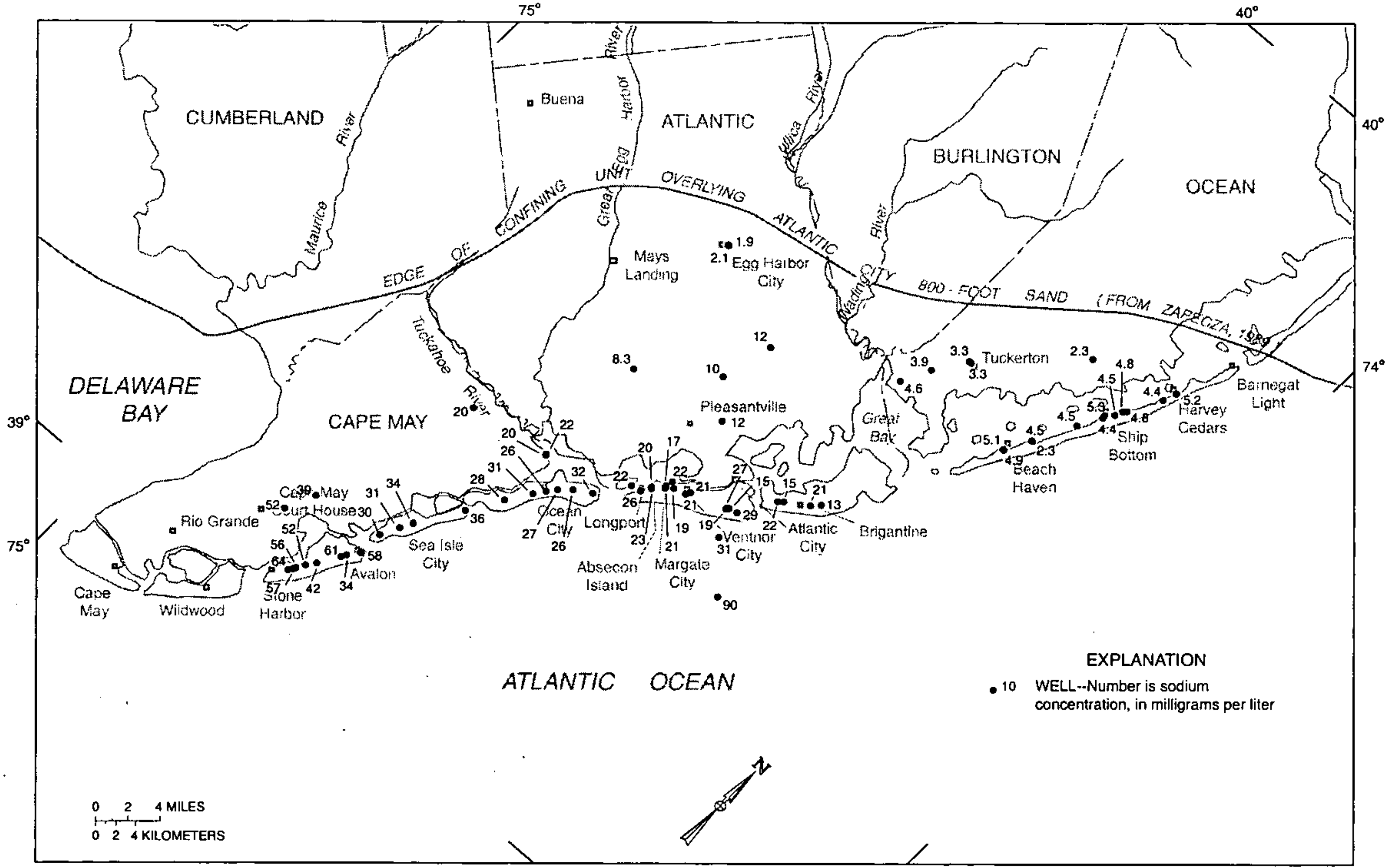


Figure 17. Variation in sulfate concentration with pH in samples of ground water from the Atlantic City 800-foot sand, New Jersey, 1984-86.

Water-quality data from the 66 wells sampled during 1984-86 indicate a downdip gradient of chloride concentration that is somewhat similar to the gradients for sodium and alkalinity concentrations. The smallest chloride concentrations, ranging from 2.9 to 5.5 mg/L, were in water from wells in Ocean County. Chloride concentrations in water from Atlantic County wells were varied (less than 0.1 to 77 mg/L) but were generally smaller than concentrations reported for water from Cape May County wells. The largest chloride concentration (77 mg/L) reported for water sampled during the 3-year period (Barton and others, 1993), however, was from the observation well 5 mi offshore of Atlantic City. Concentrations of chloride in water from Ocean County wells typically were less than 5 mg/L, and thus were similar to chloride concentrations in water from the unconfined Kirkwood-Cohansey aquifer system. A map of chloride concentrations in the Atlantic City 800-foot sand with the estimated location of the 250-mg/L isochlor in 1984-85 is shown in figure 19.

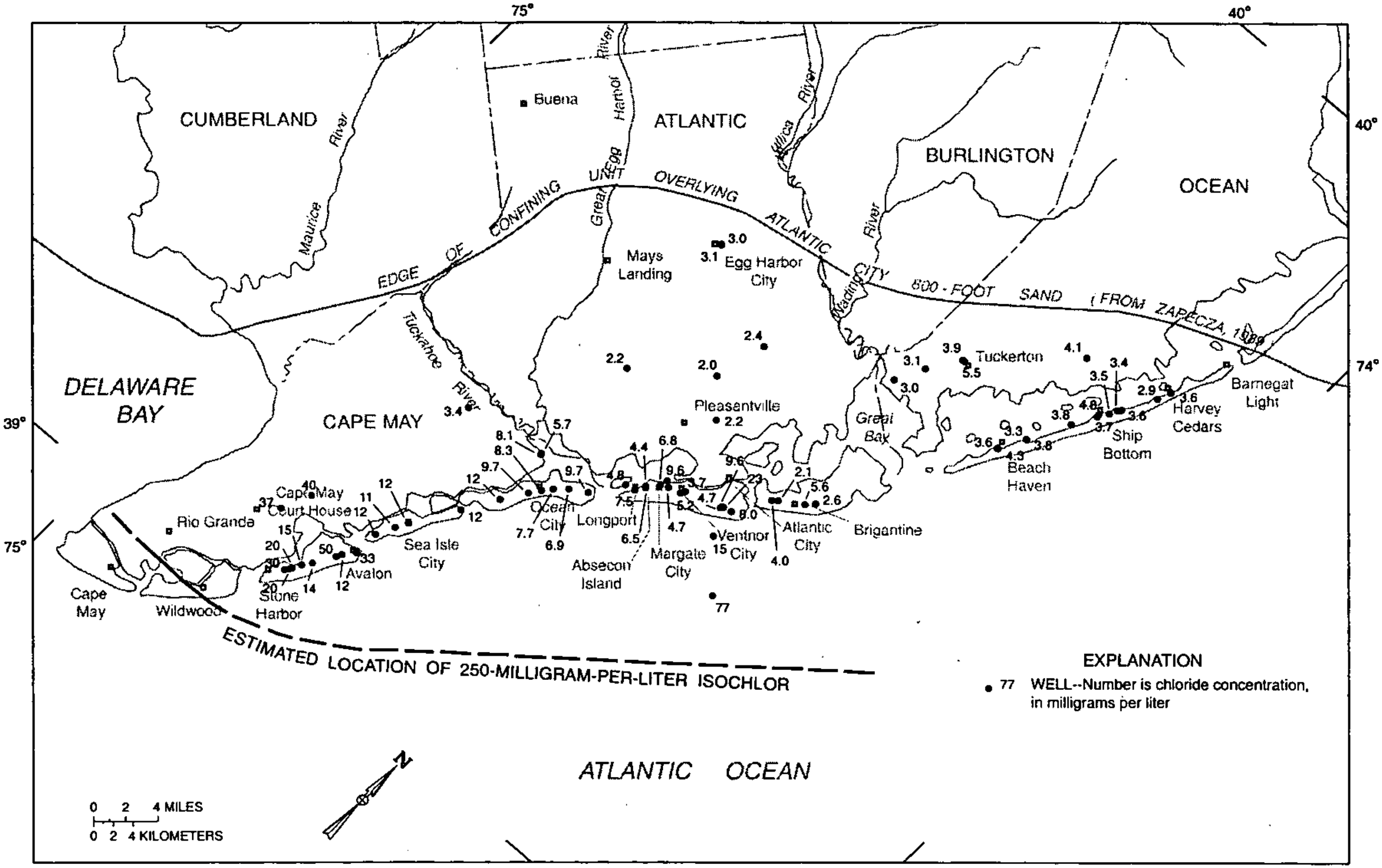
Effects Of Human Activity

Studies of chloride concentrations in water from the Atlantic City 800-foot sand were prompted by concerns over "landward encroachment of the surrounding saline surface waters and the movement of subsurface saline waters into centers of aquifer pumpage" (Seaber, 1963, p. 1). Gill (1962, p. 103) reported that chloride concentrations in the Atlantic City 800-foot sand exceeded 200 mg/L in Wildwood; that chloride concentrations were 352 mg/L in Wildwood Crest, 1 mi south of Wildwood; and that chloride concentrations were reported to be 1,510 mg/L



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 18. Concentrations of sodium in samples of ground water from the Atlantic City 800-foot sand, New Jersey, 1984-86.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 19. Concentrations of chloride in samples of ground water and location of the 250-milligram-per-liter isochlor, 1984-85, in the Atlantic City 800-foot sand, New Jersey.

in a Cape May Point well. Earlier, elevated chloride concentrations had been reported for southern Cape May County, and Thompson (1928, p. 118) concluded that drawdown in wells in Atlantic City might induce saltwater to move into the aquifer in the Atlantic City area. Barksdale and others (1936) pointed out that water from a group of wells near the principal pumping center in Atlantic City had higher concentrations of chloride than water in surrounding areas, although the water was still potable. Periodic sampling of ground water was begun by D.G. Thompson of the USGS in 1923; the sampling program was expanded by H.C. Barksdale, also of the USGS (Seaber, 1963, p. 7). Semiannual chloride sampling from a data network, using selected wells tapping the Atlantic City 800-foot sand, was begun in the mid-1930s. Although some of the original wells were dropped from the network, 174 wells were sampled during 1924-85. The two offshore wells, drilled in 1985, became part of the chloride monitoring network. Chloride concentrations in 1985 were 15 mg/L in water from well 1-711, located 1.9 mi offshore of Atlantic City, and 77 mg/L in water from well 1-710, located 5.3 mi offshore of Atlantic City. Hydraulic-head data from these two offshore wells indicate that flow within that coastal part of the aquifer is landward. Moreover, concentrations of boron and bromide also were higher in water from the well 5.3 mi from shore than in water from the well 1.9 mi from shore. Therefore, mixing of ground water with seawater appears to have occurred to a greater extent in the well located farther offshore. Changes in water chemistry in the Atlantic City 800-foot sand from an inland well to the farthest offshore well are shown in figure 14.

The 250-mg/L isochlor in figure 19 is based on the distribution of chloride concentrations. The position of the line near the southern peninsula of Cape May County is based on data from Gill (1962, p. 102), updated with more recent data from the chloride monitoring network. The line is drawn with greatest confidence offshore of Atlantic City than elsewhere because of data from the offshore wells. The 250-mg/L isochlor is drawn by extending trends in chloride concentrations observed in Cape May County to offshore areas of Atlantic County. The 250-mg/L isochlor is estimated to have been 10 mi offshore of Atlantic City in 1986. Saltwater intrusion does not appear to be an immediate threat for Atlantic City, but it remains a long-term concern. The 250-mg/L isochlor is estimated to be 10 mi from supply wells in Atlantic County, but only about 5 mi from supply wells in Cape May County at Stone Harbor. Thus the effects of saltwater intrusion are likely to be seen at Stone Harbor before they are seen in Atlantic City. Analysis of rates of ground-water flow is presented in the modeling section of this report to indicate the severity of the saltwater-intrusion potential. Although the wells in the chloride monitoring network have not yielded significant evidence of increased concentrations of chloride, the network continues to serve as an early warning system for the water supply. Despite the high concentrations of chloride found at several wells during the 1930's, data from most wells in the chloride-monitoring network show little or no sustained increase in chloride concentration with time that is considered to be a result of lateral saltwater intrusion. Discernible changes in concentration have been noted at 33 wells during the monitoring period, including fluctuations, gradual increases, gradual decreases, abrupt increases, and abrupt increases followed by decreases back to the antecedent chloride concentration (Barton and others, 1993). Leaking well casings were postulated as causes of some chloride increases in wells tapping the Atlantic City 800-foot sand (Thompson, 1928; Barksdale and others, 1936). The shallow ground water above the Atlantic City 800-foot sand on Absecon Island is reported to be brackish (Barksdale and others, 1936, p. 122-125), and connection between the two aquifers through leaky casings or annular openings could contaminate the Atlantic City 800-foot sand. Proper well sealing would address the potential for vertical saltwater contamination through leaky casings. Chloride anomalies (abrupt increases followed by a return to former chloride concentrations) can be caused by flooding by seawater due to peak tides or severe storms in conjunction with leaky casings or boreholes (table 3).

Table 3. Anomalous chloride concentrations in water from the Atlantic City 800-foot sand, New Jersey

[Anomalous concentrations are defined as concentrations of chloride that exceed the mean concentration for each well by 10 milligrams per liter or more. Flood tide dates from Thomas and Edelen (1962). Peak tide dates from WATSTORE Peak Flow File (U.S. Geological Survey, 1975)]

U.S. Geological Survey well number	Date of peak tide (P) or flood tide (F)	Sampling date	Chloride concentration (milligrams per liter)
1-679	11/05/39 (P)	08/30/39	120
1-679		03/19/40	35
1-679		07/26/40	480
1-680		07/26/40	300
	09/14/44 (F)		
1-19	09/24/44 (P)	09/28/44	650
1-664		09/28/44	59
1-668		09/27/44	25
1-373	11/01/47 (P)	04/21/48	26
29-559		04/28/48	24
1-26	11/24/50 (P)	03/26/51	19
	10/23/53 (F)		
1-32	11/07/53 (P)	04/05/54	18
1-367	01/10/56 (P)	04/04/56	27
1-367		08/29/56	36
1-368		04/04/56	150
1-600	02/19/60 (P)	04/04/60	27
9-126		04/05/60	47
1-676	04/13/61 (P)	08/21/61	84
9-132		08/22/61	230
9-126	01/17/65 (P)	04/13/65	40
29-9		08/26/65	16
9-2	10/29/73 (P)	04/05/74	44
9-106		04/05/74	23
1-39	01/17/80 (P)	08/28/80	36

Anomalous concentrations are defined as concentrations of chloride that exceed the mean concentration for each well by 10 mg/L or more, as seen in flood tide dates from Thomas and Edelen (1962) and peak tide dates from the WATSTORE Peak Flow File (U.S. Geological Survey, 1975).

Although confined aquifers are less susceptible to contamination from surficial sources than unconfined aquifers are, contaminants can be introduced along improperly grouted wells. Elevated concentrations of three organic compounds (benzene, ethylbenzene, and toluene) were reported for a Cape May County well tapping the Atlantic City 800-foot sand (Barton and others, 1993). The concentration of benzene (0.018 mg/L) exceeded the New Jersey Primary Drinking Water Criterion of 0.001 mg/L. Concentrations of toluene and ethylbenzene were 0.460 and 0.150 mg/L, respectively. The well was contaminated by gasoline leaking from a storage tank at the time the well was drilled.

Other chemical constituents, such as nitrates, orthophosphates, or trace elements, can be introduced through particular land-use practices, but land use typically affects water quality in unconfined aquifers more than in confined aquifers. Nitrate concentrations in water from the Atlantic City 800-foot sand typically have been small. Of 51 wells sampled for nitrate or nitrate plus nitrite, none yielded water with nitrate concentrations in excess of 0.5 mg/L (as nitrogen), and 45 concentrations reported were below the minimum reporting level of 0.01 mg/L. These results contrast with the nitrate concentrations reported for the unconfined part of the aquifer system (Barton and others, 1993; E.F. Vowinkel, U.S. Geological Survey, written commun., 1988), where about 20 percent of wells sampled in Atlantic County between 1978 and 1988 yielded water with nitrate concentrations in excess of 3 mg/L.

In contrast with nitrate, orthophosphate concentrations typically were higher in water from the Atlantic City 800-foot sand than in water from the overlying unconfined part of the Kirkwood-Cohansey aquifer system, although concentrations in water from Ocean County wells generally were at or below the minimum reporting level of 0.01 mg/L, similar to those in water from the unconfined part of the system. Orthophosphate concentrations in water from wells in Atlantic and Cape May Counties typically ranged from 0.1 to 0.3 mg/L. The probable source of the phosphate is phosphate-bearing minerals in the matrix of either the Atlantic City 800-foot sand or the underlying Piney Point aquifer.

Concentrations of lead, arsenic, and cadmium were at or below the minimum reporting levels for these elements (5 μg/L, 1 μg/L, and 1 μg/L, respectively) in water from virtually all wells sampled. Only two wells sampled yielded water with concentrations of lead greater than 5 μg/L, and those concentrations were small (6 and 7 μg/L).

The potential for saltwater intrusion is thus the most likely water-quality issue to affect the use of the Atlantic City 800-foot sand. Analysis of rates of ground-water flow can be used to estimate time of travel of conservative constituents such as chloride.

Simulation of Ground-Water Flow and Saltwater Movement

Results of simulations of ground-water flow in the Atlantic City 800-foot sand were used to evaluate predevelopment conditions, recent (1986) conditions, and possible future conditions through the year 2040 under four water-supply alternatives. Simulated water levels, flow directions, flow budgets, and rate of flow from locations of salty ground water toward pumping centers are discussed. The method of simulation, model design, boundary conditions, and model calibration also are discussed.

Description of Ground-Water Flow Model

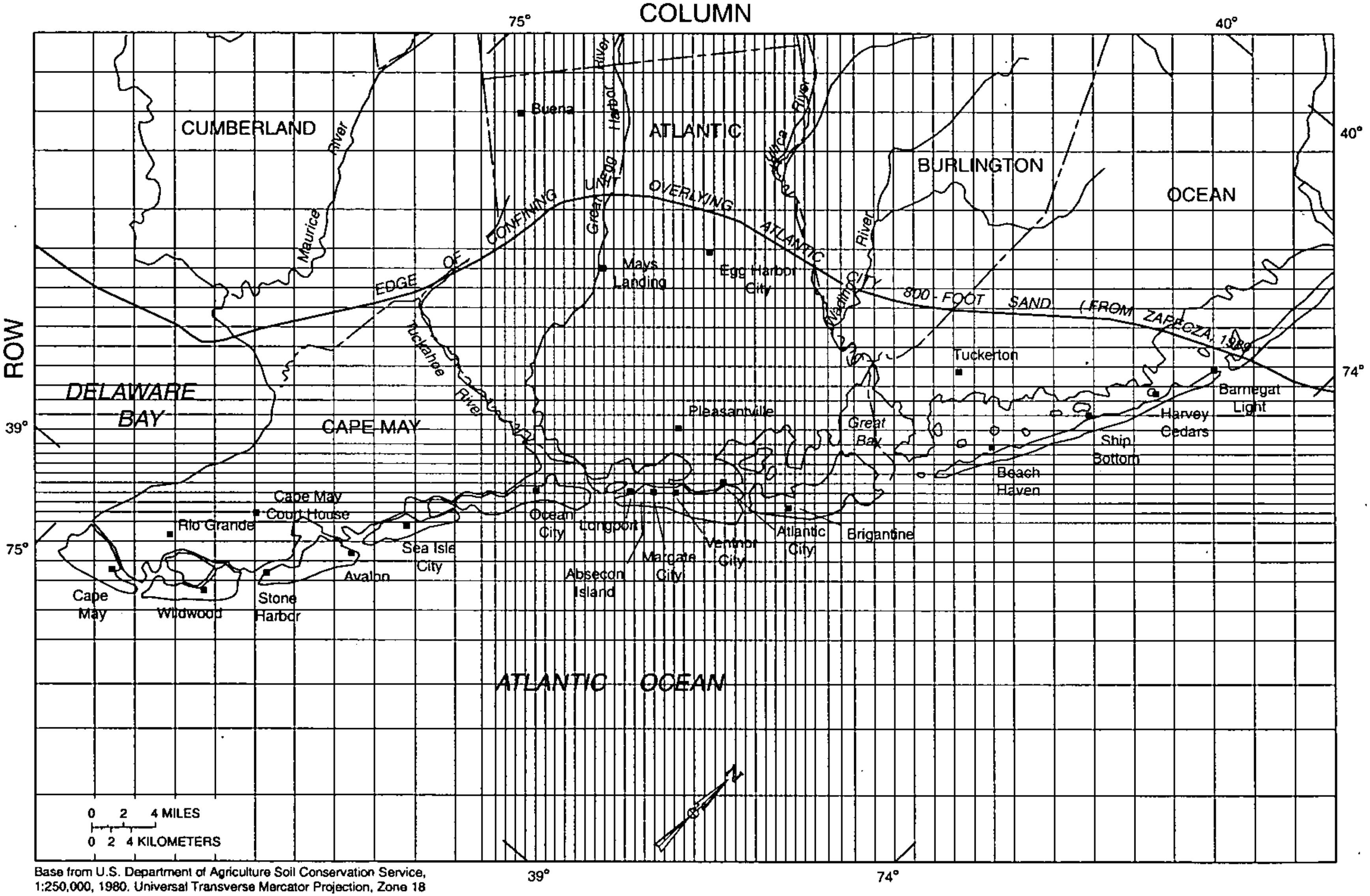
Ground-water withdrawals have affected water levels, flow directions, and flow rates in the Atlantic City 800-foot sand. In order to evaluate the effects of withdrawals, the ground-water flow system was simulated by use of the USGS modular three-dimensional finite-difference ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988). A quasi-three-dimensional representation of the aquifers and confining units was used, in which ground-water flow was assumed to be only horizontal within the aquifers and only vertical through the confining units. Water levels within the confining units were not simulated, but vertical flow through the confining units is accounted for in the model and is controlled by values of vertical leakance (hydraulic conductivity divided by thickness). Input data for the ground-water flow model were taken from the model of ground-water flow in the New Jersey Coastal Plain (Martin, 1998) and updated with data collected and analyzed during 1981-86. The regional model of Martin (1998) was also used to supply boundary conditions for the subregional model of the Atlantic City 800-foot sand. Steady-state prepumping flow conditions before 1896 were simulated, and transient flow conditions from January 1, 1896, to September 30, 1986, were simulated to analyze historical system responses to changes in ground-water withdrawals. The maximum and minimum annual pumpage conditions in 1986 were simulated to evaluate effects of seasonal pumpage on the Atlantic City 800-foot sand. The response of the flow system to possible alternative ground-water withdrawal schemes projected for the period 1986-2040 were then evaluated with the digital flow model. Ground-water flow velocities from the model were used to evaluate the potential for saltwater intrusion in the Atlantic City 800-foot sand.

Model Design and Configuration

The modeled area includes the onshore extent of the Atlantic City 800-foot sand and the part of the unconfined system that supplies recharge to the Atlantic City 800-foot sand (fig. 20). The modeled area was extended in all directions from the major pumping center at Atlantic City so that the effects of artificial model boundaries would be minimized.

The simulated aquifers were discretized using a finite-difference grid (fig. 20). The simulated area was divided into 33 rows, 63 columns, and 5 layers for a total of 10,395 block-centered model cells. All nodes are not active; however, perimeter nodes are active unless otherwise stated. Heads computed by the model solution methods are at the nodes at the geometric centers of the model cells, and the hydraulic-head value for a node is representative of an average hydraulic head over the area of the model cell. Model cells are designated in this report by layer, row, and column number, or simply by row number, followed by column number, if the layer number is expressed in other words.

Variable grid spacing was used in order to concentrate computational and interpretive effort in areas where evaluation of the response of the hydrologic system to stresses was important to the objectives of the study, for example, by resolving the shape of the potentiometric surface where hydraulic gradients are steep. Grid spacing is largest around the perimeter of the model area. Cell areas range from less than 0.4 mi^2 to more than 15.8 mi^2. The model cells with the smallest areas are in places where the Atlantic City 800-foot sand is overlain by a confining unit and in proximity to principal areas of ground-water withdrawals on the barrier islands of Atlantic County and Ocean City, Cape May County. The model cells with the largest areas are in places that are distant from well fields, in places where the confining unit overlying the Atlantic City 800-foot sand is absent, and in offshore areas where few or no hydrologic data are available.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 20. Areal extent of simulation and model-grid discretization for hydrologic simulations, New Jersey.

The model consists of five layers (fig. 21). The uppermost layer represents surface-water boundaries. Four aquifers and three confining-unit functions are simulated with the flow model: the Holly Beach WBZ (Martin, 1998), the confining unit overlying the Kirkwood-Cohansey aquifer system in Cape May County, the Kirkwood-Cohansey aquifer system, the confining unit overlying the Atlantic City 800-foot sand, the Atlantic City 800-foot sand, the confining unit overlying the Piney Point aquifer, and the Piney Point aquifer. The hydrogeologic units above and below the Atlantic City 800-foot sand are simulated in the same manner as in the regional model of Martin (1998), but with a finer discretization.

Layer 1 in the flow model represents surface-water boundaries where the Holly Beach WBZ is present. Elsewhere in model layer 1, the model cells are inactive. Long-term stream stage is represented by constant-head boundaries. Each model cell area generally contains several streams; each boundary head is selected to represent the average stage of all streams within the model-cell area. The flow between the aquifer outcrop area and streams is simulated in the same manner as that of the Coastal Plain model of Martin (1998). The difference between long-term streamflow and estimated ground-water recharge is referred to as "deep percolation" by Martin and represents flow to the underlying confined aquifers. Lateral flow is not simulated in layer 1; only vertical flow between streams and the Holly Beach WBZ is simulated.

Layer 2 contains two types of active cells: variable-head cells representing the Holly Beach WBZ and constant-head cells representing surface-water bodies. Onshore constant-head cells represent surface-water bodies as described previously for layer 1. Constant-head model cells in offshore areas (figs. 20 and 21) represent the ocean and bays. Only freshwater flow in aquifers is simulated. The Holly Beach WBZ is present only in peninsular Cape May County, and it is surrounded by constant-head lateral boundaries that represent the ocean and bays on all but the northwestern or inland boundary, where the aquifer nodes are bounded by constant-head lateral boundaries that represent the streams overlying the Kirkwood-Cohansey aquifer system. Throughout its extent the Holly Beach WBZ is simulated as containing freshwater, even though, due to model-cell sizes used, some of the areal extent simulated as freshwater may be brackish, as indicated by Gill (1962, p. 128-141). Recharge is applied to the cells representing the Holly Beach WBZ. Both horizontal and vertical flow occurs in the model cells that represent the Holly Beach WBZ. The confining unit underlying the Holly Beach WBZ is represented by leakance values that control vertical leakage to and from layer 3, which represents the Kirkwood-Cohansey aquifer system.

Model layer 3 represents the Kirkwood-Cohansey aquifer system. The units that compose the flow-model-designated Kirkwood-Cohansey aquifer system are considered to be hydraulically similar and function as one hydrologic unit. This arrangement is identical to the upper Kirkwood-Cohansey aquifer system layer of Martin (1998, p. H39). In areas where the confining unit that overlies the Atlantic City 800-foot sand is absent (fig. 20), model layer 3 represents the unconfined sediments of the Kirkwood-Cohansey aquifer system to a depth of approximately two-thirds of the thickness of all water-bearing sediments that overlie the Piney Point aquifer. Throughout most of the onshore extent, the modeled Kirkwood-Cohansey aquifer system is unconfined. The Kirkwood-Cohansey aquifer system is confined by the estuarine clay in the peninsular part of Cape May County. It is assumed that the Kirkwood-Cohansey aquifer system is confined in offshore areas as well. The confining unit overlying the Atlantic City 800-foot sand is represented by leakance values as part of the input data for model layer 3. Layer 3 contains active and inactive model cells. The Kirkwood-Cohansey aquifer system is present almost everywhere except in some areas under the Delaware Bay, where the outcrop of the confining unit that overlies the Atlantic City 800-foot sand is assumed to be the uppermost unit. In these areas of the Delaware Bay, layer 3 model cells are inactive. Elsewhere in layer 3, horizontal and vertical flow is simulated. The Kirkwood-Cohansey aquifer system water is assumed to be fresh everywhere, even though Gill (1962, p. 116) indicates that brackish water is near the shore.

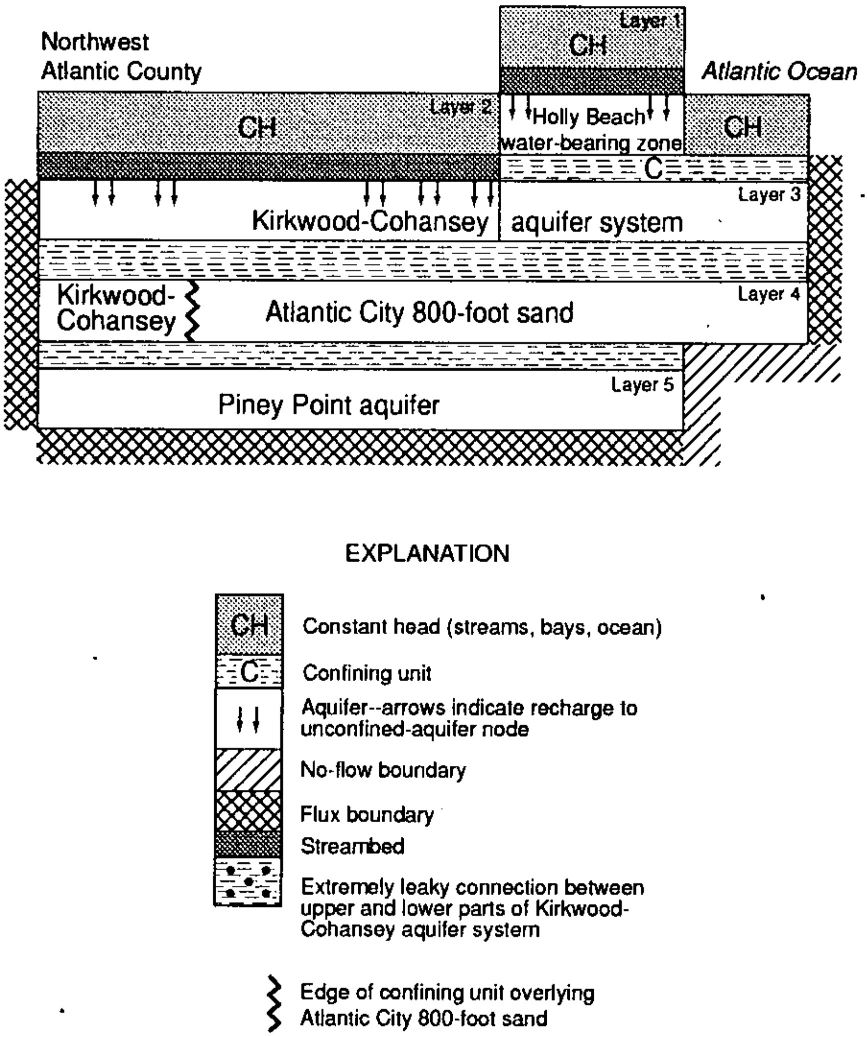


Figure 21. Schematic representation of simulated flow system, New Jersey.

Leakage can occur between the Kirkwood-Cohansey aquifer system and surface-water bodies, between the Kirkwood-Cohansey aquifer system and the overlying Holly Beach WBZ, and between the Kirkwood-Cohansey aquifer system and the underlying Atlantic City 800-foot sand. Recharge is applied to all active cells in layer 3.

Model layer 4 represents the Atlantic City 800-foot sand and the lower part of the Kirkwood-Cohansey aquifer system. In areas where the confining unit overlying the Atlantic City 800-foot sand is present (fig. 20), model layer 4 represents the confined Atlantic City 800-foot sand. In areas where the confining unit overlying the Atlantic City 800-foot sand is absent, layer 4 represents the lower third of the unconfined Kirkwood-Cohansey aquifer system. This representation provides a lateral connection between the Atlantic City 800-foot sand and the Kirkwood-Cohansey aquifer system, although the hydraulic connection has not been investigated (Zapecza, 1989, p. B17). Layer 4 contains only active model cells, and no recharge is applied to layer 4. In offshore areas, initial water levels for the Atlantic City 800-foot sand were estimated from Martin (1998). The confining unit that underlies the Atlantic City 800-foot sand is represented by leakance values.

Model layer 5 represents the Piney Point aquifer described by Zapecza (1989, p. B16-B17) and is identical to the Piney Point aquifer simulated by Martin (1998, p. H32-H33). The Vincentown-Manasquan confining unit at the base of the Piney Point aquifer is represented by a small (nearly zero) specified flux. Recharge is not applied to layer 5.

Boundary Conditions

The row direction of the grid is approximately parallel to the Fall Line and the strike of the Coastal Plain hydrogeologic units. The columns generally align with the downdip direction of the hydrologic units, the principal direction of lateral flow in the aquifer. The area of the grid for the model of ground-water flow in the Atlantic City 800-foot sand is a part of the area of the grid for the New Jersey Coastal Plain model (Martin, 1998). The orientation of the two model grids is identical. The discretization of the New Jersey Coastal Plain model was subdivided to meet the needs of the subregional model of the Atlantic City 800-foot sand. The number of subdivisions of New Jersey RASA model grid cells used to create Atlantic City model cells is variable and ranges from 0 to 16. Boundary conditions are shown (fig. 21) in cross-sectional view from northwest to southeast.

The lateral boundaries of layers that represent the Kirkwood-Cohansey aquifer system, the Atlantic City 800-foot sand, and the Piney Point aquifer are specified fluxes that supply flow from the regional Coastal Plain model to the Atlantic City 800-foot sand model. Lateral boundary flows were computed from flow-budget output from the regional Coastal Plain model. The lateral boundary flows were computed for each stress period and applied across the Coastal Plain model-cell faces that are common to the perimeter model-cell faces of the Atlantic City 800-foot sand model. If the Atlantic City 800-foot sand model-cell areas consist of only a fraction of the area of a Coastal Plain model-cell area, then the lateral boundary flow was proportionately subdivided. The final stress period of the Coastal Plain model represents pumping conditions from January 1, 1978, to January 1, 1981. The lateral boundary flows computed from the final stress period of the Coastal Plain model were used as lateral boundary flows to the Atlantic City 800-foot sand model in all stress periods during 1981-86. Although pumpage during 1981-86 is about 3 percent greater than pumpage during 1978-81 (fig. 8), the effect on lateral boundary flow is considered to be small and acceptable to study objectives. In the Coastal Plain model, well-field pumpage is lumped into large model-cell areas. In this model, effects of pumpage are dispersed because individual-well pumpage is distributed among a greater number of small-area model cells.

The locations of the lateral boundaries of the Atlantic City 800-foot sand were selected with the assumption that the distance from pumping centers was great enough that drawdown at lateral boundaries is insignificant throughout simulations. Freshwater is assumed to be present in the Atlantic City 800-foot sand about 45 to 55 mi further downdip from the coast, beyond the southeastern lateral model boundary, on the basis of depth to chloride concentrations that are greater than 10,000 mg/L (Meisler, 1980, fig. 4) and the estimated altitude of these aquifers offshore. Brackish water may be present in the interval, however. The southeastern lateral boundary of the Piney Point aquifer is represented with a specified flux of zero because the Piney Point aquifer terminates a few miles from the coast.

The lower boundary of the Piney Point aquifer is the top of Vincentown-Manasquan confining unit described by Martin (1998, p. H32) and part of the composite confining unit described by Zapecza (1989, p. B14-B16). This lower boundary is represented by a specified-flux boundary; however, only small fluxes occur, and this boundary is treated with the significance of a no-flow boundary.

Recharge is applied as a specified-flux boundary condition to variable-head model cells in layers 2 and 3 under unconfined conditions. A value of 20 in/yr was used to represent the long-term and areal average ground-water recharge in the New Jersey Coastal Plain. This value is consistent with those of other researchers (Martin, 1998, table 6). The water table, represented throughout layer 2 and in layer 3 except in the peninsular area of Cape May County, is a head-dependent flux boundary. Stream stages in layers 1 and 2 are simulated as constant heads and represent long-term average stream stage. The values used in the Coastal Plain model were rediscretized and compared to topographic elevation to estimate stream stage.

Ground-water-withdrawal data used in transient simulations were taken from Zapecza and others (1987, tables 2 and 3) for the period 1896 through 1980. Ground-water withdrawals for the period January 1, 1981, through September 30, 1986, were determined from data on monthly water use in computer files of the New Jersey District Office of the USGS, and from pumpage records obtained from water users. Water-use history for the Atlantic City 800-foot sand is given in figure 8 and table 2.

Fourteen stress periods were used to simulate changes in pumpage or ground-water withdrawals between January 1, 1896, and September 30, 1986. The stress periods range in duration from 4 months to 25 years; all stress periods are 1 year or longer except stress period 13 (January 1, 1986, to April 30, 1986) and stress period 14 (May 1, 1986, to September 30, 1986). Stress periods 13 and 14 were used to simulate the response of the ground-water system to seasonal changes in pumpage.

Calibration

Simulation results were compared to measured water levels, gradients, and flows in order to calibrate the simulation results to field data and to concepts derived from analysis of field conditions. The model was calibrated to three sets of conditions: (1) steady-state prepumping conditions, (2) transient conditions at the end of an annual minimum pumping season in April 1986, and (3) transient conditions at the end of an annual maximum pumping season in September 1986.

Calibration to prepumping steady-state hydrologic conditions was attained primarily by trial-and-error adjustment of aquifer hydraulic characteristics, notably aquifer transmissivity and confining-unit leakance, until simulated heads and streamflows equaled measured heads and streamflows or resembled measured values within acceptable limits as described in the calibration criteria below. The flow directions and flow budgets of the simulation were also compared to the conceptual model of the system.

The steady-state calibration was considered to be acceptable when the following criteria were met:

1. The prepumping water levels were reproduced to within 10 ft. (The measured data were taken from Zapecza and others (1987, p. 112-119).)

2. Hydraulic gradients and flow directions determined from simulated water levels in areas with little or no measured water-level data were compatible with water-level gradients and flow directions determined from measured water levels and shown on a map of prepumping water levels (fig. 7).

3. Hydraulic characteristics representing the flow system, including aquifer transmissivity, confining-unit vertical leakance, and flow between aquifers and streams, were compatible with the range of hydraulic characteristics measured in a laboratory or computed from an aquifer test and to flow rates postulated in the conceptual model.

4. Average ground-water discharge to streams was 20 in/yr.

5. The mass balance between inflows and outflows of the model had minimal error.

The criteria for an acceptable match between simulated conditions and field conditions is subjective. A comparison between simulated and measured water levels is made to quantify the calibration. The calibration target of reproduction of simulated water levels to within 10 ft of measured water levels was met at each of seven well locations in the simulation of steady-state prepumping conditions. Measured water levels and well numbers of field data are shown in figures 7, 9, and 10, and the residuals between measured and simulated water levels are given in figures 24, 28, and 29. The standard deviation, or the root-mean-squared error (RMS error), of the residuals is 5.78 ft, computed as:

$$\text{RMS error} = \left(\frac{1}{n} \sum_{i=1}^{n} (h_m - h_s)_i^2 \right)^{0.5} ,$$

where h_m is measured head,
h_s is simulated head, and
n is number of residuals.

The error associated with the residuals can result from several circumstances. The field data are subject to measurement errors, whether at the field site or at the office (during determination of elevation of the measurement point from a topographic map). The simulated water levels can differ from measured water levels because of the difference between the location of the well and the location of the model node: the simulated water level is an average water level for a model-grid cell area, whereas the measured water level represents the hydraulic potential at the exact point of measurement.

The ratio of the RMS error to the total change in head (in response to pumpage, for example) provides a measure of the acceptability of error (Anderson and Woessner, 1992). The error associated with the residuals is considered to be of little significance compared to the total gradient throughout the pre-pumping flow system. The RMS error (5.78 ft) is small compared to the total head loss (50 ft) from the edge of the confining unit, where the water level is 50 ft, to the location where ground water discharges to the sea, where the water level is about sea level. The ratio of the RMS error to the systemwide gradient is about 0.1 and indicates that the residuals represent only a small part of the total change in head simulated in the flow system. The total head change between prepumping conditions and pumping conditions in April 1986 cannot be computed because no data from prepumping observation wells (fig. 24) were available for 1986. Water levels measured at four supply wells (29-112, 1-117, 9-124, and 9-4; fig. 13) that are near prepumping observation wells (numbers 1, 3, 4, and 6, respectively; fig. 24) were averaged to compute the total head-change ratio and evaluate the average error acceptability. The average total head change at four sites during prepumping to April 1986 was 41 ft, and the ratio of RMS error to total head change was 0.14, an indication that the error of the residuals is small compared to the total head change simulated by the model.

The gradients and flow directions determined from simulated water levels closely resemble gradients and flow directions postulated from field data. These subjects are discussed in greater detail later in the report, in the section "Simulated Predevelopment Conditions." The hydraulic properties used in the simulation closely match the range of hydraulic properties postulated in the conceptual analysis and inferred from field data. The average ground-water discharge to streams is 20 in/yr throughout the model. The mass-balance error of 0.01 percent between inflows and outflows of the model is considered minimal.

The simulation of transient hydrologic conditions was calibrated to measured potentiometric data and to average annual rates of ground-water discharge to streams. Simulated synoptic water levels and long-term simulated water-level trends were compared to field data.

Calibration to transient hydrologic conditions was attained primarily by trial-and-error adjustment of hydraulic characteristics—notably, aquifer transmissivity, confining-unit vertical leakance, and aquifer storage coefficient—until simulated heads resembled measured heads within acceptable limits as described in the calibration criteria.

Interpreted potentiometric surfaces constructed from simulated heads were compared to gradients and flow directions shown in Clark and Paulachok (1989). Transient-state calibration was considered to be acceptable when the following criteria were met:

1. The water levels measured in observation wells in April 1986 and September 1986 were reproduced to within 15 ft.
2. Measured heads were reproduced to within 15 ft at the end of each stress period and trends in fluctuations were reproduced at observation wells.
3. Simulated water-level gradients in areas with few or no measured water levels were compatible with observed gradients.
4. Hydraulic characteristics used in the simulation were similar to hydraulic characteristics determined from other analytical methods that were interpreted and hypothesized from field data.
5. Average ground-water discharge to streams was 20 in/yr, and the model mass-balance error between inflows and outflows was minimal.

The simulated hydrologic conditions in the Atlantic City 800-foot sand at the end of April 1986 generally met the criteria for similarity to measured conditions. The RMS error of the 13 residuals was 10.13 ft for conditions during April 1986 and 6.63 ft for conditions during September 1986. The error associated with the residuals can result from the same circumstances described previously in the discussion of steady-state conditions. In addition, water levels measured in pumped wells are especially prone to measurement error. During the measurement of water levels in April 1986 and September 1986, the pumps were shut off for a period of time to permit complete recovery of the water levels; however, this recovery was not always achieved. The simulated water levels were quantitatively compared only to measured water levels in observation wells. The observation wells either have no pumps, or, in the case of well 1-40, had not been pumped for several weeks before the measurement.

The calibration target for transient-simulation head residuals (≤15 ft) was greater than that for steady-state simulation residuals (≤10 ft) because effects of storage and heterogeneous field conditions not represented in the simulation can increase the difference between measured and simulated water levels at observation wells. The error associated with the residuals (10.13 ft) is considered to be small compared to the average of the total change in water levels (65.5 ft) over the transient period from 1896 to April 1986. The ratio of the RMS error to the average of the total head change, 0.15, indicates that the residuals were small in comparison with the total change in head observed during the transient period from 1896 to April 1986. The ratio of RMS error (6.63 ft) to the average of the total head change during 1896-September 1986 (88 ft) was 0.07 and also indicates that the residuals were small in comparison with the total head change observed in the flow system.

Water levels simulated for the end of the period from January through April 1986 at node locations in model cells are within 15 ft of water levels measured at observation wells during April 1986 except at two locations (fig. 9). The simulated water level at well 1-702 is 19 ft higher than the measured water level. Well 1-702 is near the center of the greatest concentration of pumping in the study area. Although all pumping was to be discontinued for several hours before water-level measurement, the water levels at the observation well most likely reflect unaccounted-for effects of recent pumping rather than an average water level during winter 1986. The water level simulated during January through April 1986 at the center of the model cell closest to observation well 1-711 is 19 ft higher than the water level observed at well 1-711 during April 1986. Simulated water levels at both offshore locations are higher than observed water levels. The transmissivity was lowered during the simulation effort in offshore areas on the basis of data from the offshore wells, but any further decrease in transmissivity would have gone beyond implications of the offshore data. The boundary condition in the offshore direction may not accurately represent actual flow conditions. The model receives flow at the offshore boundary from the regional New Jersey Coastal Plain flow model. In the regional model, freshwater is assumed to extend to about 50 mi offshore. If saltwater is present, the freshwater fluxes that occur at the model boundary would be lessened, and the result would be lower freshwater heads in offshore areas.

Water levels simulated at the end of the period of maximum pumping (September 1986) are within 10 ft of water levels measured at observation wells during September 1986 except at one location. The measured water level at observation well 1-180 is 15 ft higher than the water level simulated at the nearest model cell. Simulated water levels in offshore areas are again higher than water levels observed at wells 1-711 and 1-710, but only by 6 ft and 8 ft, respectively.

Water levels in long-term observation wells are simulated to within 15 ft at two observation wells, 1-180 and 1-578. Water levels are simulated to within 20 ft at observation wells 1-366 and 1-37 during 1973-86. Differences between observed and simulated water levels before 1973 were greater than 20 ft in some wells. The greater differences may have been due to less accurate reporting of water use before 1955, when only average estimates for entire well fields were reported to regulatory agencies (Zapecza and others, 1987). The comparison between simulated and observed water levels at long-term observation wells is discussed further in the section "Simulated Postdevelopment Conditions."

The third calibration criterion was generally met throughout the flow system and is described in greater detail in the discussion of water levels and flow directions under recent (1986) ground-water-supply conditions. The fourth calibration criterion was also generally met and is described in greater detail in the section "Values of Hydraulic Properties Used in Model." The average ground-water discharge to regional streams was 20 in/yr throughout the model. The difference between inflow to and outflow from the model at the end of simulations ending in April 1986 and in September 1986 was 0.01 percent, a difference that met the calibration criterion for mass-balance error.

Sensitivity Analysis

The sensitivity of the model to changes in values of hydraulic characteristics was analyzed after model calibration. Values of selected hydraulic input parameters, such as transmissivity and vertical leakance, were increased to twice reported levels and then lowered to one-half of reported levels for model cells near large pumping centers. The results were not tabulated, but they were similar to results of a sensitivity analysis by Martin (1998, p. H116-H123) for the New Jersey Coastal Plain model. The simulated water levels in the Atlantic City 800-foot sand were affected by large changes in transmissivity or in leakance of the overlying confining unit. When transmissivity was doubled, simulated water levels increased substantially, and the differences from measured levels again failed to meet the calibration criterion near the pumping centers. When transmissivity values were decreased by 50 percent, the water levels decreased so that differences from measured levels again failed to meet the calibration criterion near pumping centers. The accuracy of simulation results probably would be improved by additional data that describe hydraulic characteristics in areas near pumping centers. The results of the sensitivity analysis are similar to Martin's results because the transmissivities and vertical leakances are similar to those used in the New Jersey Coastal Plain model.

Model sensitivity to changes in the storage coefficient was not determined, because the values used were the same as those used by Martin. Model sensitivity to boundary flows also was not determined because flows used for boundary fluxes were taken from the Coastal Plain model. Martin (1998, p. H121-H122) showed that, because boundary flows are small compared to pumpage, their effect on simulated water levels is small.

Values of Hydraulic Properties Used in Model

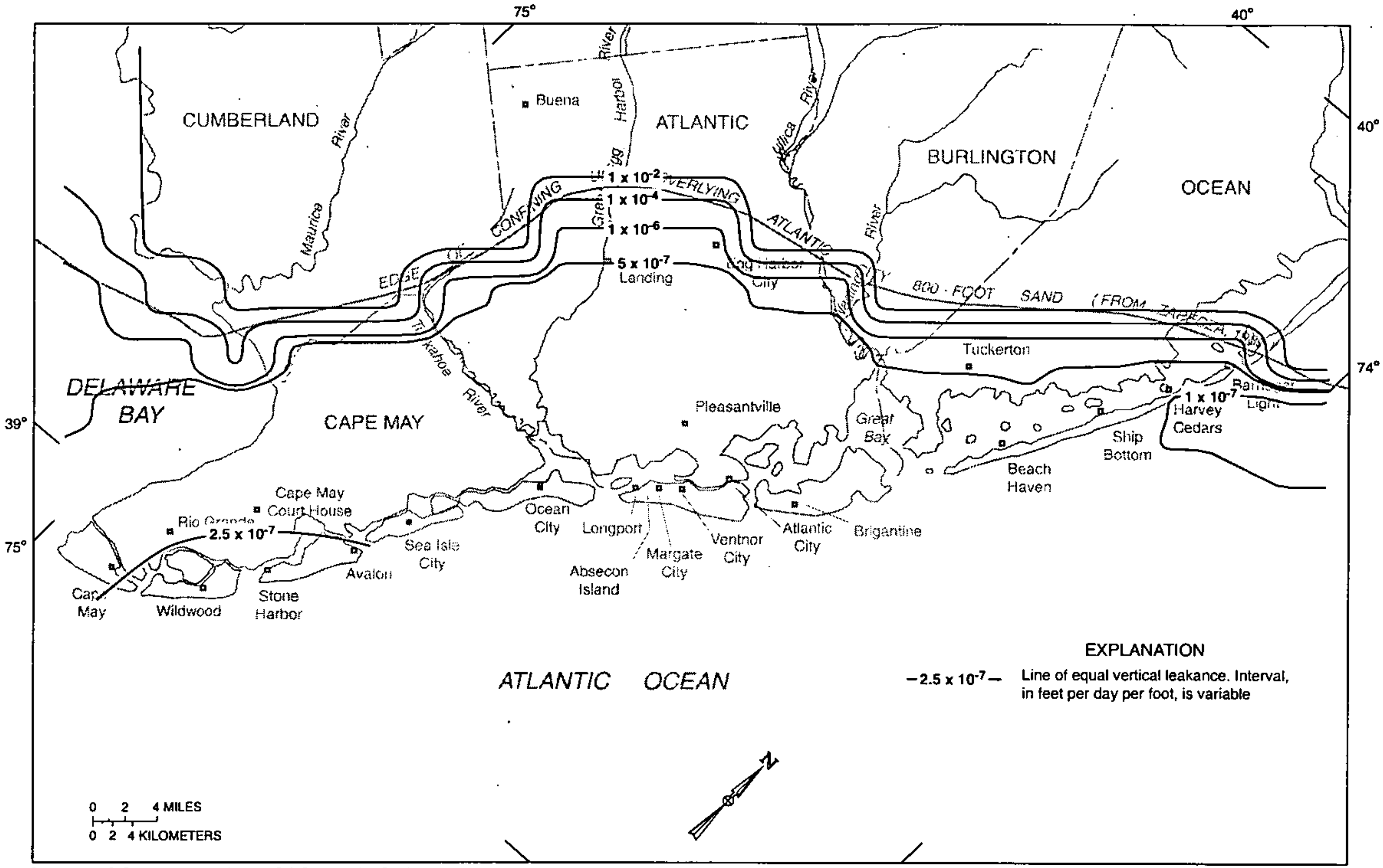
Data describing transmissivity, hydraulic conductivity, storage coefficient, hydrogeologic-unit thickness, porosity, and lithology were taken for use in simulations from analyses done during 1983-88 and from earlier studies and reports, as described previously. In all model layers, transmissivity was used as input data rather than hydraulic conductivity and aquifer thickness because the aquifers are considered to act as confined systems or as unconfined systems in which the saturated thickness does not change significantly (or changes gradually). A transmissivity of zero was assigned to each model cell that represents stream stage so that only vertical flow between streams and aquifers would be simulated.

Vertical leakances were assigned to represent the streambed leakance in the model. The streambed leakance, which represents the extent and degree of the hydraulic connection between streams and the unconfined aquifer, ranges from 4.35×10^{-4} to 4.58×10^{-3} (ft/d)/ft.

Transmissivities and storage coefficients used to simulate flow in the unconfined aquifers (including the Kirkwood-Cohansey aquifer system and the Holly Beach WBZ) and vertical leakances between streams and the water table were the same as those used by Martin (1998, p. H87-H99). Transmissivity of the Holly Beach WBZ in the model ranges from 4,500 to 7,500 ft^2/d. Transmissivity of the Kirkwood-Cohansey aquifer system ranges from 270 to 11,660 ft^2/d; transmissivity is lowest in the updip areas, where the aquifer thins, and greatest along the coast. Vertical leakance between the Holly Beach WBZ and the Kirkwood-Cohansey aquifer system in Cape May County ranges from 5.0×10^{-7} (ft/d)/ft to 1.0×10^{-6} (ft/d)/ft. The storage coefficients used are 0.15 for the Holly Beach WBZ and unconfined areas of the Kirkwood-Cohansey aquifer system and 0.0001 for confined areas of the Kirkwood-Cohansey aquifer system.

Vertical leakance used to simulate the confining unit overlying the Atlantic City 800-foot sand (fig. 22) ranges from 1.0×10^{-7} (ft/d)/ft to 1.0×10^{-2} (ft/d)/ft. The leakance, multiplied by the confining-unit thickness, corresponds to the vertical hydraulic conductivity of the confining unit. The range of corresponding vertical hydraulic conductivities used is similar, within an order of magnitude, to estimates by previous researchers and to values obtained during this study.

The sediments that compose the confining unit near the northwestern and western edges of the Atlantic City 800-foot sand are an interfingered sequence of clay, silt, and some sand. The sand content and the vertical hydraulic conductivity decrease over a short distance downdip from the edge. Because the vertical leakance of this unit decreases rapidly downdip but the thickness increases only gradually, it is probable that sediment size decreases downdip. The vertical leakance decreases rapidly, from 1.0×10^{-2} to 5.0×10^{-7} (ft/d)/ft, downdip, or southeast, of the confining-unit edge. Further downdip, and to the south in Cape May County, the vertical leakance decreases to 2.5×10^{-7} (ft/d)/ft because thickness of the confining unit increases in that direction to greater than 400 ft. In the northern part of the modeled area, in coastal Ocean County and on Long Beach Island north of Ship Bottom, the sandy Rio Grande water-bearing zone above the confining unit is absent (Zapecza, 1989, pl. 5), yet the clay confining unit between the Rio



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 22. Vertical leakance of confining unit overlying the Atlantic City 800-foot sand, New Jersey.

Grande water-bearing zone and the Kirkwood-Cohansey aquifer system remains. The vertical hydraulic conductivity is decreased, and the thickness increases, so that the vertical leakance is decreased to 1.0×10^{-7} (ft/d)/ft.

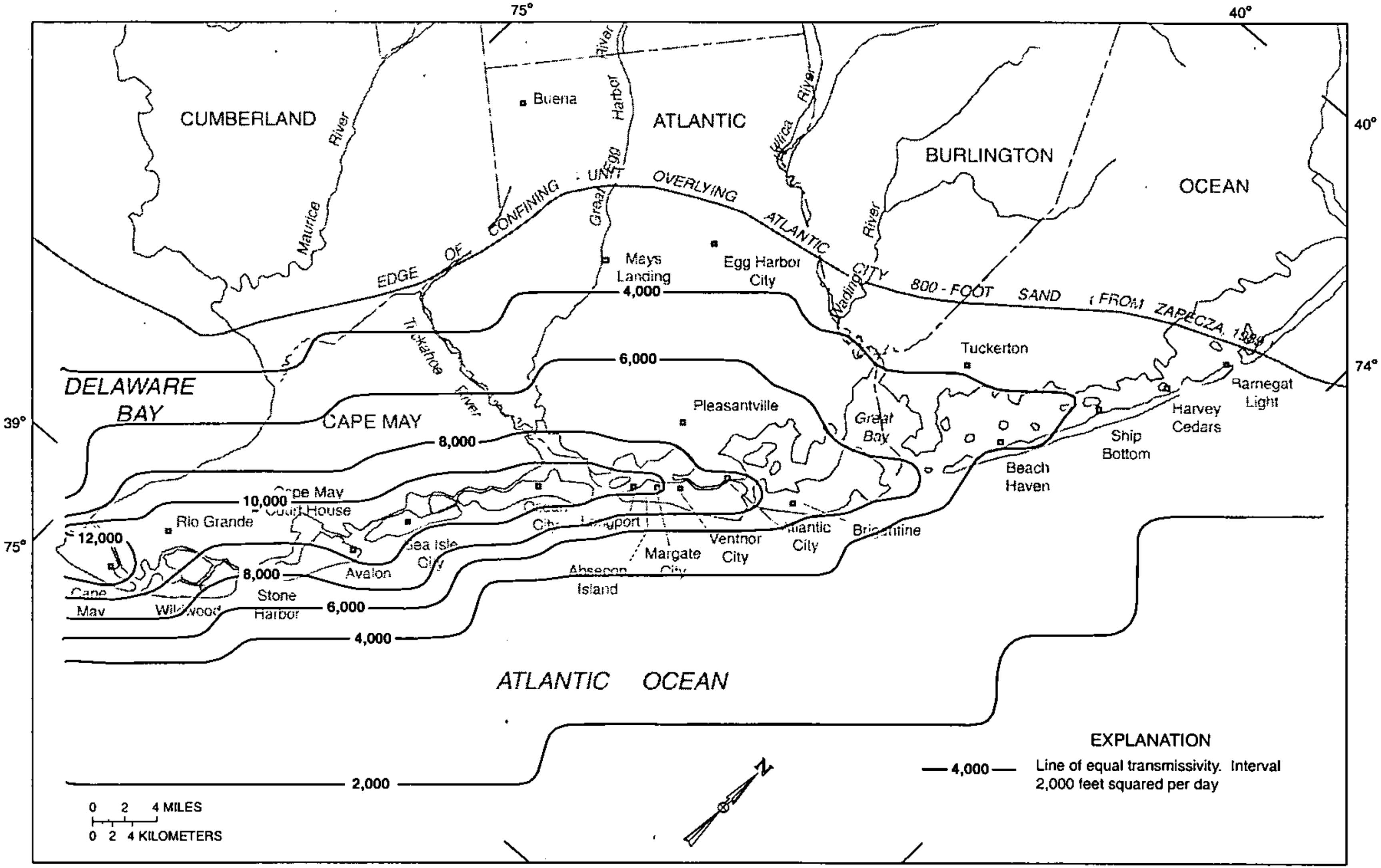
Updip from the edge of the confining unit, flow between the deep and shallow parts of the Kirkwood-Cohansey aquifer system is controlled by a relatively large vertical leakance that ranges from 1.0×10^{-2} to 1.0×10^{-1} (ft/d)/ft. The decrease in vertical leakance represents an increased silt content and a gradually increased thickness downdip.

The variability of transmissivity of the Atlantic City 800-foot sand, shown in figure 23, is a result of different geologic depositional environments, and this variability is confirmed by the analysis of aquifer-test data. The onshore and nearshore transmissivity ranges from 2,000 to 12,000 ft/d and is greatest in a tongue-shaped area along the coast, south of the Atlantic County-Ocean County border. Transmissivity decreases in all directions from the tongue-shaped area except to the southwest. Transmissivity of the freshwater Atlantic City 800-foot sand is controlled by the lithology, extent, and thickness of the sediments. Analysis of the depositional environments of the Atlantic City 800-foot sand of the Kirkwood Formation indicates that the aquifer sediments are a sequence of gravel, sand, silt, and fragment shell material representative of nearshore marginal-marine deposition (Hathaway and others, 1979; Isphording and Lodding, 1969; Owens and Sohl, 1969). The sediments deposited nearest to shore are sandy and highly permeable. The sandy sediments are interfingered with less permeable silts as the distance from the shore increases. Two layers of sand separated by a clayey unit are present within the Atlantic City 800-foot sand (C.L. Tilley and A.J. Straus, U.S. Geological Survey, written commun., 1978; Zapecza, 1989). The upper layer of sand extends nearly to the westward limit of the overlying confining unit.

The extent of the lower layer of sand in the Atlantic City region is not reported to date. However, the lower sand limit is assumed to be east and south of the upper sand limit. The lower and upper sands can be seen in gamma-log traces for wells downdip from well 1-834 in figure 3. The Atlantic City 800-foot sand was simulated as a single layer; however, the distribution of transmissivity takes into account the upper and lower sand extents as well as the change in thickness. The tongue-shaped area of high transmissivity along the coast is near the updip limit, or nearshore depositional setting, of the lower sand, where highly permeable sand and gravel has been deposited. Transmissivity is high in the southern tip of Cape May County, where the total aquifer thickness is also greatest. Throughout the coastal area north of Stone Harbor, screens of many wells are open to the lower sand. High hydraulic conductivities are generally computed from aquifer tests using the wells in the coastal area whose screened intervals are in the lower sand.

The hydraulic conductivities used to compute transmissivity in the model range from 57 to 67 ft/d in the area along the coast from Cape May to Atlantic City. West of the coast, the thickness of the aquifer decreases, and the lower sand is assumed to be absent about midway from the coast to the limit of the upper sand. Hydraulic conductivity decreases westward, to 35 ft/d near Mays Landing. Transmissivity also decreases westward, to less than 4,000 ft^2/d near Mays Landing. The aquifer thins and becomes more silty to the north. Transmissivity and hydraulic conductivity also decrease northward. Near Ship Bottom, the transmissivity is 4,000 ft^2/d and the hydraulic conductivity is 32 ft/d. Results of logging and pumping the offshore wells indicate that thickness and hydraulic conductivity both decrease southeast of the coast. The transmissivity decreases over a short distance offshore, to less than 4,000 ft^2/d 5 mi offshore.

The storage coefficient is 0.0001 in most areas, although it was adjusted where the aquifer thickness changes. Storage coefficients for the Atlantic City 800-foot sand range from 0.00001 to 0.0001. The storage coefficient is 0.00001 in the northern part of the aquifer, where thickness decreases.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 23. Transmissivity of the Atlantic City 800-foot sand, New Jersey.

The confining unit underlying the Atlantic City 800-foot sand extends throughout the modeled area. In most of its extent, the vertical leakance of this confining unit is 1.0×10^{-7} (ft/d)/ft, and the vertical hydraulic conductivity is estimated to range from 1.0×10^{-5} to 1.4×10^{-5} ft/d. From near Ship Bottom to the northern extent of the Atlantic City 800-foot sand at the edge of the overlying confining unit in Ocean County and from southeastward under the ocean to the northeastern model boundary, the vertical leakance of the underlying confining unit increases slightly to a maximum of 1.0×10^{-6} (ft/d)/ft. This is because the thickness of the confining unit increases gradually to the southeast (Martin, 1998, p. H21) and also to the north and northeast, and the vertical hydraulic conductivity increases to a range of 1.0×10^{-4} to 8.0×10^{-4} ft/d because of increased sandy-silt content. In areas beyond the extent of the Atlantic City 800-foot sand, the vertical leakance of the confining unit that underlies the lower part of the Kirkwood-Cohansey aquifer system is similar to that used by Martin (1998) and ranges from 1.0×10^{-7} to 5.0×10^{-4} (ft/d)/ft. Vertical leakance is greater near the outcrop of the confining-unit material because the sandy-silt content is greater.

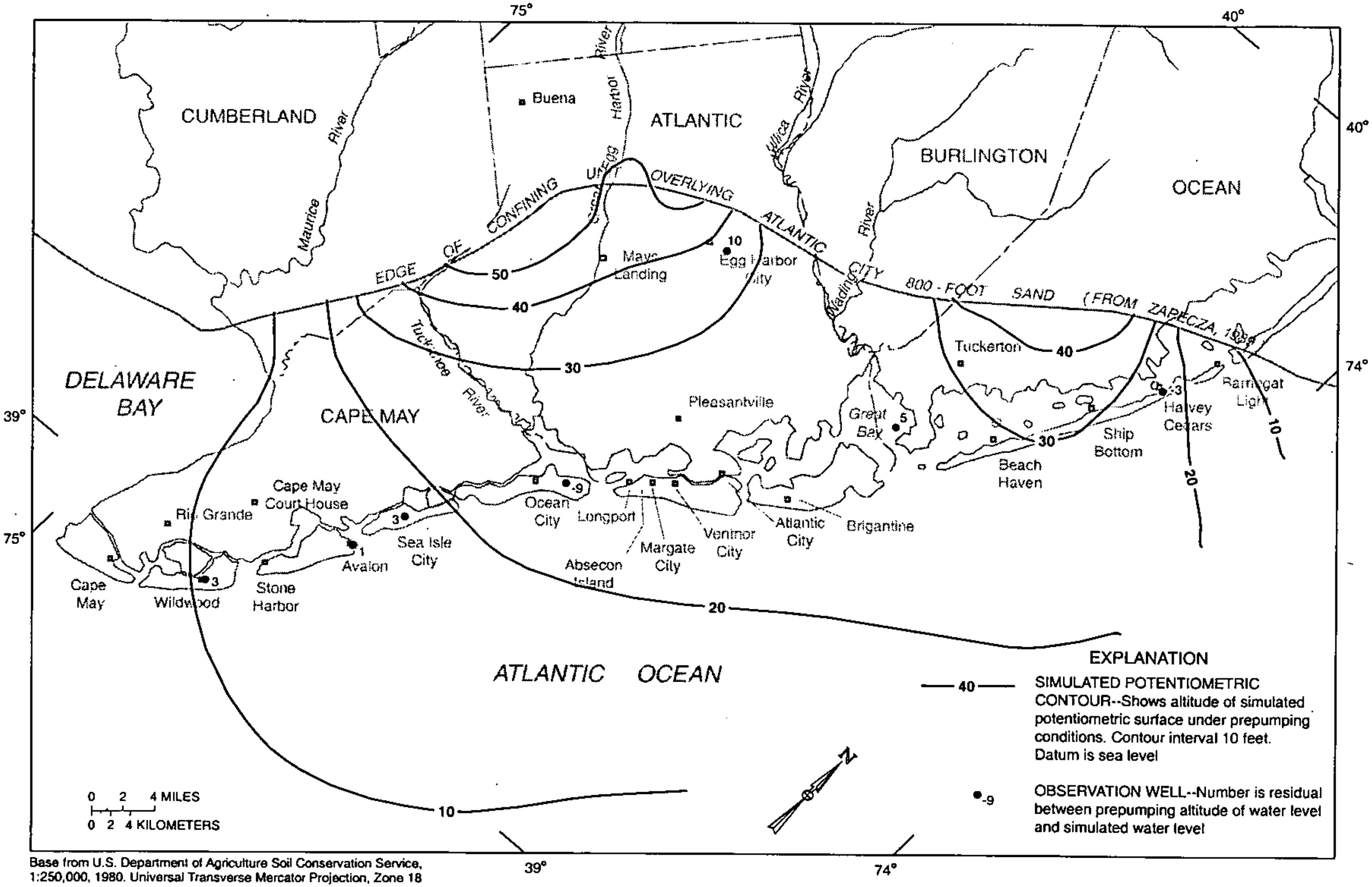
Simulated Predevelopment Conditions

In this section of the report, results of the simulation of prepumping conditions are compared to interpretations of prepumping conditions made previously by other researchers (Zapecza and others, 1987) and an improved analysis of the prepumping flow conditions is described. The system was analyzed by evaluating the significance of water levels, the principal flow directions, and the flow budget.

Water Levels and Flow Directions

Simulated water levels in the Atlantic City 800-foot sand are all above sea level under prepumping conditions (fig. 24). The water levels are as high as 50 ft above sea level northwest of Egg Harbor City and Mays Landing near the updip extent of the overlying confining unit. Water levels onshore are as low as 10 ft above sea level near Barnegat Light on the northeasternmost barrier island in Ocean County, and throughout peninsular Cape May County, south of Wildwood and south of Rio Grande. Water levels on the barrier islands between Ship Bottom and Sea Isle City are more than 20 ft above sea level. Simulated water levels are generally lower than measured levels (figs. 24 and 9) except in Ocean County, where simulated water levels are higher than measured levels. The mean of the absolute difference between measured prepumping water levels and simulated prepumping water levels (the mean residual) is 4.85 ft. The RMS is 5.78 ft. The match between measured and simulated water levels is considered to be close, given that each measured water level is compared to the simulated water level at the nearest model node.

Ground water flows into the Atlantic City 800-foot sand laterally from updip areas and vertically from overlying and underlying aquifers. Water levels in the Atlantic City 800-foot sand are maintained higher than overlying water levels by the confining unit and are not influenced by topography, as is the water table. Most of the ground water flows laterally through the aquifer, generally from inland areas northwest of the coast toward the freshwater-saltwater interface, southeast of the coast and many miles offshore. Meisler (1984, p. 6, fig. 3) estimated that the interface is at about 50 mi offshore in the Miocene-age sediments that include the Atlantic City 800-foot sand. Some ground water flows laterally to discharge upward at or near the edge of the overlying confining unit, eventually flowing into the Delaware Bay or the Atlantic Ocean or barrier-island bays through the intervening Kirkwood-Cohansey aquifer system. The extent of the Kirkwood-Cohansey aquifer system in offshore areas is not investigated during this study, but Martin (1998, p. H34) assumed that it is confined offshore by the overlying ocean floor. Flow directions determined from the simulated water levels generally agree with flow directions determined from the prepumping potentiometric surface (Zapecza and others, 1987, fig. 9), except in



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 24. Prepumping potentiometric surface of the Atlantic City 800-foot sand, New Jersey, interpreted from simulated heads.

the area of the Mullica River and the Wading River near the Atlantic County border with Burlington County. The Mullica River in that area is only about 3 to 5 ft above sea level; consequently, water levels in the Atlantic City 800-foot sand are lowered to less than 20 ft above sea level. Ground water in the Atlantic City 800-foot sand flows from the aquifer area underlying the interstream areas in Atlantic County laterally along strike direction toward the edge of the confining unit near the Mullica River, and then upward toward the river. Some ground water also flows from Ocean County areas toward the area underlying the Wading River. Flow to the Wading River is not indicated in the interpretation of Zapecza and others (1987, fig. 9) because the 30-ft contour of Zapecza and others is not deflected relative to the location of the Mullica and Wading Rivers. Figure 24 shows the 30-ft contour deflected and a 20-ft contour present near the rivers. The increased gradient between recharge areas and discharge areas in the Atlantic City 800-foot sand underlying the Mullica and Wading Rivers will result in more flow toward these rivers than had been inferred previously. Ground water also flows toward the Great Egg Harbor River at the edge of the overlying confining unit in Atlantic County and toward the Tuckahoe River at the edge of the overlying confining unit at the border between Atlantic County and Cumberland County.

Flow Budget

Simulation of prepumping steady-state conditions demonstrates how ground-water recharge flows into the confined Atlantic City 800-foot sand as deep-leakage contributions from uplands or areas near ground-water divides. About 3.9 Mgal/d flows laterally from updip areas, and about 0.1 Mgal/d leaks vertically through the overlying confining unit (fig. 25). The lateral-flow value is similar to the estimate of lateral recharge (3.36 Mgal/d) made previously in this report on the basis of generalized approximations of flow rates. About 1.4 Mgal/d flows into the Atlantic City 800-foot sand as diffuse leakage through the underlying confining unit from the Piney Point aquifer, throughout the extent of the Atlantic City 800-foot sand. Ground water discharges eventually to surface-water bodies. About 2.3 Mgal/d discharges near the edge of the overlying confining unit. About 1.1 Mgal/d discharges to the part of the Kirkwood-Cohansey aquifer system that underlies the Delaware Bay, the Atlantic Ocean, and adjacent bays, near the edge of the confining unit. This flow would likely discharge into the ocean and the bays as vertical leakage through the ocean or bay floor. Flow of 1.9 Mgal/d discharges through the overlying confining unit as diffuse leakage throughout the modeled extent of discharge areas that overlie the Atlantic City 800-foot sand. Flow of 1.2 Mgal/d leaves the model area to eventually discharge to the ocean floor at or near the freshwater-saltwater interface. Inflows and outflows are balanced and total 5.4 Mgal/d.

Simulated Postdevelopment Conditions

By 1986, pumpage from the Atlantic City 800-foot sand for water supply had increased to 20.85 Mgal/d and had resulted in significant drawdown of water levels in a large regional cone of depression. The pumpage rates and drawdowns vary seasonally. The extensive drawdowns have altered the direction of ground-water flow so that some ground water from offshore flows toward the Atlantic City area. The flow of water from offshore serves to alert water-supply planners and managers of the potential for saltwater intrusion. Results of the simulation of the ground-water flow system were used to evaluate 1986 water levels, flow directions, and flow budget and to examine the potential for saltwater intrusion.

Pumpage

The reported rate of increase of annual pumpage remained similar during 1896-1955, greatly increased during 1955-77, then leveled off to nearly zero during 1977-86. The changes in pumpage are approximated in the computer model by division of the pumpage data into 14 stress

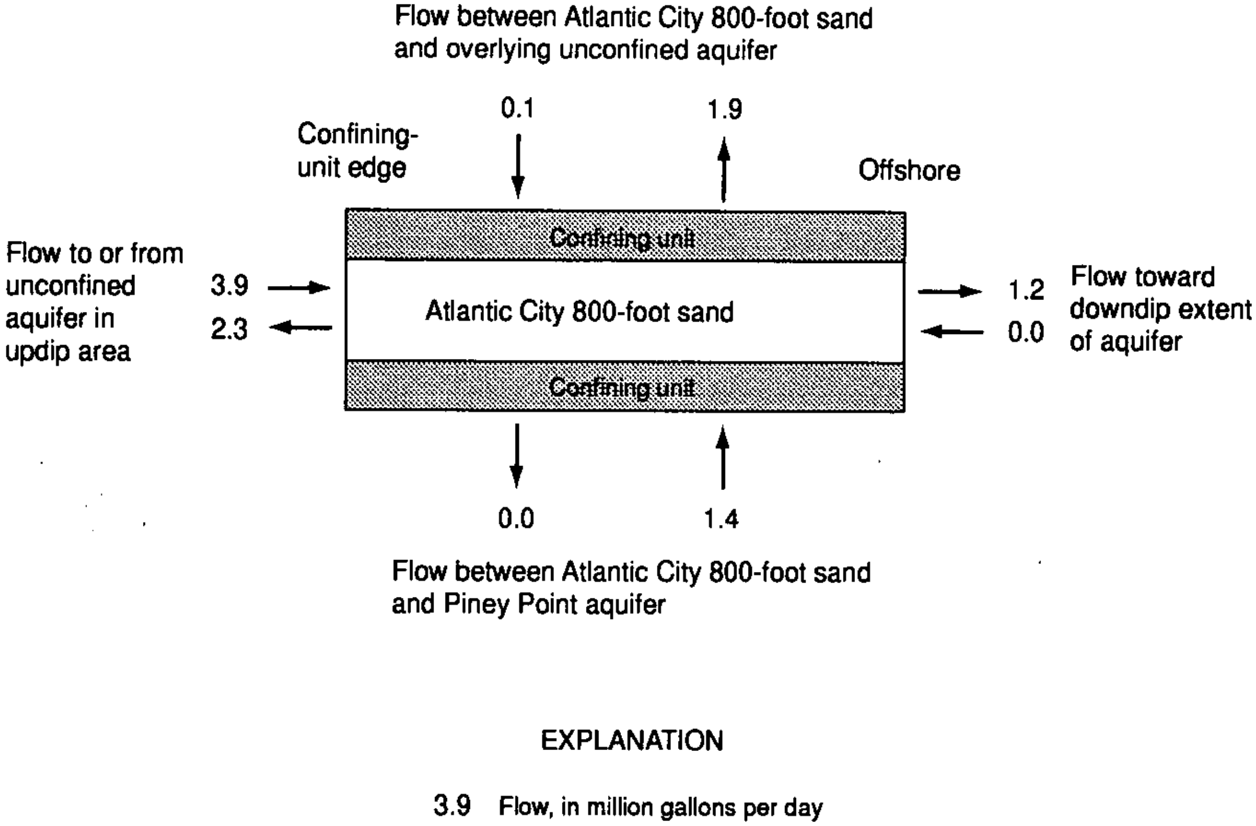


Figure 25. Flow budget for the Atlantic City 800-foot sand, New Jersey, under prepumping conditions.

periods that each simulate one rate of pumpage but that together closely resemble the changes in pumpage during 1896-1986 shown in figure 8. The long-term trends in hydrographs of simulated water levels respond to the long-term trends in pumpage (fig. 26). An initial rate of water-level decline from the start of record to 1945 (the end of stress period 2 in the simulation) is followed by an increased rate of decline in water levels during 1945-68 (at the end of stress period 6), which is followed by a very moderate rate of water-level decline during 1968-86. Before 1986, average annual pumpage is combined in stress periods to simulate long-term water-level responses as a series of steady-withdrawal simulations. The stairstep pattern of the simulated water levels shows that a new state of equilibrium is reached less than 1 year after the change in the pumpage rate. The long-term trend of declining measured water levels before the mid-1960's coincides with the trend of simulated water levels, although simulated water levels are much higher than measured water levels. Simulated and measured water levels begin to match more closely after the mid-1960's. This closer match probably reflects improved recordkeeping programs for New Jersey State pumpage records (Zapecza and others, 1987, p. 7-9) and consequently better representation of pumpage in simulations. Beginning with stress period 7, simulated water levels at the end of each stress period are within 15 ft of the average of the measured water levels over the stress period.

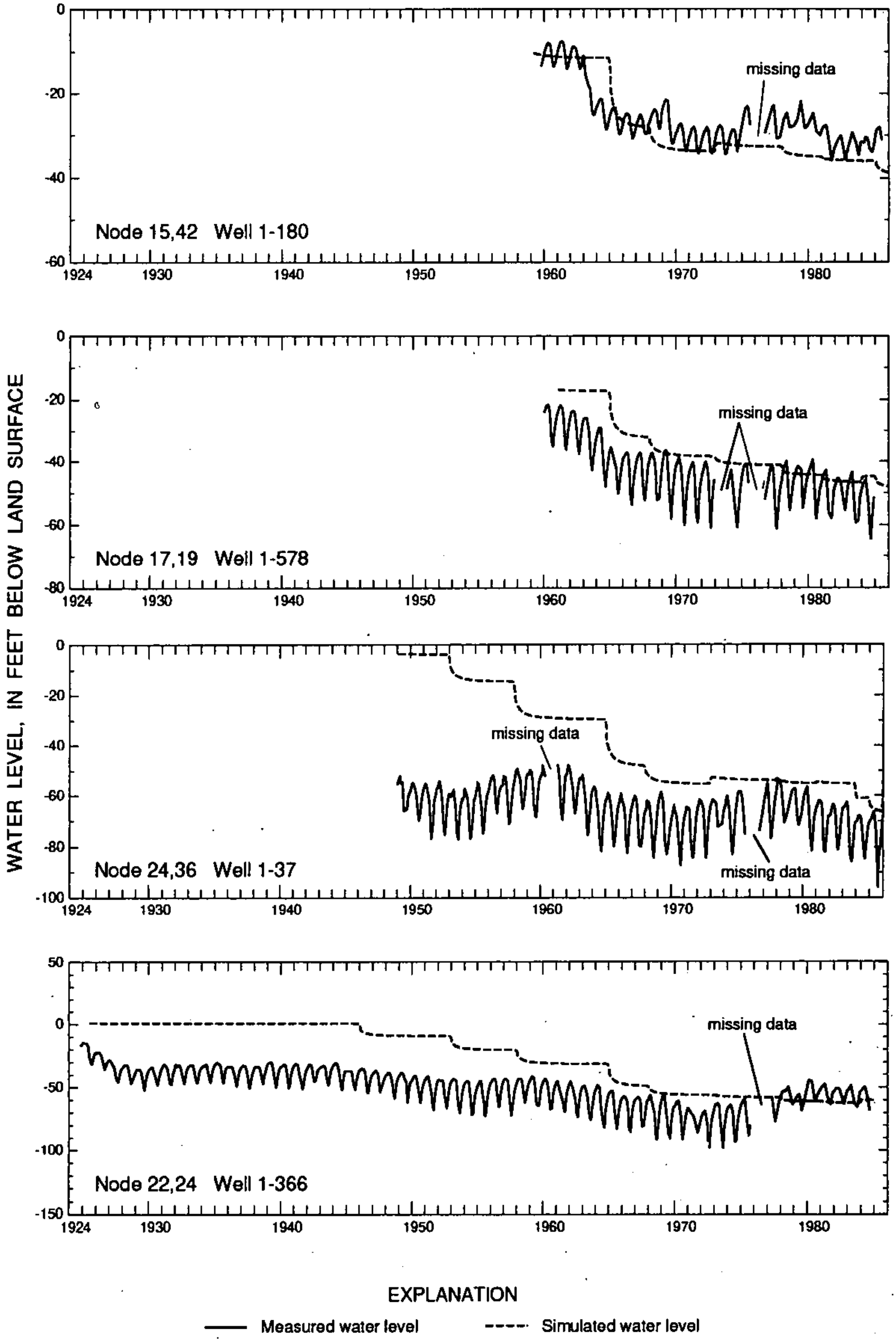


Figure 26. Simulated and measured water levels in selected long-term observation wells, New Jersey.

The seasonal water demand from the Atlantic City 800-foot sand is not included in the simulation, except for 1986. During stress period 13, representing the 120 days from January 1, 1986, to April 30, 1986, monthly pumpage rates are averaged to simulate winter, or annual minimum, pumping rates. During stress period 14, representing the 153 days from May 1, 1986, to September 30, 1986, monthly pumpage rates are averaged to simulate water-level response to summer, or annual maximum, pumping rates.

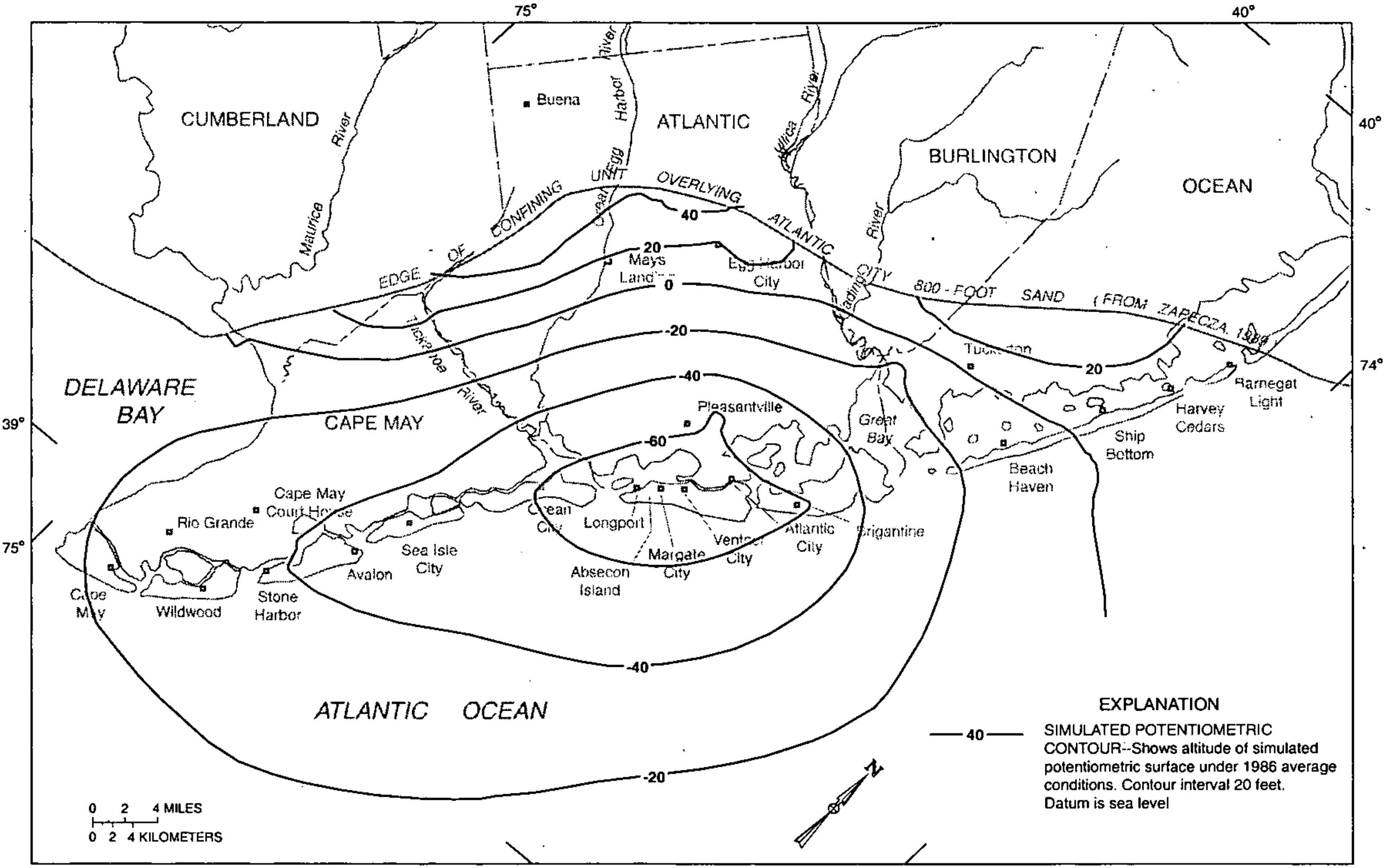
A comparison of simulated water levels to measured water levels shows that an equilibrium condition is not reached in the simulation of 1986 winter and summer pumpage. The simulated water-level increases are similar to measured water-level increases at observation wells during winter, but the simulated decline in water levels is greater than declines in measured water levels during summer at observation wells 1-37, 1-180, and 1-578, although all differences are less than 15 ft (fig. 26). The effect of large seasonal increases in pumpage in one stress period in the model is a large water-level decline. In the field, pumping rates change daily; but over weeks or months, water levels fluctuate as a seasonal decline gradually develops.

Overall, the water levels reproduced in the series of steady-withdrawal simulations reflect average long-term measured water-level trends during transient pumping conditions, and measured seasonal conditions are approximated by the simulation of 1986 minimum and maximum pumpage. The overall long-term trend is one of declining water levels with increased pumpage; and although the recent rate of decline is less than that for the entire period of record, the overall decline still continues and is most influenced by the maximum pumpage of each summer season. The measured water level has declined on average more than 55 ft during nearly 60 years of record at observation well 1-366 on Absecon Island in Longport. Simulated water levels have declined about 115 ft, from 25 ft above sea level to 90 ft below sea level, during summer months at observation wells 1-366 and 1-37 (at Atlantic City).

Water Levels, Flow Directions, and Saltwater Movement

Average water levels in the Atlantic City 800-foot sand under average 1986 pumping rates (table 2) were simulated in order to compare these levels with simulated prepumping levels. Both simulations represent steady-state conditions, so that temporary effects of storage do not enter into the evaluation of the effects of pumping on the flow system. In this simulation, seasonal pumpage is not included, and the average 1986 pumping rates are used in the final stress period of the model. Through evaluation of simulated water levels and flow direction, in conjunction with chloride-concentration data, the potential for saltwater intrusion under conditions of recent pumping was determined.

In 1986, average water levels throughout the Atlantic City 800-foot sand were below sea level except within about 4 mi of the edge of the overlying confining unit (fig. 27). A large regional cone of depression had formed in response to pumping and was centered on the immediate Atlantic City vicinity. Water levels were nearly 80 ft below sea level near Margate City and Ventnor City. Water levels were 35 ft below sea level at Stone Harbor and remained below sea level throughout peninsular Cape May County. To the northeast, toward Ocean County, water levels were below sea level south of Ship Bottom. These water levels were considerably lower than prepumping water levels (fig. 24). From Avalon north to the Great Bay where the Mullica River discharges, reported prepumping water levels ranged from 19 to 24 ft above sea level, and ground water flowed from wells at many locations (Woolman, 1895, p. 63-96; Zapecza and others, 1987). By 1986, average water levels had declined by more than 80 ft near Atlantic City, by about 64 ft near Avalon, and by about 40 ft near the Great Bay. Further from the regional cone center, the total decline was not as great. In Wildwood, the water levels had declined by 40 ft.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

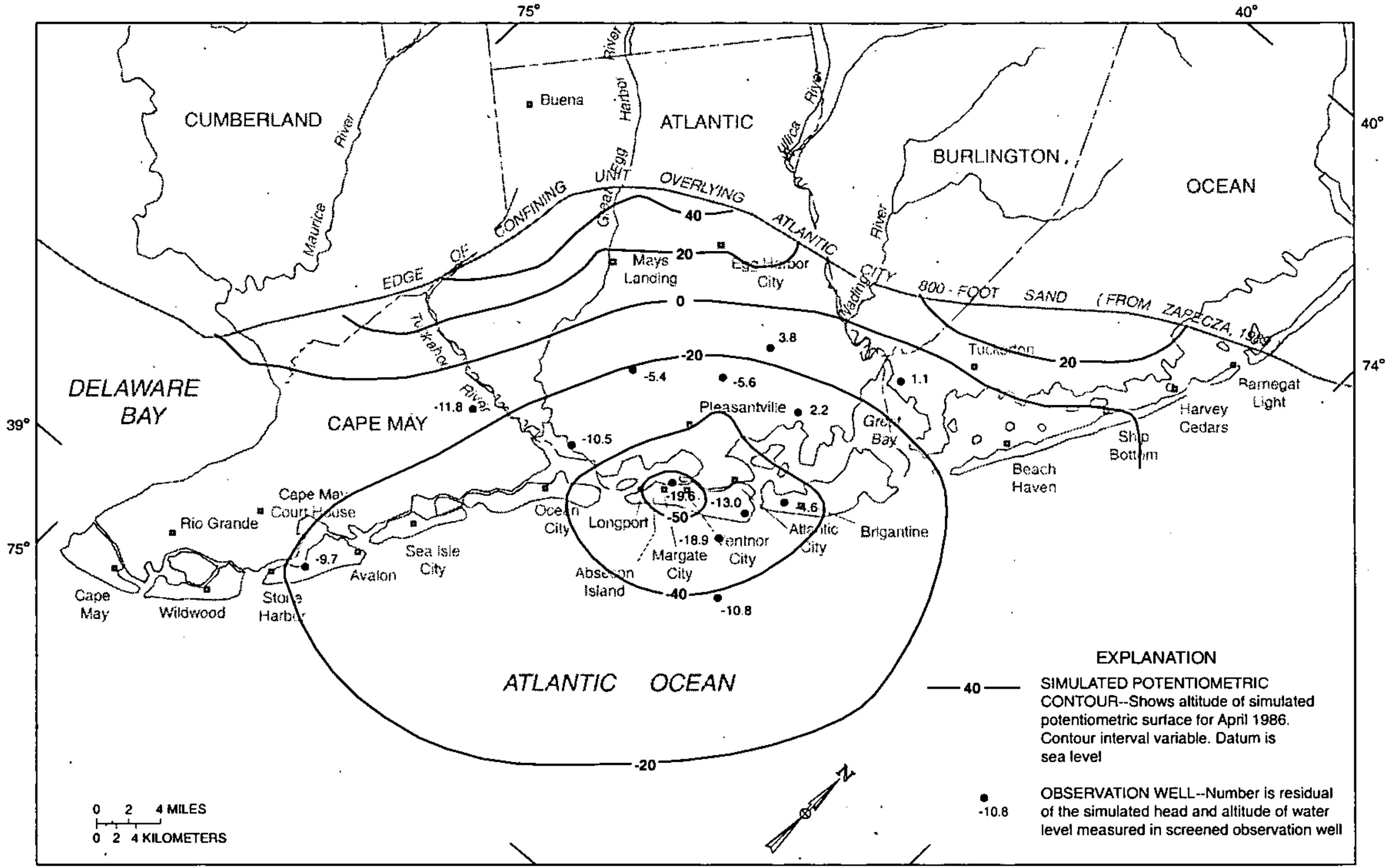
Figure 27. Average 1986 potentiometric surface of the Atlantic City 800-foot sand, New Jersey.

Under recent (1986) pumping conditions, as under prepumping conditions, ground water continues to flow into the confined Atlantic City 800-foot sand as deep horizontal regional flow contributed from the unconfined aquifer or shallow flow system in areas updip from the edge of the overlying confining unit. By 1986, however, the water-level gradient has changed significantly. Assuming that the prepumping water level was 24 ft near Atlantic City, the gradient between Egg Harbor City and Atlantic City under prepumping conditions was about 26 ft over a distance of about 17 mi, or 0.00029. The water-level gradient under recent conditions is 92 ft over 17 mi, or 0.001. During prepumping conditions, ground water flowed laterally from recharge areas at the edge of the confining unit to discharge areas offshore at the freshwater-saltwater interface. Under recent conditions, recharge from the shallow system beyond the confining-unit edge flows laterally toward the pumping centers and also from offshore areas, from the zone of diffusion, toward the pumping centers. As water levels decline in offshore areas, the equilibrium condition between fresh and salty water changes. Any water-level decline permits the flow of salty water into aquifer pores previously filled with freshwater.

Simulated water levels using annual minimum pumping rates differ from measured water levels of April 1986 by less than 15 ft everywhere, except at two locations (fig. 28). At observation well 1-711, located 1.9 mi offshore of Atlantic City, the simulated water level is 19 ft higher than the measured water level. At observation well 1-702 in Margate City, the simulated water level is 20 ft higher than the measured water level. Observation well 1-702 is within the pumping center of communities on Absecon Island that pump at high rates, and the computer-model discretization of the area cannot represent water levels near pumped wells with great accuracy. In addition, the simulation did not reach an equilibrium, and ground water continued to flow into storage at the end of the simulated period of annual minimum pumping rates. If the simulated stress period had been continued until a new equilibrium was reached, the water levels would likely have declined and compared more closely to measured water levels. Throughout the modeled area, simulated water levels are generally higher than measured water levels at observation wells using annual minimum pumping rates except at observation wells 1-180, 1-40, 1-706, and 29-462, where simulated water levels are 2, 4, 3, and 1 ft lower than measured water levels, respectively. Water levels near Ship Bottom during April 1986 are lower than average 1986 water levels because some wells in the Ship Bottom area were out of service during part of 1986, but not during January-April 1986.

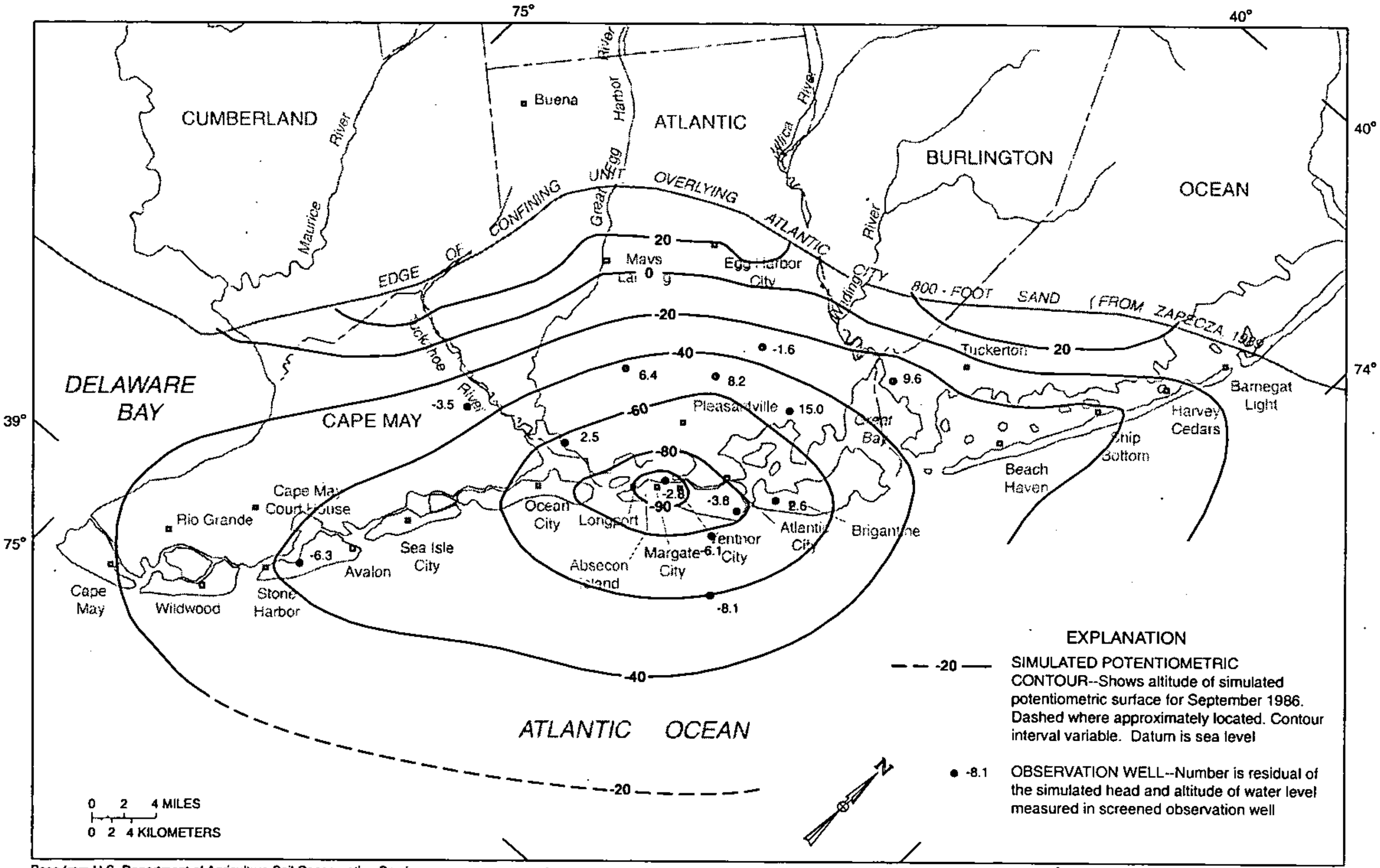
Simulated water levels using annual maximum pumping rates differ from measured water levels at observation wells by 10 ft or less at all locations except at well 1-180, where the measured water level is 15 ft higher than the simulated water level (fig. 29). At seven observation wells, simulated water levels are lower than measured water levels, and at six observation wells, simulated water levels are higher than measured water levels.

The regional cone of depression remains centered around Absecon Island under annual maximum and minimum pumping conditions. Water levels decline about 40 ft during April-September 1986 on Absecon Island and between 20 and 40 ft during the same period throughout much of the barrier islands. The orientation of the regional cone of depression changes during the seasonal change in pumpage. The gradient increases at a greater rate to the southwest, through the coastline of Cape May County, than in any other direction from Absecon Island. The hydraulic gradient also increases perceptibly northeastward, through the barrier islands of Ocean County. The hydraulic gradient is greater during the summer season than during the off-season in inland (northwestern) and offshore (southeastern) directions within 15 mi of Atlantic City; at a distance of about 15 mi, however, the hydraulic gradients are similar under annual maximum and minimum pumping conditions. During both seasonal pumping conditions, the hydraulic gradient remains steepest in the area between the edge of the overlying confining unit and the coast, particularly near Absecon Island. This condition shows that a significant amount of ground water flows laterally from the water table beyond the edge of the confining unit to pumping centers near the



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 28. Simulated potentiometric surface of the Atlantic City 800-foot sand, New Jersey, using annual minimum pumping rates (April 1986) and residuals of the simulation.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 29. Simulated potentiometric surface of the Atlantic City 800-foot sand, New Jersey, using annual maximum pumping rates (September 1986) and residuals of the simulation.

coast. Throughout the year, ground water flows from all directions—from the inland water table and from offshore areas—toward the pumping centers near the coast.

Since the late 1800's, salty water has been moving toward the pumping centers in response to pumping of the Atlantic City 800-foot sand; however, chloride concentrations are only slightly greater than those originally reported at some locations in the Atlantic City area (Barksdale and others, 1936, p. 114-125) and in Cape May County (Gill, 1962, p. 96-108) and have not compromised potability.

The NJDEP and area water users are concerned about the likelihood of intrusion of salty, unpotable water into the supply wells tapping the Atlantic City 800-foot sand. Although previous researchers have stated that the idealized freshwater-saltwater interface (defined herein as the location where chloride concentrations of ground water equal 10,000 mg/L) is between 7 mi (Thompson, 1928, p. 96-118; Barksdale and others, 1936, p. 117-125) and 50 mi offshore (Meisler, 1984, p. 6, fig. 3) of Atlantic City, chloride concentrations greater than 250 mg/L exceed USEPA Secondary Drinking Water Standards, and can impart a salty taste or cause corrosion of pipes. This water may be considered unpotable by many water users because of the salty taste. An examination of measured chloride concentrations in Atlantic County and offshore and in Cape May County permits an estimation of the location of the 250-mg/L isochlor. This estimated location, used in conjunction with a model of ground-water flow, permits an estimate of the traveltime of ground water from the 250-mg/L isochlor to supply wells near Atlantic City.

The chloride concentration of 77 mg/L measured at well 1-710 located 5.3 mi offshore of Atlantic City indicates that well 1-710 is within a zone of mixing or diffusion that extends landward from the freshwater-saltwater interface. Chloride concentrations greater than 250 mg/L have been measured in Cape May County, but no concentration greater than 77 mg/L has been measured near Atlantic City.

The distances over which the range of chloride concentrations common to both areas can be compared and the relations between the two rates of change of concentration can be used to estimate the location of the 250-mg/L isochlor. In Cape May County in 1958-60 (Gill, 1962, p. 103), chloride concentrations increased from 14 to 77 mg/L over 3.04 mi and from 77 to 250 mg/L over 3.38 mi. Offshore of Atlantic City in 1985, the chloride concentration increased from 15 mg/L at well 1-711 to 77 mg/L at well 1-710; the distance between these wells is 3.4 mi. The distance required for the increase in chloride concentration from 14 or 15 mg/L to 77 mg/L is greater offshore of Atlantic City, by a factor of 1.12, than in Cape May County. Thus, the factor 1.12 can be multiplied by the distance between the 77-mg/L isochlor and the 250-mg/L isochlor in Cape May County (3.38 mi) to estimate a distance of 3.78 mi between these isochlors offshore of Atlantic City. Thus, the total distance to the 250-mg/L isochlor offshore of Atlantic City is 5.30 mi (distance to the 77-mg/L isochlor) plus 3.78 mi (distance from the 77- to the 250-mg/L isochlor), or about 9 mi (fig. 19).

This 9-mile distance is large enough that saltwater intrusion into the public-supply wells near Atlantic City from offshore lateral flow is most likely a long-term concern rather than an immediate one. The average current hydraulic gradient between Atlantic City and well 1-710 is 15 ft over 5.3 mi, or 0.00053. If a simplified average ground-water velocity in the offshore part of the Atlantic City 800-foot sand is estimated to be about 39 ft/yr on the basis of hydraulic conductivity (50 ft/d), simulated hydraulic gradient, and porosity (0.25), then water near offshore well 1-710 would reach Atlantic City in 717 years. This estimate considers only advective movement and neglects the effects of a moving freshwater-saltwater interface and the potential for salty, denser water to move at a different rate at the top than at the bottom of the Atlantic City 800-foot sand. Nonetheless, even if the estimate is too long by an order of magnitude, saltwater intrusion into Atlantic City area wells still seems to be several decades away. The concern for saltwater intrusion into public-supply wells in the Stone Harbor area, however, is greater. Public-supply wells in Stone Harbor are only about 4 mi from the estimated location of the 250-mg/L isochlor near Wildwood during 1958-60 (Gill, 1962). In addition, the 250-mg/L isochlor as drawn in figure 19 lies about 6 mi offshore of Avalon. Ground water flows toward the public-supply wells from both offshore directions, east and southeast of Cape May County, and from the direction of the Delaware Bay. The overlying confining unit is assumed to truncate under the Delaware Bay and would thus provide a direct connection between saltwater in the Delaware Bay and water in the Atlantic City 800-foot sand. The exact location of the confining-unit truncation is not known, but if the truncation is near the bayside shore of Cape May County and if permeability of the bay floor is not extremely low, then saltwater can flow from the Delaware Bay toward public-supply wells in Cape May County.

Flow Budget

Under conditions represented by average 1986 water levels and pumping rates, ground water flows into the Atlantic City 800-foot sand from all directions toward the pumping centers (fig. 30). Most of the water flows laterally to pumping centers from updip areas of the water table beyond the extent of the overlying confining unit, but ground water also flows from offshore areas and vertically toward the pumping centers. Under 1986 conditions, 13.6 Mgal/d flows laterally from updip areas beyond the edge of the confining unit, and only 0.4 Mgal/d flows toward updip areas; this contrasts markedly to prepumping conditions, under which 3.9 Mgal/d flows to downdip confined areas and 2.3 Mgal/d flows to updip unconfined areas (fig. 25). Pumpage of 20.9 Mgal/d under average annual recent conditions results in a total increased flow of 9.7 Mgal/d from areas beyond the confining-unit extent compared to prepumping conditions, as well as a decrease in flow to unconfined areas of 1.9 Mgal/d. The source of this flow is leakage from streams or diversion of ground water that under predevelopment conditions would have discharged to streams. In particular, ground water from the Atlantic City 800-foot sand under prepumping conditions flows toward the Mullica River and toward the Tuckahoe River near the edge of the confining unit. Under 1986 conditions, flow is away from the rivers. Near the presumed edge of the confining unit under the Delaware Bay, ground water flows toward the bay under prepumping conditions, but flow is toward pumping centers from the edge of the confining unit under the Delaware Bay by 1986. Under the Delaware Bay, the sediments of the Atlantic City 800-foot sand are considered to be in contact with salty bay water. Thus, the analysis indicates that salty water is flowing toward pumping centers and may be approaching the wells in Stone Harbor and in Cape May Courthouse that tap the Atlantic City 800-foot sand wells near to the Delaware Bay. The edge of the confining unit under the Atlantic Ocean in Ocean County is a discharge area under prepumping conditions; under 1986 conditions, ground water continues to discharge from the Atlantic City 800-foot sand in this area, but the gradient is reduced. This is another area where salty water may be in hydraulic contact with the sediments of the Atlantic City 800-foot sand and where salty water has the potential to flow toward wells tapping the aquifer if water levels continue to decline. Under prepumping conditions, ground water flows offshore, toward the freshwater-saltwater interface, at a rate of 1.2 Mgal/d; however, under 1986 conditions, ground water flows from offshore areas at an average rate of 2.2 Mgal/d; so that salty water from the zone of diffusion is flowing toward pumping centers. Vertical flows to and from overlying sediments have also reversed directions and increased under 1986 conditions, from a prepumping recharge rate of 0.1 Mgal/d and discharge rate of 1.9 Mgal/d to a 1986 recharge rate of 3.5 Mgal/d and discharge rate of only 0.2 Mgal/d. Much of the Atlantic City 800-foot sand underlying interstream areas is a discharge area under prepumping conditions; however, only areas very near to the confining-unit edge are discharge areas under 1986 conditions. At the end of the simulation of average 1986 conditions, 0.8 Mgal/d flows out of storage to meet pumping demands. Total flow in 1986, 21.6 Mgal/d, is increased from total prepumping flow, 5.4 Mgal/d, because of the pumpage rate of 20.9 Mgal/d and flow from storage of 0.8 Mgal/d, ± 0.1 Mgal/d due to rounding error.

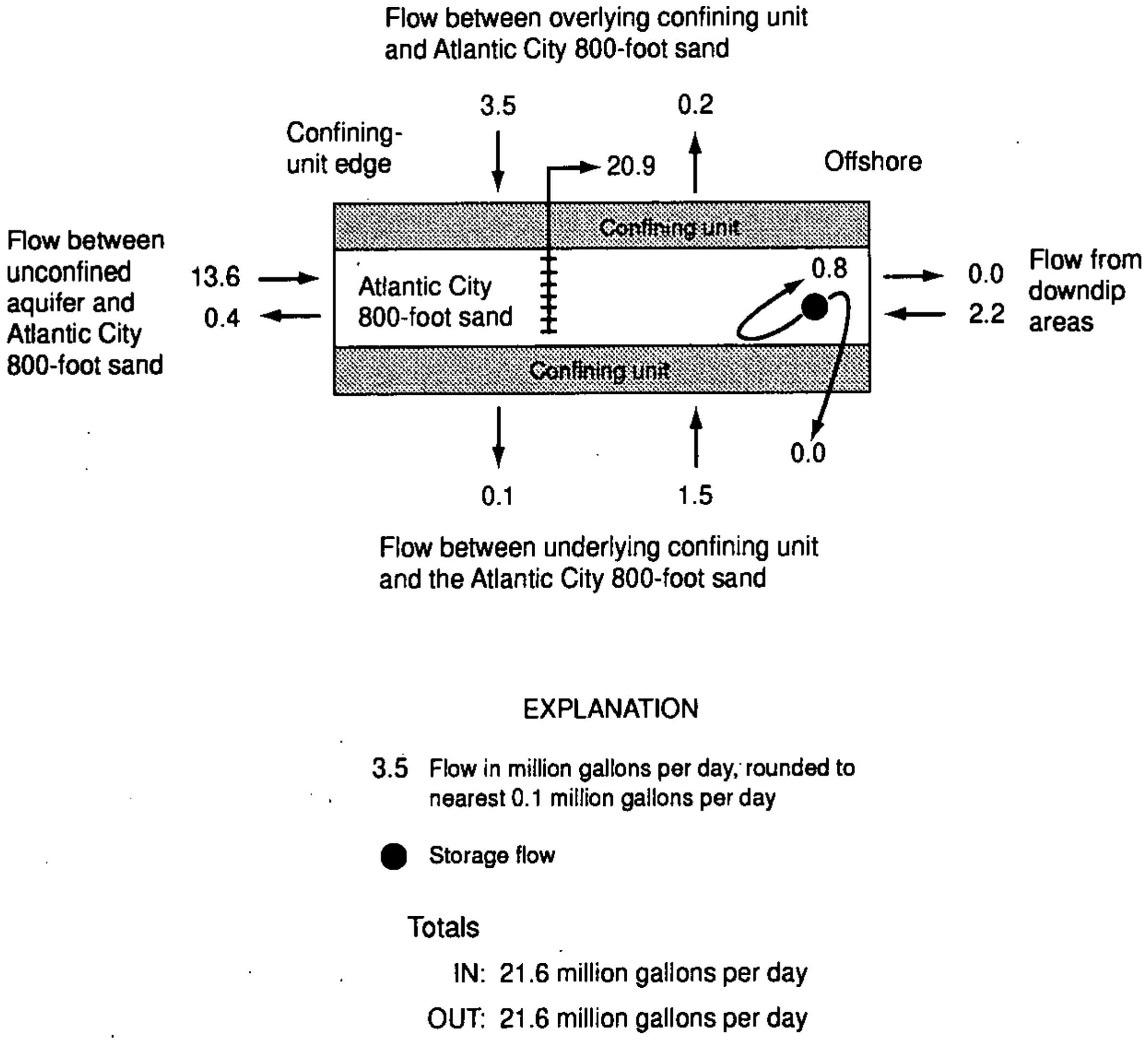


Figure 30. Flow budget for the Atlantic City 800-foot sand, New Jersey, under average 1986 conditions.

Effects of Hypothetical Ground-Water-Supply Alternatives, 1986-2040

The model of ground-water flow in the Atlantic City 800-foot sand was used to evaluate effects of four hypothetical water-use/water-supply alternatives on ground-water levels and flow by the year 2040. Each alternative presents a possible supply scenario that natural-resource managers and planners, as well as purveyors, other water users, and citizens, could use to evaluate effects of anticipated growth in ground-water demand. Water-level decline, flow-budget changes, potential for saltwater intrusion, and data-collection networks that could facilitate monitoring for saltwater intrusion are discussed for each alternative.

Pumping Rates and Distribution

Responses of the lower Kirkwood Formation ground-water flow system to various ground-water withdrawal (pumpage) rates and locations during 1986-2040 were simulated in the four following ground-water supply alternatives: (1) continuation of constant average 1986 pumpage until 2040; (2) increase of 1986 pumpage rates by 35 percent by 2040; (3) relocation of the 35-percent pumpage increase predicted by 2040 for the coastal communities on Absecon Island, the Brigantine area (on the barrier island north of Atlantic City), and Ocean City to well fields in more inland areas in Atlantic County; and (4) a decrease in predicted pumpage from the Atlantic City 800-foot sand as the pumpage-rate increase predicted for the communities on Absecon Island, the Brigantine area, and Ocean City is extracted from the Kirkwood-Cohansey aquifer system. In this discussion, alternative 1 is referred to as the "constant-rate alternative," alternative 2 as the "increased-rate alternative," alternative 3 as the "relocation alternative," and alternative 4 as the "decreased-growth alternative." The anticipated increases in pumpage rates are based on the average population growth predicted for the study area (Robert Kecskes, and Walter Olivant, New Jersey Department of Environmental Protection, written commun., 1988). The pumping rates are increased from average 1986 rates, and seasonal changes in pumpage are not simulated.

In the constant-rate alternative, responses of the Atlantic City 800-foot sand to the continuation of average 1986 pumpage rates to January 1, 2040, are evaluated. All other flow-model input data used in the calibrated transient simulation are extended to 2040.

In the increased-rate alternative, responses of the Atlantic City 800-foot sand to a gradual 35-percent increase of 1986 pumpage rates during 1986-2040 are evaluated. Pumpage rates for all wells simulated in all aquifers are increased by equal percentages. The 1986 averaged pumpage rates are increased by 11.67 percent between December 31, 1986, and January 1, 2005; by 23.33 percent between January 1, 2005, and January 1, 2025; and by 35 percent between January 1, 2025, and January 1, 2040.

In the relocation alternative, responses of the Atlantic City 800-foot sand to the increased 1986 pumpage rates of 35 percent by 2040 are reevaluated after a redistribution of pumpage locations. The predicted increased pumping rates of Ocean City and of the barrier-island communities of Atlantic County—including Longport, Margate City, Ventnor City, Atlantic City (all on Absecon Island), and Brigantine—are relocated to more inland areas. The above-mentioned communities pump much of the increase in water (37 percent, 2.7 Mgal/d) withdrawn from the Atlantic City 800-foot sand. In this alternative, 1986 pumping rates are simulated for 1986-2040 at the above-mentioned communities. The predicted increase in pumpage rates is applied to only two locations about 10 mi inland from the coast in Atlantic County, near the Great Egg Harbor River and near the Mullica River. This hypothetical relocation of the increased pumpage is an exercise to evaluate the responses of the flow system to pumpage as distance from the brackish water is increased; the exact location of the simulated withdrawals is not important. No specific location of an area suitable to constructing additional wells is advocated by these simulations. All other data used for simulating the relocation alternative is identical to data used for the increased-rate and constant-rate alternatives.

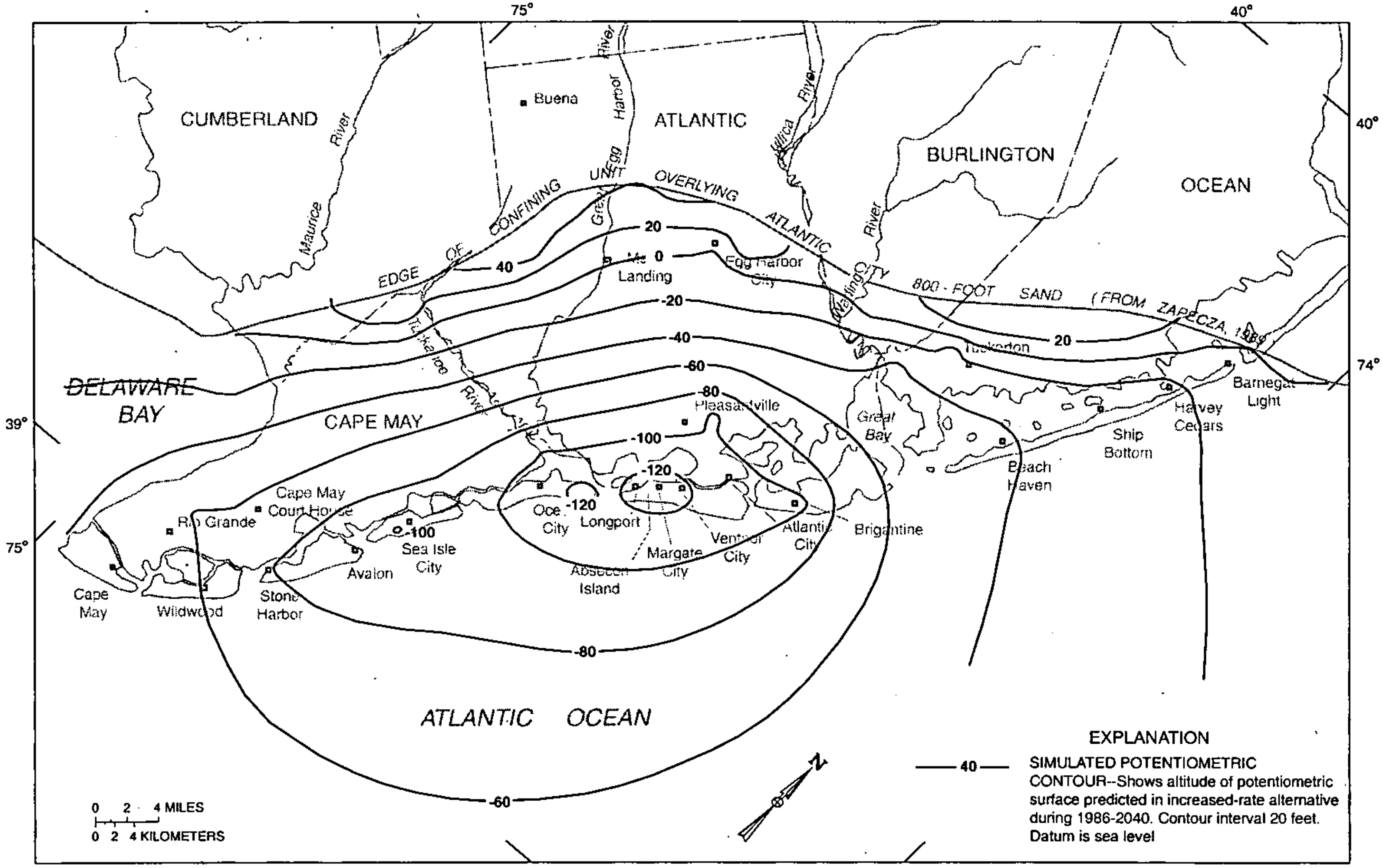
In the decreased-rate alternative, responses of the Atlantic City 800-foot sand to increased 1986 pumpage rates of 35 percent by 2040 are evaluated after a redistribution of some of the withdrawals to another aquifer. The predicted increase in pumpage during 1986-2040, for Ocean City and for the barrier-island communities of Atlantic County, is relocated to inland areas and to the Kirkwood-Cohansey aquifer system. The simulated inland-area locations are identical to those described for the relocation alternative. Predicted pumping-rate increases in all other areas of the Atlantic City 800-foot sand are identical to those in the increased-rate alternative.

Water Levels and Flow Directions

In response to withdrawals under the constant-rate alternative, water levels continue to decline slightly, generally less than 2 ft, throughout the Atlantic City 800-foot sand by 2040; however, the shape of the regional cone of depression is virtually unchanged from that of average 1986 conditions, and the water levels and gradients are nearly identical to those shown in figure 27.

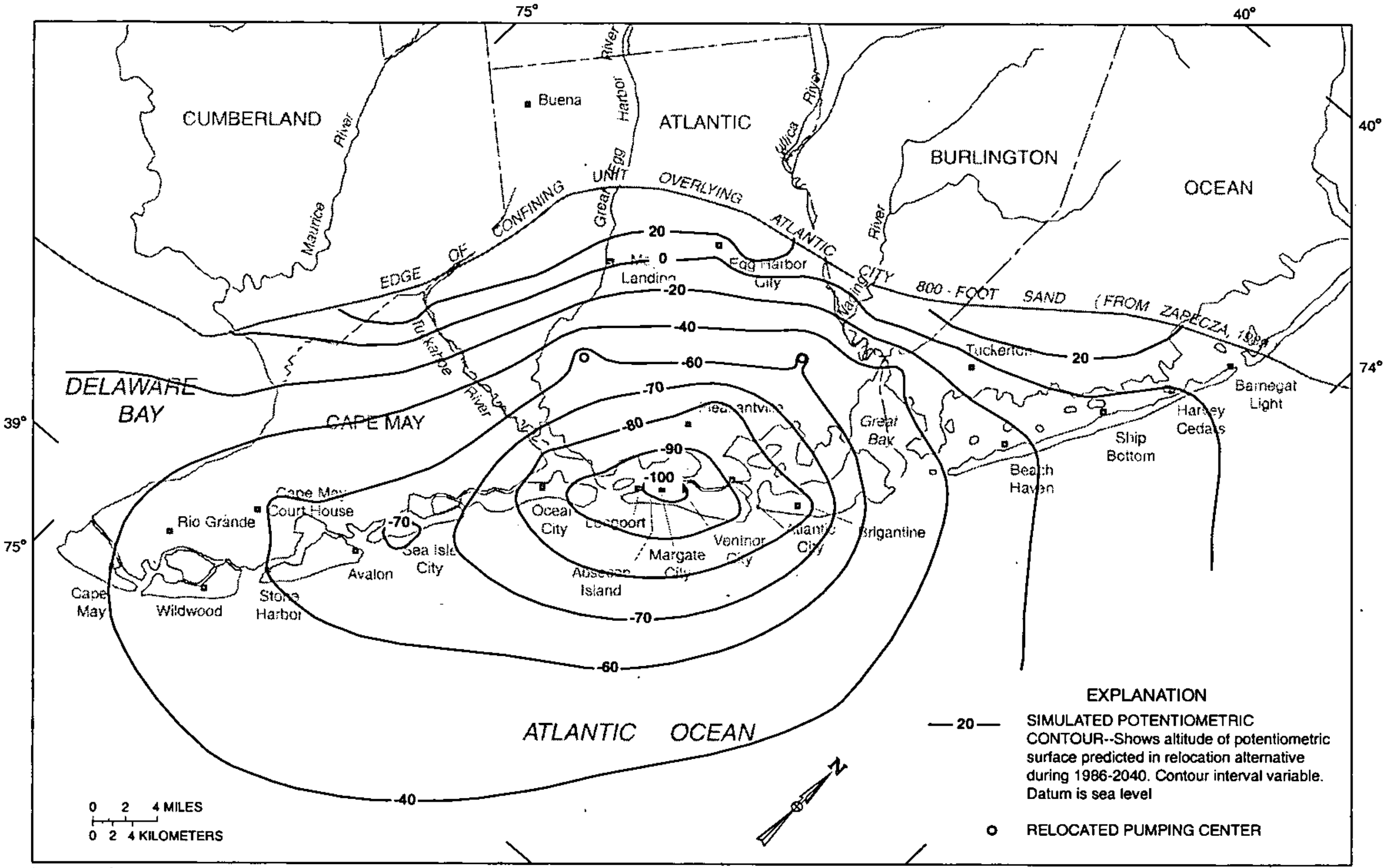
In the increased-rate alternative, average annual water levels in the Atlantic City 800-foot sand decline as much as 50 ft by 2040 (fig. 31). Water levels decline more than 40 ft throughout all coastal communities in Atlantic County, in Cape May County north of Wildwood, and to a distance of 5 mi inland of the coast. In the offshore direction, water-level declines of greater than 25 ft extend to a distance of more than 10 mi. Water levels generally decline more than 20 ft as far away as Egg Harbor City. Water levels decline 40 ft in the Stone Harbor area, about 25 ft as far south as Cape May Point, and about 30 ft as far north as Ship Bottom, in Ocean County. Overall, water levels decline significantly in the increased-rate alternative throughout most of the area of the Atlantic City 800-foot sand; and, in communities near Atlantic City such as Margate City, Ventnor City, Ocean City, and Brigantine, the depth to water increases by more than 50 ft by 2040. The hydraulic gradient also increases throughout the Atlantic City 800-foot sand. The hydraulic gradient is greater near the edge of the overlying confining unit than under average 1986 conditions, indicating an increase in flow from the water table to the Atlantic City 800-foot sand. The gradient between the offshore observation wells and Atlantic City also increases, indicating that flow rates of salty water offshore toward coastal pumping centers also increases.

In the relocation alternative, water levels decline as much as 45 ft from 1986 to 2040 in the vicinity of the hypothetical well fields 10 mi inland of the coast (fig. 32). Water levels decline 25 to 30 ft throughout much of the inland area between the Atlantic County barrier islands and 10 mi inland. Water levels in most of the coastal areas decline 20 to 25 ft. The water-level declines in much of the area are significantly less than those produced by the increased-rate alternative. In the coastal area from Stone Harbor to Atlantic City, simulated water levels are as much as 30 ft higher because of the relocation of the 35-percent increase of pumpage. Compared to the increased-rate alternative, water levels are as much as 15 ft higher for about 20 mi offshore of Atlantic City, and water levels are 20 ft higher in the Ship Bottom area. In the relocation alternative, the hydraulic gradient is increased greatly between the confining-unit edge and the inland hypothetical well fields compared to the constant-rate alternative. The gradient increase between the confining-unit edge and the coastal communities is less than the increase simulated during the increased-rate alternative. The gradient increase between the offshore observation wells and the coastal communities of Atlantic County and Cape May County also is less than the gradient increase simulated during the increased-rate alternative, resulting in reduced flow velocities and reduced rate of movement of the 250-mg/L isochlor toward water-supply wells.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 31. Simulated water levels in the Atlantic City 800-foot sand, New Jersey, in the increased-rate alternative, 1986-2040.



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 32. Simulated water levels in the Atlantic City 800-foot sand, New Jersey, in the relocation alternative, 1986-2040.

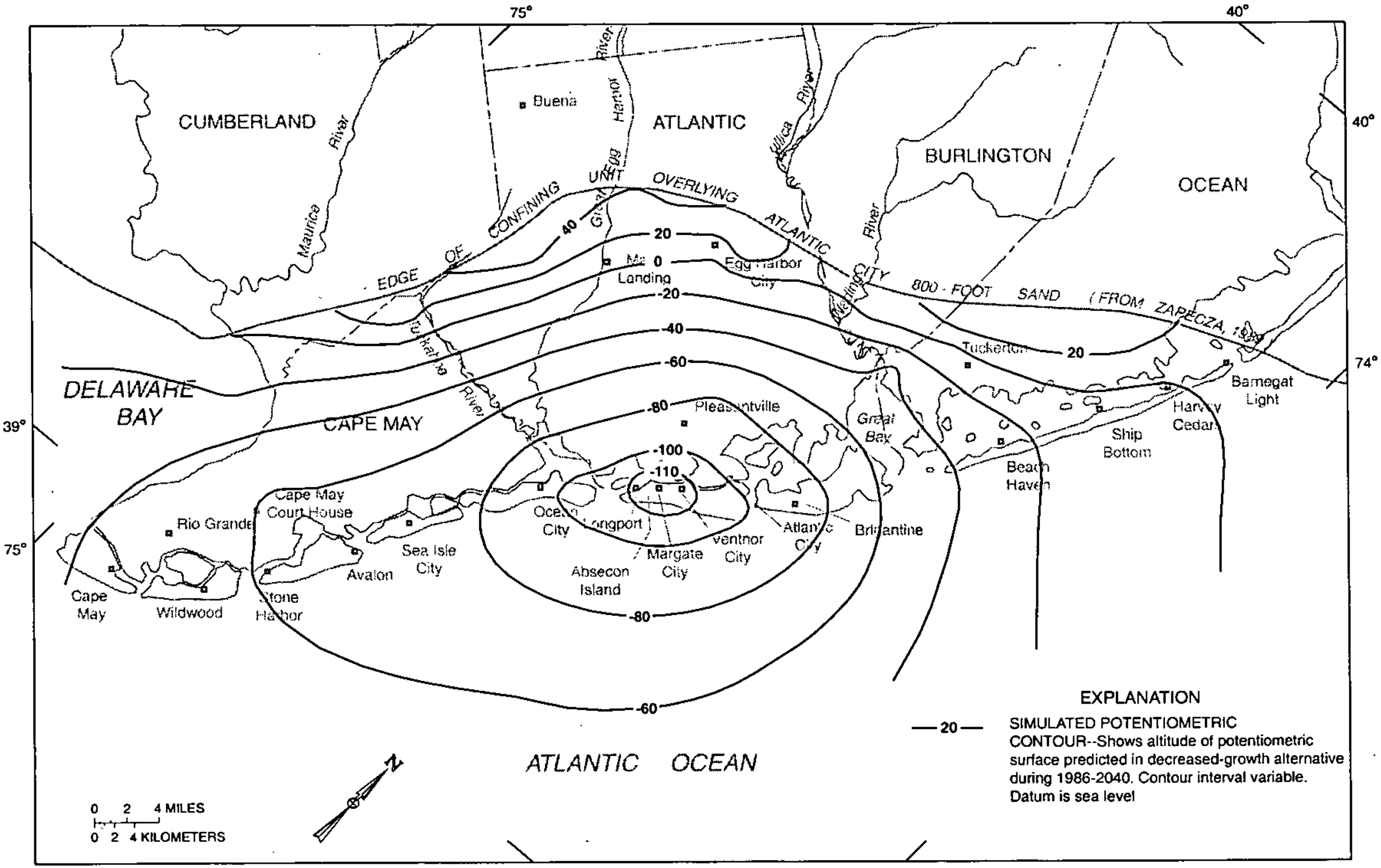
Water levels in the decreased-growth alternative are about equal to water levels in the relocation alternative in Cape May County south of Ocean City, but they are generally 10 ft lower than water levels in the relocation alternative in areas within a 10-mi radius of Atlantic City (fig. 33). This condition demonstrates that pumpage in Cape May County affects water levels in Atlantic County and vice versa because pumpage-rate increases can affect water levels regionally in a large confined aquifer system. Although the quantity of pumpage is important to consider when evaluating effects on a confined aquifer system, location of the pumping also is important. In the relocation alternative, a greater quantity of water is pumped from the Atlantic City 800-foot sand than in the decreased-growth alternative; however, the relocated pumpage intercepts much of its induced recharge from updip areas and has a smaller effect on downdip water levels than the decreased-growth alternative, in which pumpage is increased in downdip (coastal) areas and the effects of the pumping spread regionally along the coast and in more of a radial pattern. Water levels within 5 mi offshore of Atlantic City generally are 10 ft lower than water levels in the relocation alternative at the same locations. The lower water levels create a larger gradient and permit greater movement of salty water toward coastal water-supply wells compared to the relocation alternative. Water levels in the decreased-growth alternative generally are lower than water levels in the constant-rate alternative and higher than water levels in the increased-rate alternative. Average annual water levels decline as much as 40 ft below average 1986 water levels. Water levels between Stone Harbor and Atlantic City generally are 20 ft higher than water levels in the increased-rate alternative. The response of the unconfined aquifer to the increased pumpage is not evaluated with this model; however, the increased pumpage would likely result in decreased ground-water discharge to streams and increased leakage from streams to the aquifer.

Flow Budget

The flow budget of the Atlantic City 800-foot sand changes to varying degrees in response to the various water-supply alternatives. In response to increased pumping of the Atlantic City 800-foot sand, most of the increased flow (about 67 percent) comes into the Atlantic City 800-foot sand as lateral flow from the unconfined aquifer in updip areas beyond the edge of the overlying confining unit. Vertical leakage through the overlying confining unit accounts for about 20 percent of the flow in each pumping alternative, as diffuse flow throughout the extent of the Atlantic City 800-foot sand. Flow from offshore directions increases also, but the increase is smaller than the increase in lateral flow from the unconfined aquifer and the increase in vertical leakage from the confining unit overlying the aquifer; generally, flow from offshore makes up less than 10 percent of the flow toward pumping centers. Vertical leakage through the underlying confining unit also increases, but the increase is small.

The greatest increase in lateral flow past the confining-unit edge, from 13.6 Mgal/d under 1986 conditions to 19.2 Mgal/d by 2040, is in the relocation alternative. This increase is a result of the greater drawdown at the hypothetical inland pumping centers. The lateral flow past the confining-unit edge also increases greatly during the increased-rate alternative, from 13.6 Mgal/d to 18.8 Mgal/d. Increased lateral flow would result in decreased flow to surface-water bodies, principally streams, in the unconfined system and more flow of salty water toward pumping wells if the salty water of the Delaware Bay is in contact with the freshwater of the Atlantic City 800-foot sand at or near the confining-unit edge. In the decreased-rate alternative, less increase in lateral flow takes place compared to the two alternatives that involve increased pumpage from the Atlantic City 800-foot sand. In the constant-rate alternative, lateral flow is nearly the same for 2040 as for 1986.

In alternatives involving increased pumpage from the Atlantic City 800-foot sand, relocation of the pumping centers further inland results in less flow of salty water toward the pumping centers, either from offshore directions or from the direction of the Delaware Bay, than if pumping centers near the coast continue to withdraw more water. If growth in water demand is



Base from U.S. Department of Agriculture Soil Conservation Service, 1:250,000, 1980. Universal Transverse Mercator Projection, Zone 18

Figure 33. Simulated water levels in the Atlantic City 800-foot sand, New Jersey, in the decreased-rate alternative, 1986-2040.

less than anticipated, or if increased water demand can be supplied by other sources or other aquifers, then the flow from saltwater areas toward shore will also be reduced compared to additional pumping near the coast but increased compared to 1986 conditions.

Ground-Water Velocities From Saltwater Areas Toward Pumping Centers

The velocity of ground water at the estimated position of the 250-mg/L isochlor can be computed by use of model output. The distance that the ground water would travel from the 250-mg/L isochlor toward public-supply wells can then be computed by applying the velocity over the time interval of the simulated water-supply alternatives (54 years). Such an analysis was done for pumping centers near Atlantic City and near Stone Harbor.

Assumptions made during the computations of distance traveled under each simulated pumpage alternative are the following:

- The salt in water at the 250-mg/L isochlor is transported primarily by advective flow at the computed velocity across the area through which flow occurs (fig. 19).
- The discharges used in the velocity computation are taken from water-budget output from the model at the end of each alternative.
- The porosity is 0.25 offshore of Atlantic City and 0.20 at Wildwood, near Stone Harbor. The porosity is increased offshore because of lithologic variations discussed previously.
- The area through which flow would occur is 3,300 ft (width) by 100 ft (thickness) at the model cell about 10 mi offshore of Atlantic City (row 30, column 29 in fig. 20). The area through which salty water would flow toward Stone Harbor wells is 9,900 ft wide by 135 ft thick at the model cell about 4 mi south of Stone Harbor (row 28, column 5 in fig. 20).

The velocity is computed by

$$\bar{V} = \frac{\frac{Q}{A}}{\Theta} ,$$

where $\bar{V}$ is average velocity,
Q is discharge through model cell face,
A is model cell area through which lateral flow occurs, and
Θ is porosity.

The distance traveled is then computed as

$$d = \bar{V} \bullet t ,$$

where $\bar{V}$ is average velocity and
t is time (54 years).

The distance traveled toward Atlantic City from offshore by 2040 is only a small fraction of the distance to the salty water, in any of the simulated alternatives. In the increased-rate alternative, salty ground water travels 1,000 ft toward Atlantic City but would remain about 8.8 to 9.8 mi offshore. In the relocation alternative, the salty ground water travels about 900 ft; in the decreased-growth alternative, it travels about 800 ft; and in the constant-rate alternative, it travels about 800 ft. By this analysis, the threat of saltwater intrusion to Atlantic City wells appears to be a concern for the distant future, far beyond the water-supply planning end date of 2040. The offshore USGS observation wells could provide an early warning of encroachment, and data from the wells could be used to verify the results of this flow-modeling analysis. The velocity and travel-distance analyses are limited by the assumption of advective flow and by the extent of the model, which does not extend to the saltwater position.

The maximum simulated distance that salty water travels toward the Stone Harbor wells from 4 mi south of Stone Harbor is about 1,900 ft during 1986-2040 (in the increased-rate alternative). The salty water is not predicted to reach the Stone Harbor wells during the 54-year planning period. However, because the assumption of advective flow limits the analysis, it is possible to underestimate the distance by an order of magnitude. If this were so, then the salty water would reach or be very near the Stone Harbor wells by 2040. The same statement can be made for travel distance in the other predictive alternatives (1,800 ft for relocation, 1,700 ft for decreased growth, and 1,500 ft for constant rate). The possibility of the arrival of salty water at Stone Harbor wells within the 54-year planning period indicates that additional observation wells would be useful for monitoring chloride concentrations in ground water between Stone Harbor and the nearest 250-mg/L isochlor position, near Wildwood City, to serve as the early warning system for the Stone Harbor wells.

In summary, although saltwater is not likely to reach public-supply wells in the Atlantic City area by 2040, and is unlikely to reach the Stone Harbor wells, saltwater will continue to move toward the pumping centers as long as pumping continues. The analysis of the predicted flow conditions lacks consideration of the density effects of saltwater on the flow field; neither does the modeled area extend to natural boundaries. To do either of these things would require both greatly increased computer modeling effort and much more data to describe offshore conditions and historical sea levels. These analyses were beyond the objectives of this study. The analysis presented here does provide information that could be used to design a chloride-monitoring network to protect the freshwater supply.

SUMMARY AND CONCLUSIONS

The regional, confined Atlantic City 800-foot sand is the principal source of water supply to coastal communities in southern New Jersey. In response to extensive use of the aquifer, an average pumpage of 20.85 Mgal/d in 1986, water levels of the Atlantic City 800-foot sand have declined to about 100 ft below sea level near Atlantic City (predevelopment water levels were about 20-25 ft above sea level) and are below sea level throughout the coastal areas of southern New Jersey. This condition permits the lateral movement of saltwater from offshore areas of the Atlantic City 800-foot sand toward pumping centers and public-water-supply wells.

The Atlantic City 800-foot sand consists mostly of medium- and coarse-grained sand and shell material, ranges in thickness from 40 ft to 200 ft, and extends through parts of Ocean County, Burlington County, Atlantic County, Cape May County, and Cumberland County. The Atlantic City 800-foot sand is overlain by a confining unit that consists of clay and silt and is underlain by a clay confining unit. The Atlantic City 800-foot sand and both confining units extend offshore at least 5.3 mi to the southeast and are considered to extend to the continental slope. Water samples from two observation wells, drilled 1.9 and 5.3 mi offshore, indicate that freshwater extended beyond 5.3 mi offshore because the chloride concentration at that point was 77 mg/L in 1985. The sediments become more silty, and so less conductive, in the offshore direction. The hydraulic conductivity of the Atlantic City 800-foot sand ranges from 38 to 320 ft/d, based on aquifer-test analysis; the storage coefficient ranges from 0.0001 to 0.00001.

Before pumping from the Atlantic City 800-foot sand began, ground water flowed into the sand at a rate of about 4 Mgal/d as lateral flow contributed from the unconfined aquifer beyond the updip edge of the overlying confining unit. Vertical flow also leaked at small rates from interstream areas through the overlying confining unit and into the Atlantic City 800-foot sand. Ground water flowed laterally downdip, to the southeast or to the southwest, to discharge at areas overlain by lower reaches of large streams and by bays and by the ocean. The aquifer contained saltwater at great distances offshore, as a result of sea-level changes over time. Water levels in the Atlantic City 800-foot sand ranged from about 50 ft above sea level to just above sea level in offshore areas. Ground water flowed above land surface from wells in the Atlantic City area.

Water levels declined during development in response to pumping. By 1986, in response to an average pumpage of 20.85 Mgal/d, water levels were below sea level in wells open to the Atlantic City 800-foot sand throughout the coastal areas, and in the observation well 5.3 mi offshore. Pumpage varies seasonally, and the pumpage during the summer is more than twice the pumpage during the winter, reflecting heavy water use in coastal resort areas during the summer season. Water levels during the 1986 summer season declined to 101 ft below sea level near Atlantic City and were at least 30 ft below sea level throughout the coastal communities. During the 1986 nonsummer season, water levels recovered by 10 to 30 ft in coastal areas, and the lowest water levels were 69 ft below sea level near Atlantic City. Ground water flows from all directions, including from offshore directions, toward pumping centers under current (1986) conditions.

Changes in the quality of water in the Atlantic City 800-foot sand have occurred as ground water has evolved chemically downdip, along the direction of flow. Generally, pH, bicarbonate alkalinity, and concentrations of sodium, chloride, and sulfate increase downdip. Water quality appears to have changed relatively little, except for chloride concentrations, in response to pumping. Historically, chloride concentrations reported in southern Cape May County have been as high as 1,510 mg/L and are likely the result of saltwater encroachment toward pumping centers as water levels decline. Chloride concentrations of water of the Atlantic City 800-foot sand are not high in the Atlantic City area, but chloride concentration does increase from 15 mg/L 1.9 mi offshore to 77 mg/L at 5.3 mi offshore of Atlantic City.

Results of a ground-water flow model simulation were used to quantitatively analyze the response of the Atlantic City 800-foot sand flow system to pumping and to evaluate potential saltwater intrusion under 1986 conditions, and conditions predicted during 1986-2040 for four hypothetical water-supply alternatives. Because of the great distances to natural limits, or boundaries, of the flow system, the quasi-three-dimensional finite-difference computer model was coupled to a regional-scale model of ground-water flow throughout the New Jersey Coastal Plain. The regional Coastal Plain model provided fluxes to the bottom and all lateral boundaries of the model of the Atlantic City 800-foot sand flow system. Constant heads, representing stream elevations, control the upper head-dependent flux boundary of the model of the Atlantic City 800-foot sand flow system. The variably spaced model grid includes cell areas as small as 0.4 mi^2 so that finer details can be represented near pumping centers. The grid spacing is expanded in the offshore direction so that the location of salty, undesirable water can be included in the modeled area. The model was calibrated to measured water levels, to ground-water discharges to surface water, and to premodeling concepts of the effects of stresses and boundary conditions on water levels, flow directions, and flow budgets. The differences between simulated and measured water levels are generally less than 15 ft. Ground-water discharges to surface water from the simulation agree closely with measured long-term average streamflows at lower stream reaches.

In response to simulated average 1986 pumpage of 20.85 Mgal/d from the Atlantic City 800-foot sand, ground water flows at increased rates from every direction toward coastal pumping centers. Lateral flow from the updip unconfined aquifer increases nearly 10 Mgal/d over prepumping conditions to 13.6 Mgal/d. About 3.5 Mgal/d leaks downward from overlying units, 1.5 Mgal/d leaks upward through underlying units, and 2.2 Mgal/d flows laterally from offshore directions. In addition, ground-water discharge to surface water is reduced over the extent of the Atlantic City 800-foot sand. Water levels decline to below sea level, not only throughout coastal areas, but also to 20 mi offshore of Atlantic City and to the edge of the confining unit under the Delaware Bay. The hydraulic gradient increases as drawdown near the coast increases, and salty water moves laterally toward pumping centers. The public-supply wells at Stone Harbor are closer, within 4 mi, to the position of undesirable salty water in Cape May County, which is represented by the 250-mg/L isochlor, than wells near Atlantic City, which are about 9 mi from the 250-mg/L isochlor offshore. The Atlantic City 800-foot sand is a regionally extensive confined aquifer, however, and pumpage near Atlantic City decreases water levels near Stone Harbor and vice versa.

Results of the ground-water flow model simulation are analyzed to determine the effects during 1986-2040 of four hypothetical water-supply alternatives on water levels, flow budget, and saltwater movement toward pumping centers. The four water-supply alternatives are (1) continued constant 1986 rate of pumpage, (2) an increase of 35 percent in pumpage rates at current locations, (3) relocation of the 35-percent increase at the largest pumping centers (near Atlantic city and near Ocean City) to inland locations, and (4) a relocation of the anticipated 35-percent pumpage increase for the largest pumpage centers to inland areas and to the Kirkwood-Cohansey aquifer system rather than the Atlantic City 800-foot sand.

In the first alternative (no change from 1986 pumping rates), little change occurs in water levels, the flow budget, or movement of salty water toward pumping centers by 2040.

In the second alternative (increased-rate), as pumpage increases 35 percent at current locations, water levels near Atlantic City decline by as much as 50 ft from 1986 levels. The hydraulic gradient increases throughout the aquifer compared to that in the first alternative. The hydraulic gradient is greater near the edge of the overlying confining unit than in the first alternative, indicating that flow from the water table to the Atlantic City 800-foot sand increases. An increase in the gradient between the offshore wells compared to that in alternative 1 indicates that flow rates of salty water from offshore toward pumping centers also increase.

In the third alternative (relocation), water-level declines and flow from offshore areas or from the Delaware Bay toward pumping centers are lessened considerably if the increase in pumpage from the largest pumping centers (in Ocean City and near Atlantic City) is relocated inland. Throughout coastal Cape May County, water levels decline 20 to 25 ft from 1986 levels rather than 25 to 45 ft when pumpage is increased at present locations (alternative 2). Lateral flow from the unconfined aquifer increases under the relocation alternative, resulting in some decrease of ground-water discharge to streams. The precise effects of pumping from the Atlantic City 800-foot sand on streams could be evaluated with a more detailed analysis of flow in the unconfined aquifer system.

In the fourth alternative (decreased-rate), water levels within a 10-mi radius of Atlantic City are higher than those in the increased-rate alternative (alternative 2) but lower than those in the relocation alternative (alternative 3). Water levels in Cape May County are comparable to those in the relocation alternative. Water levels decline near Atlantic City because pumping from the aquifer affects regional water levels, particularly when the pumping is distant from updip sources of recharge. Flow from the updip unconfined aquifer and flow through the overlying confining unit represents most of the increase in flow toward pumping centers in response to pumping in the decreased-growth alternative, but some of the increase is flow from offshore directions and from the edge of the confining unit in the Delaware Bay.

In comparison to both the increased-rate (alternative 2) and decreased-rate (alternative 4) alternatives, flow from offshore areas and vertical leakage decrease, whereas lateral flow from the unconfined aquifer increases, if the increase in pumpage is relocated inland (alternative 3).

Salty water travels 800 ft toward Atlantic City and 1,500 ft toward Stone Harbor when current pumpage continues until 2040 (alternative 1). When pumpage increases 35 percent (alternative 2), salty ground water travels 1,000 ft closer to Atlantic City and 1,900 ft closer to Stone Harbor. Under the relocation alternative (alternative 3), salty ground water travels 900 ft closer to Atlantic City and 1,800 ft closer to Stone Harbor. The salty water travels 800 ft toward pumping centers near Atlantic City and 1,700 ft toward pumping centers in Stone Harbor under the decreased-rate alternative (alternative 4). The movement of saltwater toward Atlantic City and Stone Harbor is greatest under the increased-rate alternative (alternative 2) and least when pumping continues at current rates (alternative 1).

The results of simulation of the four hypothetical alternatives indicate that salty ground water is not likely to reach supply wells during the 1986-2040 planning period. These results, however, are based on assumptions of advective flow, do not account for the effects of a saltwater-freshwater interface on flow velocities, and rely on a location of 250-mg/L isochlor estimated without the benefit of chloride-concentration values near the freshwater-saltwater interface. If the distance-traveled calculations were increased by one order of magnitude, salty ground water would reach the Stone Harbor wells about 2040. Regular collection of data from the offshore observation wells could serve as an early warning system for the Atlantic City pumping centers, and regular sampling from observation wells in the Wildwood area could serve as an early warning system for the Stone Harbor pumping centers. The installation of additional monitoring wells between supply wells and the salty water could improve calculations of saltwater movement made during future studies.

SELECTED REFERENCES

Anderson, H.R., and Appel, C.A., 1969, Geology and ground-water resources of Ocean County, New Jersey: New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 29, 93 p.

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Ca., Academic Press, 381 p.

Atlantic County, New Jersey Department of Regional Planning and Development, 1985, Population projections to 2000, Atlantic County, New Jersey: Atlantic County, New Jersey Department of Regional Planning and Development, 52 p.

Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498-A, 42 p.

Barksdale, H.C., Sundstrom, R.W., and Brunstein, M.S., 1936, Supplementary report on the ground-water supplies of the Atlantic City region: New Jersey State Water Policy Commission, Special Report 6, 139 p.

Barringer, J.L., Kish, G.R., and Velnich, A.J., 1993, Corrosiveness of ground water in the Kirkwood-Cohansey aquifer system of the New Jersey Coastal Plain: U.S. Geological Survey Water-Resources Investigations Report 90-4180, 79 p.

Barton, G.J., Storck, D.A., and Paulachok, G.N., 1993, Records of wells, exploratory boreholes, and ground-water quality, Atlantic County and vicinity, New Jersey: U.S. Geological Survey Open-File Report 92-631, 95 p.

Bauersfeld, W.R., Moshinsky, E.W., Pustay, E.A., and Jones, W.D., 1988, Water resources data, New Jersey, water year 1987, volume 1, Atlantic Slope Basins, Hudson River to Cape May: U.S. Geological Survey Water-Data Report NJ-87-1, 347 p.

Berner, E.K., and Berner, R.A., 1987, The global water cycle—Geochemistry and the environment: Englewood Cliffs, N.J., Prentice-Hall, 397 p.

Brady, N.C., 1974, The nature and properties of soils (8th ed.): New York, Macmillan, 639 p.

Clark, J.S., and Paulachok, G.N., 1989, Water levels in the principal aquifers of Atlantic County and vicinity, New Jersey, 1985-86: New Jersey Geological Survey Open-File Report 88-3, 33 p.

Drever, J.I., 1988, The geochemistry of natural waters, (2d ed): Englewood Cliffs, N.J., Prentice-Hall, 437 p.

Eckel, J.A., and Walker, R.L., 1986, Water levels in major artesian aquifers of the New Jersey Coastal Plain, 1983: U.S. Geological Survey Water-Resources Investigations Report 86-4028, 62 p.

Enright, Richard, 1969, The stratigraphy and clay mineralogy of the Eocene sediments of the northern New Jersey Coastal Plain, *in* Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions—Geological Society of America and Associated Societies, Annual Meeting, Atlantic City, N.J., November 1969: New Brunswick, N.J., Rutgers University Press, p. 14-20.

SELECTED REFERENCES--Continued

Faure, Gunter, 1986, Principles of isotope geology (2d ed.): New York, John Wiley and Sons, 589 p.

Friedman, L.C., and Erdmann, D.E., 1982, Quality assurance practices for the chemical and biological analyses of water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A6, 181 p.

Gill, H.E., 1962, Ground-water resources of Cape May County, New Jersey—Salt-water invasion of principal aquifers: New Jersey Department of Conservation and Economic Development Special Report 18, 171 p.

Hathaway, J.C., Poag, C.W., Valentine, P.C., Miller, R.E., Schults, D.M., Manheim, F.T., Kohout, F.A., Bothner, M.H., and Sangrey, D.A., 1979, U.S. Geological Survey Core Drilling on the Atlantic Shelf: Science, v. 206, no. 4418, p. 515-527.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Isphording, W.C., and Lodding, William, 1969, Facies changes in sediments of Miocene age in New Jersey, *in* Subitsky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions—Geological Society of America and Associated Societies, Annual Meeting, Atlantic City, N.J., November 1969: New Brunswick, N.J., Rutgers University Press, p. 235-278.

Krauskopf, K.B., 1967, Introduction to geochemistry: New York, McGraw-Hill, 721 p.

Lacombe, P.J., and Carleton, G.B., 1992, Saltwater intrusion into fresh ground-water supplies, southern Cape May County, New Jersey, 1890-1991, *in* Borden, R.C., and Lyke, W.L., eds., Proceedings of the National Symposium on the Future Availability of Ground Water Resources, American Water Resources Association, Raleigh, North Carolina, April 12-15, 1992: p. 287-297.

Leahy, P.P., and Martin, Mary, 1986, Simulation of ground-water flow--northern Atlantic Coastal Plain regional aquifer-system study, *in* Sun, R.J., ed., Regional Aquifer-System Analysis Program of the U.S. Geological Survey, summary of projects, 1978-84: U.S. Geological Survey Circular 1002, p. 169-172.

Leahy, P.P., Paulachok, G.N., Navoy, A.S., and Pucci, A.A., Jr., 1987, Plan of study for the New Jersey bond issue ground-water-supply investigations: New Jersey Geological Survey Open-File Report 87-1, 53 p.

Martin, Mary, 1998, Ground-water flow in the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-H, 146 p.

McClymonds, N.E., and Franke, O.L., 1972, Water-transmitting properties of aquifers on Long Island, New York: U.S. Geological Survey Professional Paper 627-E, 24 p.

SELECTED REFERENCES--Continued

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p.

Meisler, Harold, 1980, Preliminary delineation of salty ground water in the Northern Atlantic Coastal Plain: U.S. Geological Survey Open-File Report 81-71, 12 p.

Meisler, Harold, Leahy, P.P., and Knobel, L.L., 1984, Effect of eustatic sea-level changes on saltwater-freshwater relations in the northern Atlantic Coastal Plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.

Mullikin, L., Hutchinson, W., Sandberg, S., and Waldner, J., 1989, Hydrostratigraphy of the Kirkwood Formation in southeastern New Jersey: Annual meeting of the Geological Society of America, Northeast Section, 23-25 March 1989, New Brunswick, N. J., Abstracts with programs, v. 21, no. 3.

Nemickas, Bronius, and Carswell, L.D., 1976, Stratigraphic and hydrologic relationship of the Piney Point aquifer and the Alloway Clay member of the Kirkwood Formation in New Jersey: U.S. Geological Survey Journal of Research, v. 4, no. 1, p. 1-7.

New Jersey Department of Environmental Protection, 1981, The New Jersey Statewide Water-Supply Master Plan: 141 p.

_____ 1985, New Jersey safe drinking water act regulations, N.J.A.C. 7:10-1.1 through 7.3: New Jersey Department of Environmental Protection, Bureau of Potable Water, 22 p.

New Jersey Department of Labor, 1985, Population projections for New Jersey and Counties, 1990-2020: New Jersey Department of Labor, Office of Demographic and Economic Analysis.

New Jersey Pinelands Commission, 1983, New Jersey Pinelands Comprehensive Management Plan—A progress report on the first three years of implementation: New Lisbon, N.J., New Jersey Pinelands Commission.

Olsson, R.K., Miller, K.G., and Ungrady, T.E., 1980, Late Oligocene Piney Point transgression of Atlantic Coastal Plain: Geological Society of America, Abstracts with Programs, v. 12, no. 2, p. 76.

Owens, J.P., and Minard, J.P., 1979, Upper Cenozoic sediments of the lower Delaware Valley and the northern Delmarva Peninsula, New Jersey, Pennsylvania, Delaware, and Maryland: U.S. Geological Survey Professional Paper 1067-D, 47 p.

Owens, J.P., and Sohl, N.F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, *in* Subitsky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions—Geological Society of America and Associated Societies, Annual Meeting, Atlantic City, N.J., November 1969: New Brunswick, N. J., Rutgers University Press, p. 235-278.

Owens, J.P., Bybell, L.M., Paulachok, G.N., Ager, T.A., Gonzalez, V.M., and Sugerman, P.J., 1988, Stratigraphy of the Tertiary sediments in a 945-foot-deep corehole near Mays Landing in the southeastern New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1484, 39 p.

SELECTED REFERENCES--Continued

Rhodehamel, E.C., 1970, A hydrologic analysis of the New Jersey Pine Barrens Region: New Jersey Department of Environmental Protection Water-Resources Circular 22, 35 p.

_____ 1973, Geology and water resources of the Wharton Tract and the Mullica River Basin in southern New Jersey: New Jersey Department of Environmental Protection, Division of Water Resources Special Report 36, 58 p.

Seaber, P.R., 1963, Chloride concentrations in water from wells in the Atlantic Coastal Plain of New Jersey: New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report 22, 250 p.

Stumm, Werner, and Morgan, J.J., 1981, Aquatic chemistry (2d ed.): New York, John Wiley and Sons, 780 p.

Thomas, D.M., and Edelen, G.W., Jr., 1962, Tidal floods, Atlantic City and vicinity, New Jersey: U.S. Geological Survey Hydrologic Investigations Atlas HA-65, scale 1:12,000.

Thompson, D.G., 1928, Ground water supplies of the Atlantic City region: New Jersey Department of Conservation and Development, Bulletin 30, 138 p.

URS Consultants, Inc., in association with R.E. Wright Associates, Inc., Coopers and Lybrand, and Environmental Testing and Certification Corporation, 1987, Atlantic County water-supply study, report on water conservation alternatives: New Jersey Department of Environmental Protection, 86 p.

_____ 1988, Atlantic County Water Supply Study, supplemental report on population and water consumption projections through 2040: New Jersey Department of Environmental Protection.

_____ 1989, Atlantic County Water Supply Study, report on water system improvement alternatives: New Jersey Department of Environmental Protection.

U.S. Environmental Protection Agency, 1977, National interim primary drinking water regulations: U.S. Environmental Protection Agency, EPA-570/9-76-003, 159 p.

U.S. Geological Survey, 1975, WATSTORE User's Guide: U.S.Geological Survey Open-File Report 75-426, v. 4

Vowinkel, E.F., 1984, Ground-water withdrawals from the Coastal Plain of New Jersey, 1956-80: U.S. Geological Survey Open-File Report 84-226, 32 p.

Walker, R.L., 1983, Evaluation of water levels in major aquifers of the New Jersey Coastal Plain, 1978: U.S. Geological Survey Water-Resources Investigations Report 82-4077, 56 p.

Woolman, Lewis, 1890-1902 [annually], Report on artesian wells in southern New Jersey, *in* Annual report of the State Geologist: Geological Survey of New Jersey.

Zapecza, O.S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-B, 49 p., 24 pl.

Zapecza, O.S., Voronin, L.M., and Martin, Mary, 1987, Ground-water-withdrawal and water-level data used to simulate regional flow in the major Coastal Plain aquifers of New Jersey: U.S. Geological Survey Water-Resources Investigations Report 87-4038, 120 p.

Appendix 1. Well-construction data for wells in the Atlantic City 800-foot sand and the Piney Point aquifer used in this report

[CEN, Center; CO, Company; CONV, Convention; DEPT, Department; ELEC, Electric; MUA, Municipal Utilities Authority; WC, Water Company; WD, Water Department; ---, missing data; --, data not available]

U.S. Geological Survey well number	Owner	Local well name	New Jersey Permit number	Latitude	Longitude	Elevation of land surface (feet above sea level)	Date of well construction	Depth of well (feet below land surface)	Screened interval (feet below land surface)
Atlantic City 800-foot sand									
010015	PRESIDENT HOTEL	PRESIDENT	--	392058	742711	10	1955	831	779-831
010019	TROPICANA HOTEL	AMBASSADOR	--	392107	742643	8	1919	850	---
010020	BALLY'S	DENNIS	--	392122	742602	7	1919	856	---
010025	CLARIDGE HOTEL	CLARIDGE	--	392128	742557	8	1979	850	773-845
010026	RESORTS INTERNATIONAL	HADDON HALL OLD	56-00067	392131	742522	8	1896	840	790-840
010032	BREAKERS HOTEL	1961 WELL	--	392141	742459	8	1916	840	800-840
010037	ATLANTIC CITY MUA	GALEN HALL OBS	56-00071	392151	742459	9.54	1904	842	782-837
010039	BRIGANTINE WD	NEW 4	56-00012	392329	742348	10	1966	788	733-788
010040	BRIGANTINE WD	BAYSHORE 3	36-00057	392342	742328	10	1965	769	706-766
010041	BRIGANTINE WD	BRIG WD 1	56-00009	392431	742153	9	1950	829	769-806
010042	BRIGANTINE WD	BWD 2-14TH ST	56-00010	392456	742121	12	1929	788	718-778
010116	EGG HARBOR WC	EGG HARBOR 3	--	393212	743829	40	1942	401	342-394
010117	EGG HARBOR WC	OW41 5	32-00477	393213	743832	40	1964	432	350-432
010121	SEAVIEW WATER COMPANY	1958 WELL	36-00271	391852	743208	5	1958	783	740-780
010180	US GEOLOGICAL SURVEY	OCEANVILLE 1 OBS	--	392754	742701	27	1959	570	560-570
010227	HAMILTON TOWNSHIP MUA	HTMUA 5	36-00391	392710	744440	20	1966	347	316-347
010366	BOROUGH OF LONGPORT	LONGPORT OBS	56-00080	391821	743208	6.35	1895	803	753-803
010367	BOROUGH OF LONGPORT	LONGPORT 2	56-00038	391859	743122	10	1957	800	750-800
010368	BOROUGH OF LONGPORT	LONGPORT 1	56-00037	391859	743122	10	1963	805	738-805
010369	BOROUGH OF LONGPORT	LONGPORT 3	36-00402	391905	743128	10	1968	811	760-810
010370	CITY OF MARGATE	MCWD 6	36-00318	391928	743055	10	1962	801	748-798
010372	CITY OF MARGATE	MCWD 7	36-00326	391932	743059	5	1963	803	760-800
010373	CITY OF MARGATE	MCWD 1	----	391935	743059	10	1926	805	---
010375	CITY OF MARGATE	MCWD 4	36-00197	392002	743012	10	1955	797	745-795
010376	CITY OF MARGATE	MCWD 5	36-00278	392008	743017	10	1958	791	741-791
010568	ATLANTIC CITY MUA	ACMUA 15	36-00013	392448	743028	8	1961	636	583-633
010578	US GEOLOGICAL SURVEY	JOBS POINT OBS	--	391826	743709	10	1959	680	670-680
010593	VENTNOR CITY	VCWD 10	36-00372	392018	742945	9	1965	793	740-790

Appendix 1. Well-construction data for wells in the Atlantic City 800-foot sand and the Piney Point aquifer used in this report

[CEN, Center; CO, Company; CONV, Convention; DEPT, Department; ELEC, Electric; MUA, Municipal Utilities Authority; WC, Water Company; WD, Water Department; ---, missing data; --, data not available]

U.S. Geological Survey well number	Owner	Local well name	New Jersey Permit number	Latitude	Longitude	Elevation of land surface (feet above sea level)	Date of well construction	Depth of well (feet below land surface)	Screened interval (feet below land surface)
010595	VENTNOR CITY	VCWD 5	56-00014	392028	742850	8	1963	815	765-815
010596	VENTNOR CITY	VCWD 4	56-00013	392029	742853	8	1963	810	760-810
010598	VENTNOR CITY	VCWD 9	36-00371	392030	742852	8	1965	803	740-800
010599	VENTNOR CITY	VCWD 7	56-00015	392032	742858	8	1927	830	800-830
010600	VENTNOR CITY	VCWD 8	56-00016	392045	742840	8	1931	810	750-810
010637	EGG HARBOR WCT	EGG HARBOR 4A	32-05113	393217	743823	35	1979	428	335-425
010648	BALLY'S	BALLY 1	36-01084	392125	742604	7	1979	835	775-835
010664	RITZ CONDOMINIUMS	1	--	392110	742639	8	1924	855	780-840
010668	SEASHORE SUPPLY CO	1	--	392159	742544	8	1923	842	---
010676	RESORTS INTERNATIONAL	CHALFONTE NEW	--	392131	742525	8	1913	831	---
010679	SHELBURNE HOTEL	1	--	392120	742606	8	1900	830	---
010680	CARNIVAL CLUB	2	--	392120	742606	8	1910	835	773-835
010682	RESORTS INTERNATIONAL	1-1980	36-14819	392134	742521	8	1980	840	---
010683	BRIGANTINE WD	NEW 5	36-02091	392410	742227	8	1980	780	725-775
010700	US GEOLOGICAL SURVEY	ACGS 4	35-04274	392933	744604	40	1984	544	479-539
010702	US GEOLOGICAL SURVEY	BURK AVE TW OBS	--	392032	743008	5	1985	755	740-750
010703	US GEOLOGICAL SURVEY	FAA POMONA OBS	--	392639	743232	38	1985	575	560-570
010704	US GEOLOGICAL SURVEY	EGG HARBOR HS	--	392343	743733	51	1985	611	596-606
010706	US GEOLOGICAL SURVEY	STKTN ST COLL	36-04982-1	392933	743130	40	1985	535	520-530
010710	US GEOLOGICAL SURVEY	ACOW 2 OBS	--	391726	742221		1985	1020	973-1000
010711	US GEOLOGICAL SURVEY	ACOW 1 OBS	--	391955	742507		1985	871	820-850
090002	BOROUGH OF AVALON	AVALON WD 2R-71/NEW 7	37-00280	390420	744435	5	1971	864	821-861
090004	BOROUGH OF AVALON	AVALON WD 6	37-00265	390528	744338	10	1968	923	880-920
090005	BOROUGH OF AVALON	AVALON WD 5-76/NEW 8	37-00313	390545	744326	8	1976	839	784-839
090008	BOROUGH OF AVALON	AVALON WD 3	--	390621	744248	10	1930	930	845-925
090067	WILDWOOD WATER DEPT	RIO GRANDE 38	37-00271	390135	745352	10	1970	592	461-590
090092	NEW JERSEY WATER COMPANY	NEPTUNUS 7	37-00240	390525	744851	17	1967	791	681-791
090100	MIDDLE TWP DISTRICT	AVALON M WW 1	37-00224	390647	744438	5	1963	827	763-815
090106	NEW JERSEY WATER COMPANY	SHORE DIV 7	56-00006	391343	743755	8	1924	810	760-810
090108	NEW JERSEY WATER COMPANY	SHORE DIV 14	36-00412	391500	743645	7	1970	843	774-840
090109	NEW JERSEY WATER COMPANY	SHORE DIV 9	56-00008	391535	743611	8	1946	814	749-809

Appendix 1. Well-construction data for wells in the Atlantic City 800-foot sand and the Piney Point aquifer used in this report

[CEN, Center; CO, Company; CONV, Convention; DEPT, Department; ELEC, Electric; MUA, Municipal Utilities Authority; WC, Water Company; WD, Water Department; ---, missing data; --, data not available]

U.S. Geological Survey well number	Owner	Local well name	New Jersey Permit number	Latitude	Longitude	Elevation of land surface (feet above sea lavel)	Date of well construction	Depth of well (feet below land surface)	Screened interval (feet below land surface)
090110	NEW JERSEY WATER COMPANY	SHORE DIV 12	36-00373	391604	743539	7	1965	814	759-814
090116	NEW JERSEY WATER COMPANY	SHORE DIV 8	56-00007	391638	743451	7	1937	810	760-810
090117	NEW JERSEY WATER COMPANY	SHORE DIV 10	36-00017	391642	743447	5	1950	798	746-798
090121	NEW JERSEY WATER COMPANY	SHORE DIV 4	56-00004	391649	743449	8	1910	825	---
090122	NEW JERSEY WATER COMPANY	SHORE DIV 5	56-00005	391710	743408	6	1923	825	---
090124	NEW JERSEY WATER COMPANY	SHORE DIV 13	36-00413	391712	743340	8	1970	843	774-840
090125	NEW JERSEY WATER COMPANY	SHORE DIV 11	36-00314	391726	743352	10	1962	800	- --
090126	CITY OF SEA ISLE CITY	SICWD 5	37-00162	390747	744241	7	1957	802	736-802
090127	CITY OF SEA ISLE CITY	SICWD 4	37-00064	390847	744200	7	1954	830	742-830
090128	CITY OF SEA ISLE CITY	SICWD 3	57-00010	390902	744153	7	1930	870	800-870
090129	CITY OF SEA ISLE CITY	SICWD 2	57-00009	390926	744131	7	1926	864	801-861
090131	CITY OF SEA ISLE CITY	SICWD 1	--	390928	744135	5	1912	857	- --
090132	BOROUGH OF STONE HARBOR	SHWD 4	37-00079	390301	744545	10	1955	883	830-880
090135	BOROUGH OF STONE HARBOR	SHWD 3	37-00009	390323	744525	9	1949	882	838-878
090136	ARAMINGO WATER COMPANY	CIWC 1	56-00147	391152	743927	7	1904	834	802-834
090144	ATLANTIC CITY ELEC	ACEC 5	36-00451	391703	743756	9	1975	691	650-690
090148	ATLANTIC CITY ELEC	ACEC 3-LAYNE 4	36-00364	391707	743756	9	1964	678	645-675
090161	EASTERN SHORE CONV CEN	1	--	390704	744750	15.70	1983	654	639-654
090166	BOROUGH OF STONE HARBOR	SHWD 5	37-00312	390351	744504	7	1976	860	820-860
090173	BOROUGH OF STONE HARBOR	SHWD 6	37-00579	390314	744532	10	1981	860	810-860
090185	US GEOLOGICAL SURVEY	MACNAMARA W A	--	391621	744355	15	1985	655	640-650
290009	BEACH HAVEN BOROUGH	BHWD 8	53-00031	393346	741430	5	1957	656	572-656
290012	BEACH HAVEN BOROUGH	BHWD 7	53-00030	393346	741434	5	1940	665	572-665
290111	BOROUGH OF HARVEY CEDARS	HCWD 4	33-01180	394134	740832	9	1968	503	465-500
290112	BOROUGH OF HARVEY CEDARS	HCWD 3	33-00674	394218	740808	5	1956	493	451-493
290455	TOWNSHIP OF LONG BEACH	LBTWD 2	33-01051	393206	741548	5	1963	458	426-451
290457	TOWNSHIP OF LONG BEACH	TERRACE 3	33-01275	393510	741327	8.10	1970	653	551-650
290459	TOWNSHIP OF LONG BEACH	TERRACE 2	33-00003	393510	741330	5	1949	627	560-623
290460	TOWNSHIP OF LONG BEACH	BRANT BEACH 2	33-00041	393724	741151	6	1951	580	530-580
290461	TOWNSHIP OF LONG BEACH	BRANT BEACH 1	53-00018	393725	741150	9	1946	615	534-615
290462	LITTLE EGG HARBOR MUA	MYSTIC 3	32-00609	393253	742308	8	1969	564	509-553

Appendix 1. Well-construction data for wells in the Atlantic City 800-foot sand and the Piney Point aquifer used in this report

[CEN, Center; CO, Company; CONV, Convention; DEPT, Department; ELEC, Electric; MUA, Municipal Utilities Authority; WC, Water Company; WD, Water Department; ---, missing data; --, data not available]

U.S. Geological Survey well number	Owner	Local well name	New Jersey Permit number	Latitude	Longitude	Elevation of land surface (feet above sea level)	Date of well construction	Depth of well (feet below land surface)	Screened interval (feet below land surface)
290464	LITTLE EGG HARBOR MUA	MYSTIC 2	32-00447	393428	742202	19	1963	542	485-542
290544	BOROUGH OF SHIP BOTTOM	SBWD 4	33-00219	393839	741052	5	1953	590	536-578
290549	BOROUGH OF SHIP BOTTOM	SBWD 5	33-01723	393848	741053	5.30	1974	588	528-588
290557	STAFFORD MUA	STAFFORD 3	33-01132	394042	741411	8	1965	428	385-428
290559	BOROUGH OF SURF CITY	SCWD 3	53-00003	393912	741022	5	1947	562	516-557
290560	BOROUGH OF SURF CITY	SCWD 4	33-01091	393938	741006	5	1964	557	514-554
290561	BOROUGH OF SURF CITY	SCWD 5	33-01268	393948	740954	10	1970	564	520-562
290564	BOROUGH OF TUCKERTON	TMUA 4	32-00011	393610	742031	10	1949	481	460-481
290565	BOROUGH OF TUCKERTON	TMUA 4(OW1)	32-00479	393610	742031	10	1964	497	463-497
290590	BEACH HAVEN BOROUGH	BHWD 9	33-02451	393342	741431	5	1975	635	552-630
290597	BOROUGH OF TUCKERTON	TMUA 5(OW2)	32-05858	393610	742021	25	1978	500	400-500
290774	STAFFORD TWP MUA	STAFFORD 4	33-10547	394042	741411	8	1982	484	434-484
291064	TOWNSHIP OF LONG BEACH	LBWC BRANT BEACH 3	33-13836	393722	741142	8	1984	595	535-595
291092	BOROUGH OF TUCKERTON	SO GREEN ST OW-2	32-06055	393607	742007	11		598	---
			Piney Point						
010701	BUENA BORO MUA	BBMUA TW 1	35-03992	393148	745617	118	1984	460	410-460
010834	US GEOLOGICAL SURVEY	MARGATE FIREHOUSE 1 OBS	--	392017	743002	5	1988	997	970-991

GROUND-WATER FLOW AND QUALITY IN THE ATLANTIC CITY 800-FOOT SAND, NEW JERSEY
(New Jersey Geological Survey Report GSR 41)

ISSN 0741-7357