Analysis of Ground-Water Flow and Saltwater Encroachment in the Shallow Aquifer System of Cape May County, New Jersey

Water-Supply Paper 2490
Prepared in cooperation with
New Jersey Department of
Environmental Protection

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Analysis of Ground-Water Flow and Saltwater Encroachment in the Shallow Aquifer System of Cape May County, New Jersey

BY FREDERICK J. SPITZ

Prepared in cooperation with the
New Jersey Department of Environmental Protection

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2490

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
THOMAS J. CASADEVALL, Acting Director

1998

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Library of Congress Cataloging in Publication Data
Spitz, Frederick J.
Analysis of ground-water flow and saltwater encroachment in the shallow aquifer system of Cape May County, New Jersey / by Frederick J. Spitz
p. cm.—(U.S. Geological Survey water-supply paper; 2490)
"Prepared in cooperation with the New Jersey Department of Environmental Protection."
Includes bibliographical references.
Supt. of Docs. no.: I 19.13:2490
1. Groundwater flow—New Jersey—Cape May County. 2. Saltwater encroachment—New Jersey—Cape May County. 3. Aquifers—New Jersey—Cape May County. I. New Jersey, Department of Environmental Protection. II. Title. III. Series.
GB1197.7.S65 1997
551.49'09749'98—dc21 97—12800
CIP
ISBN 0-607-88770-2

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
inch per year (in/yr)	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallons per day (gal/d)	.003785	cubic meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second

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

Water-quality abbreviation: milligrams per liter (mg/L)

Analysis of Ground-Water Flow and Saltwater Encroachment in the Shallow Aquifer System of Cape May County, New Jersey

By Frederick J. Spitz

ABSTRACT

Cape May County, the southernmost county in New Jersey, is on a natural peninsula that is virtually surrounded by saltwater, including the Atlantic Ocean and Delaware Bay. Nearly all of the county's water supply comes from ground water, half of which comes from the shallow aquifer system. Because of its proximity to saltwater bodies, the county's freshwater supply is very limited. This report describes the results of a conceptual and numerical analysis of the shallow-ground-water resources of the county, with emphasis on the effects of saltwater encroachment on water supply.

The conceptual analysis was conducted by investigating the hydrogeologic framework, water use, flow system, and water quality. The shallow aquifer system consists of one unconfined aquifer and two confined aquifers. Recharge to the shallow aquifer system is derived mainly from precipitation. Although water-supply is greatest in the unconfined part of the system, the introduction of contaminants from the land surface has precluded extensive use of this aquifer. Withdrawals from the confined aquifers have increased through time in response to the summer influx of tourists, and the water used is ultimately discharged offshore to the Atlantic Ocean. Extensive cones of depression have resulted in these aquifers. The net freshwater loss from the system has led to saltwater encroachment and chloride contamination of the water withdrawn. Chloride contamination is even more severe in the deep aquifer system.

The numerical analysis was conducted by using a quasi-three-dimensional finite-difference model of the ground-water system and the sharp-interface approach. Limitations and assumptions inherent in the model involve data quality, computer code, and model application. The model is calibrated to predevelopment and to current hydrologic conditions.

The calibrated model was used to simulate ground-water flow under two water-supply-development alternatives for a 30-year planning period. The alternatives involve only modest increases in withdrawals in combination with desalination of brackish ground water or relocation of wells toward inland areas. Simulation results indicate that projected withdrawals for the two alternatives can be sustained without significant additional saltwater encroachment over the planning period. However, saltwater will affect some wells if the current withdrawal scheme is maintained. Finally, information is provided on the use of ground-water monitoring to detect saltwater encroachment.

INTRODUCTION

Nearly all water supply in Cape May County (fig. 1) is obtained from ground-water sources. Increases in both the permanent and summer tourist populations have increased water demand, and pumping from wells has created areas of lowered ground-water levels and saltwater contamination of the aquifers. The barrier islands of the county are the most densely populated areas, particularly in the summer. In 1990, the winter population of the county was 96,000, whereas the summer population was six times this value (Cape May County League of Women Voters, 1991).

Base modified from U.S.Geological Survey digital data, 1:100,000, 1983. Universal Transverse Mercator projection, Zone 18

Figure 1. Location of study area.

About half of the ground-water withdrawals for water supply are from the shallow aquifer system. Withdrawals from the shallow confined aquifers during the summer months can be as much as three times those during other months. Saltwater encroachment has caused the abandonment and inland relocation of water-supply wells in some areas (fig. 1).

Saltwater encroachment toward the Cape May peninsula is likely to continue if withdrawals from the shallow aquifer system are maintained at current rates, and increased withdrawals to meet projected water demands will exacerbate that encroachment. To address these concerns, the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, conducted a study to evaluate the continued availability of freshwater in the county's shallow aquifers.

Purpose and Scope

This report presents the results of a 2-year study of the shallow aquifer system of Cape May County to evaluate the continued availability of freshwater resources. The report quantifies the magnitude and extent of encroachment of saltwater into the shallow aquifer system under current and potential future withdrawals. In addition, the potential for future use of water from the unconfined aquifer is assessed qualitatively.

A previously developed ground-water flow model of the shallow aquifer system (Spitz and Barringer, 1992), modified to incorporate newly available data collected as part of a 3-year study of the county's hydrogeology (P.J. Lacombe and G.B. Carleton, U.S. Geological Survey, written commun., 1994), is used to evaluate the effects of freshwater withdrawals on the location of saline ground water (ground water having a chloride concentration greater than 250 mg/L). Resulting changes in ground-water flow patterns, recharge, and discharge are examined. Rates of advective movement of saltwater toward public supply wells are calculated by using flow-path analysis. Future water-supply-development alternatives are simulated. Lastly, the use of a data-collection network to monitor the freshwater supply and provide early warning of saltwater encroachment is described.

Description of Study Area

Cape May County is the southernmost county in New Jersey (fig. 1). The county forms a natural peninsula and is virtually surrounded by saltwater bodies, including the Atlantic Ocean and Delaware Bay. The land surface is a sandy coastal plain that reaches a maximum elevation of 60 ft in the northwestern part of the county. The county contains forested land, agricultural land, residential and commercial areas, and freshwater and tidal wetlands. In Upper Township and Woodbine, 134 mi^2 of land falls within the Pinelands Natural Reserve Area. The eastern part of the county consists of a broad tidal wetland flanked by barrier islands. Substantial tidal wetlands are present along the coast of the Delaware Bay.

The climate of Cape May County is moderated by the large surrounding saltwater bodies. Annual average precipitation ranges from 41 to 45 in/yr.

Because the county is located on the eastern seaboard, it is affected by coastal flooding.

Previous Investigations

P.J. Lacombe and G.B. Carleton (written commun., 1994) have completed the most recent comprehensive study of the county's water resources. The extensive hydrogeologic data base assembled as part of that study was used to construct the model of the shallow aquifer system in this study. A model of the deep aquifer system (Voronin and others, 1996) has also been constructed from this data base. Schuster and Hill (1995) assembled a limited data base in 1987 that was used to construct the model used in two previous studies of the shallow aquifer system (Spitz and Barringer, 1992; Spitz, 1996). The current model of the shallow aquifer system supersedes this earlier version as a result of improvements made to the data base, including the addition of information on ground-water/surface-water interaction, and to the model, including its calibration and predictive capability. Prior to the work of Lacombe and Carleton, the most comprehensive study of the county's water resources was done by Gill (1962).

HYDROGEOLOGY

The shallow aquifer system of Cape May County is part of the New Jersey Coastal Plain, which consists of a southeastward-thickening wedge of Quaternary-age sediments deposited during alternating transgressions and regressions of the Atlantic Ocean onto eastern North America. A complete discussion of the hydrogeologic framework of, water use in, flow system of, and water quality in Cape May County has been reported by P.J. Lacombe and G.B. Carleton (written commun., 1994).

U.S. Geological Survey well numbers used in this report consist of a county-code prefix followed by a unique sequence number for each well. Cape May is represented by county code 9. U.S. Geological Survey streamflow-gaging-station numbers used in this report consist of a two-digit major drainage basin number followed by a six-digit downstream-order number. Water data for these wells and gaging stations are maintained in the U.S. Geological Survey's National Water Data Storage and Retrieval System (computerized data base available at the U.S. Geological Survey office in West Trenton, N.J.).

Framework

The shallow aquifer system within Cape May County is composed of an unconfined aquifer, the Holly Beach water-bearing zone, and two confined aquifers, the estuarine sand and Cohansey aquifers. The aquifers are separated by low-permeability confining units. The top boundary of the saturated zone is the water table, which fluctuates seasonally as much as 5 ft and is located about 10 ft below land surface. The bottom boundary of the shallow aquifer system is a 100- to 175-ft thick confining unit that separates the shallow aquifer system from the deep aquifer system that includes the Kirkwood Formation aquifers. The relation between geologic units and hydrogeologic units in Cape May County is shown in table 1. Few data are available on the offshore extent and hydraulic properties of the hydrogeologic units.

Structure-contour and thickness maps of the shallow aquifer system are shown in figures 2 through 7. These maps are the simulated representation of structure contours and thickness maps prepared by P.J. Lacombe (written commun., 1994). The Holly Beach water-bearing zone, the uppermost aquifer of the system, is composed of gravel and coarse- to fine-grained sand. Silt, clay, and organic matter are present in the aquifer beneath tidal wetlands. In the northern part of the county, clay and silt beds form a local confining unit within the aquifer. The aquifer crops out at land surface and is 15 to 225 ft thick (fig. 2).

The estuarine clay, a confining unit composed of fine-grained marine clay and silt that filled an ancestral Delaware River channel, is present beneath the unconfined aquifer in the peninsular part of the county. The estuarine clay crops out in a small area at the floor of the Delaware Bay west of the peninsula. North of the peninsula, the estuarine clay is present as thin discontinuous lenses within the unconfined aquifer. The estuarine clay ranges in thickness from 20 to 95 ft (fig. 3) and may not extend far beyond the coastline.

The estuarine sand aquifer is the uppermost confined aquifer in the shallow aquifer system (fig. 4). Its extent is defined by the extent of the estuarine clay confining unit. It consists of gravel and coarse- to fine-grained sand, and ranges in thickness from 20 to 150 ft.

The estuarine sand aquifer is underlain by an areally extensive confining unit composed of fine-grained silt and clay. This unit extends beyond the northern, eastern, and western boundaries of the

Table 1. Relation of geologic and hydrogeologic units in the shallow aquifer system in Cape May County

[Modified from Zapecza, 1989, table 2]

<table>
<tr><th rowspan="2">Sytstem</th><th rowspan="2">Series</th><th colspan="2">Northern Cape May County</th><th colspan="2">Peninsular Cape May County</th></tr>
<tr><th>Geologic unit</th><th>Hydrogeologic unit</th><th>Geologic unit</th><th>Hydrogeologic unit</th></tr>
<tr><td rowspan="5">Quaternary</td><td rowspan="3">Holocene</td><td>Alluvial deposits</td><td rowspan="6">Holly Beach water-bearing zone</td><td>Alluvial deposits</td><td rowspan="3">Holly Beach water-bearing zone</td></tr>
<tr><td rowspan="2">Beach and dune deposits</td><td>Beach and dune deposits</td></tr>
<tr><td>Intertidal sands</td></tr>
<tr><td rowspan="2">Pleistocene</td><td rowspan="2">Cape May Formation</td><td rowspan="2">Cape May Formation</td><td>Estuarine clay confining unit</td></tr>
<tr><td rowspan="2">Estuarine sand aquifer</td></tr>
<tr><td rowspan="5">Tertiary</td><td rowspan="5">Miocene</td><td>Bridgeton Formation</td><td rowspan="4">Cohansey Sand</td></tr>
<tr><td rowspan="2">Cohansey Sand</td><td>Confining unit</td><td>Confining unit</td></tr>
<tr><td rowspan="2">Cohansey aquifer</td><td rowspan="2">Cohansey aquifer</td></tr>
<tr><td rowspan="2">Kirkwood Formation</td></tr>
<tr><td>Confining unit</td><td>Kirkwood Formation</td><td>Confining unit</td></tr>
</table>

county; to the south, it may reach the present-day main channel of the Delaware Bay. The confining unit is locally leaky and ranges in thickness from 10 to 50 ft (fig. 5).

The Cohansey aquifer underlies the estuarine sand aquifer in the peninsular part of the county and the Holly Beach water-bearing zone in the northern part. It is composed of gravel and coarse- to fine-grained sand, and ranges in thickness from 50 to 300 ft (figs. 6 and 7).

Reported hydraulic properties of the aquifers and confining units are listed in table 2. The values were compiled from results of various field investigations in the county. Three types of measured data are included: results of aquifer tests, slug tests, and laboratory tests. Whereas laboratory tests provide point values of a hydrogeologic property, and slug tests provide local average values, aquifer tests provide regional average values, which are the most representative for the scale of this study.

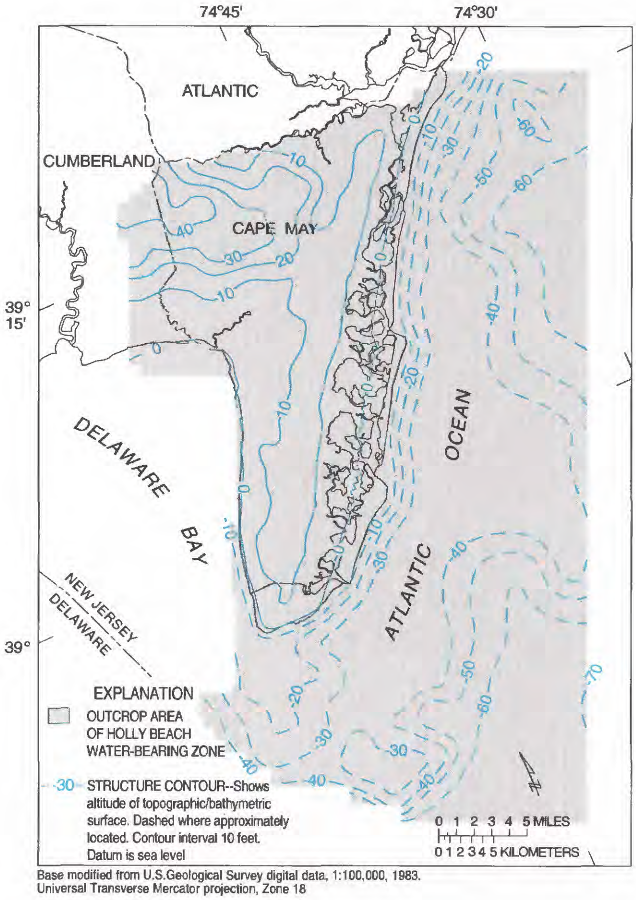


Figure 2. Altitude of the top of the Holly Beach water-bearing zone.

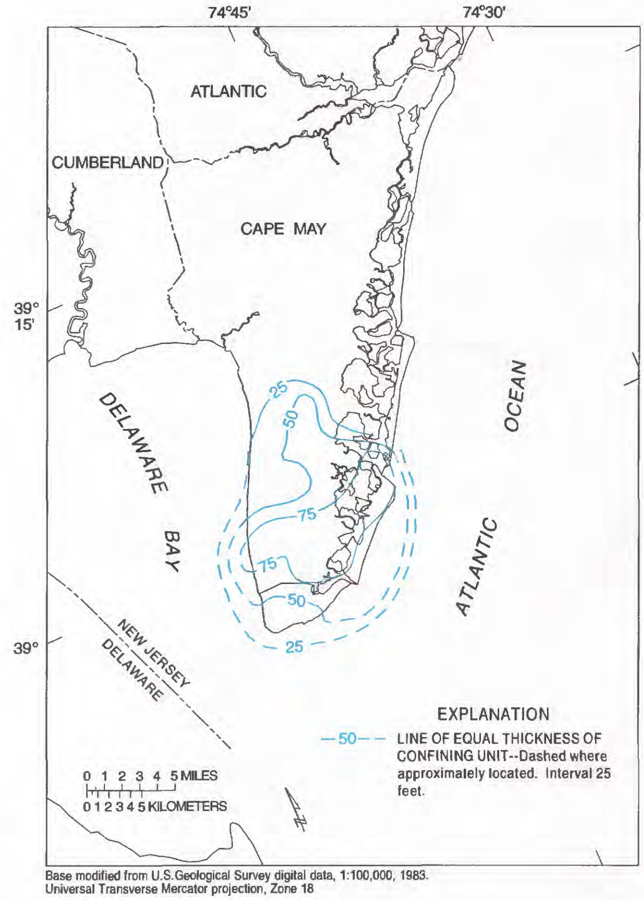


Figure 3. Thickness of the estuarine clay confining unit.

Water Use

Nearly all of the potable water supply in Cape May County comes from ground water. Surface-water sources have been little used for supply, mainly because of the costs of reservoir construction and water treatment and the low water demand by the permanent population of the county. Of the total ground-water withdrawals in 1990 (approximately 16.5 Mgal/d), 55 percent was derived from the shallow aquifer system; most of this was for public supply. Approximately 65 percent of the withdrawals from the shallow aquifer system were made from the Cohansey aquifer. Average withdrawals for 1989-90, except domestic use, are shown in figure 8.

Water from the unconfined Holly Beach water-bearing zone is used mainly for domestic and irrigation purposes. These uses are considered to be 20 and 80 percent consumptive (not returned to the aquifer), respectively (Solley and others, 1993), and account for 30 and 70 percent of the withdrawals from the aquifer, respectively. Nonconsumptively used water is returned to the aquifer locally. Comprehensive estimates of irrigation use, beyond currently available data, were not made. The estimated total consumptive withdrawals from the aquifer were 0.75 Mgal/d in 1990. Withdrawals have increased slowly over time, as shown in figure 9 (unpublished data on file at the U.S. Geological Survey, New Jersey District Office). Locations of withdrawals from the unconfined aquifer are scattered thoughout the county.

Water from the estuarine sand aquifer is used mainly for domestic (80 percent) and public supply (20 percent), including commercial. Water use is

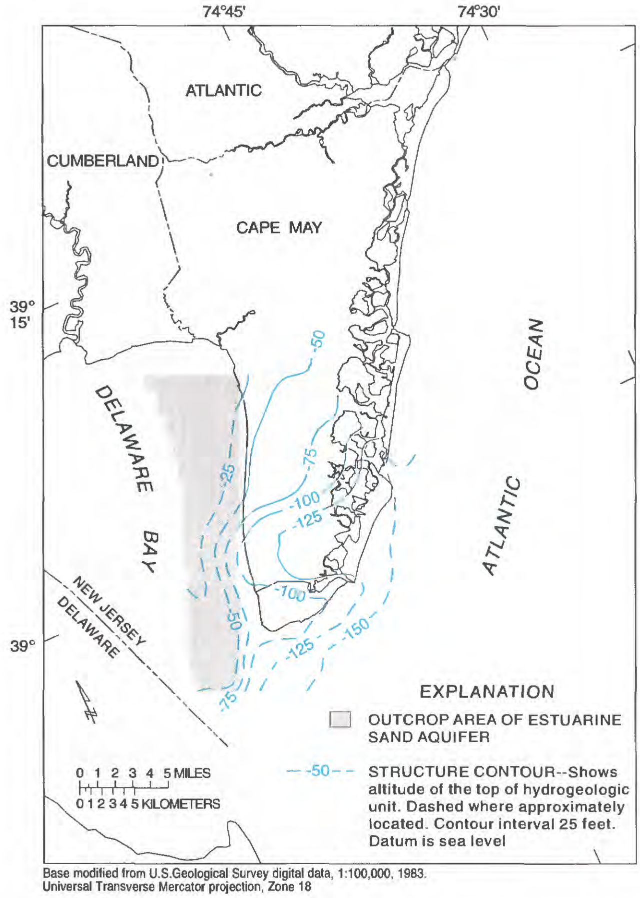


Figure 4. Altitude of the top of the estuarine sand aquifer.

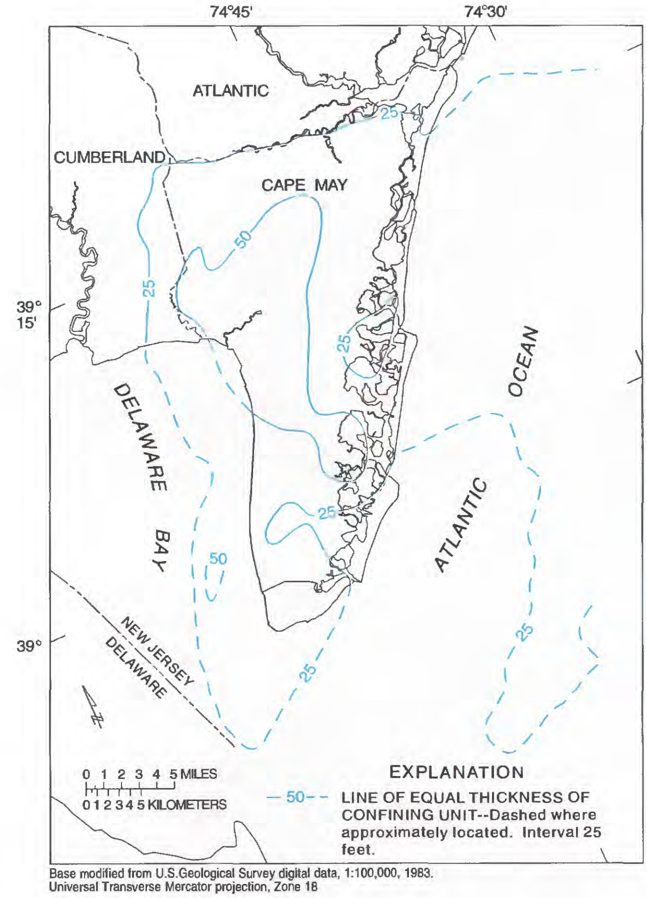


Figure 5. Thickness of the confining unit overlying the Cohansey aquifer.

completely consumptive. Withdrawals from the aquifer were estimated to be 2.2 Mgal/d in 1990. With drawals have increased gradually over time (fig. 9). The main locations of withdrawals from this aquifer are at Villas, Town Bank, and Rio Grande (fig. 1).

Water from the Cohansey aquifer is used mainly for public (90 percent) and industrial (10 percent) supply. Water use from the aquifer is completely consumptive and was estimated to be 5.9 Mgal/d in 1990. Withdrawals have increased significantly over time (fig. 9). The main locations of withdrawals from the aquifer are at Rio Grande, Cape May City, and Lower Township (fig. 1). Withdrawals have increased at each of these locations except Cape May City, where withdrawals peaked in the 1960's and have since decreased because of saltwater contamination. Withdrawals from this aquifer during the summer tourist season can be as much as three times those during other months.

In the Wildwood area, four wells are used to recharge the two confined aquifers to help meet summer water demand (Lacombe, 1996). The recharge water is withdrawn at the Rio Grande well field located near Green Creek. Net recharge was estimated to be 0.15 Mgal/d in 1990. More recently, Cape May City Water Department has injected water purchased from Lower Township into one of its wells (9-45) to help meet summer water demand. Typical rates of injection during 1994 were 0.3 to 0.5 Mgal/d (D.A. Carrick, Cape May City Water Department, oral commun., 1995).

After use, most of the ground water from the confined aquifers, excluding some used for domestic

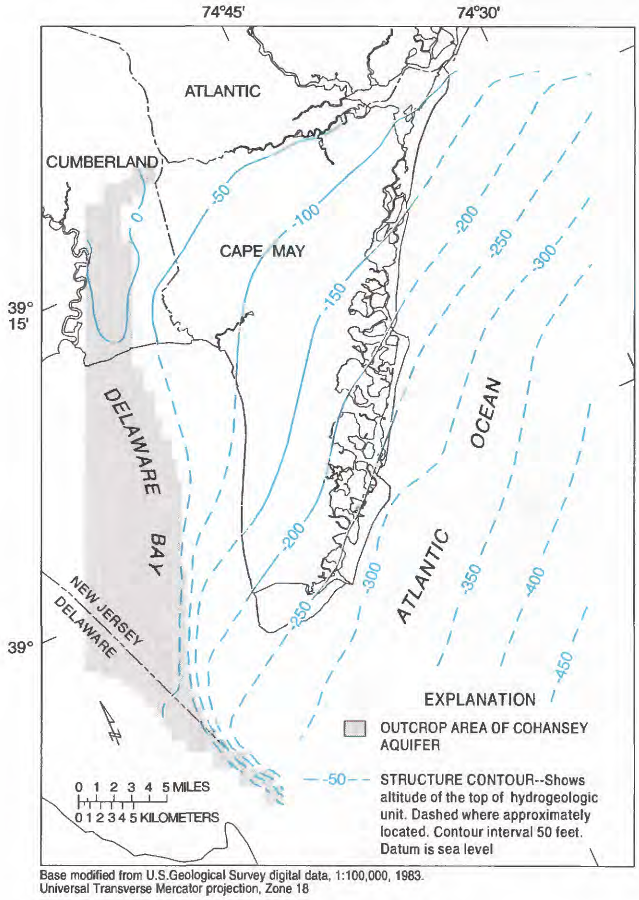


Figure 6. Altitude of the top of the Cohansey aquifer.

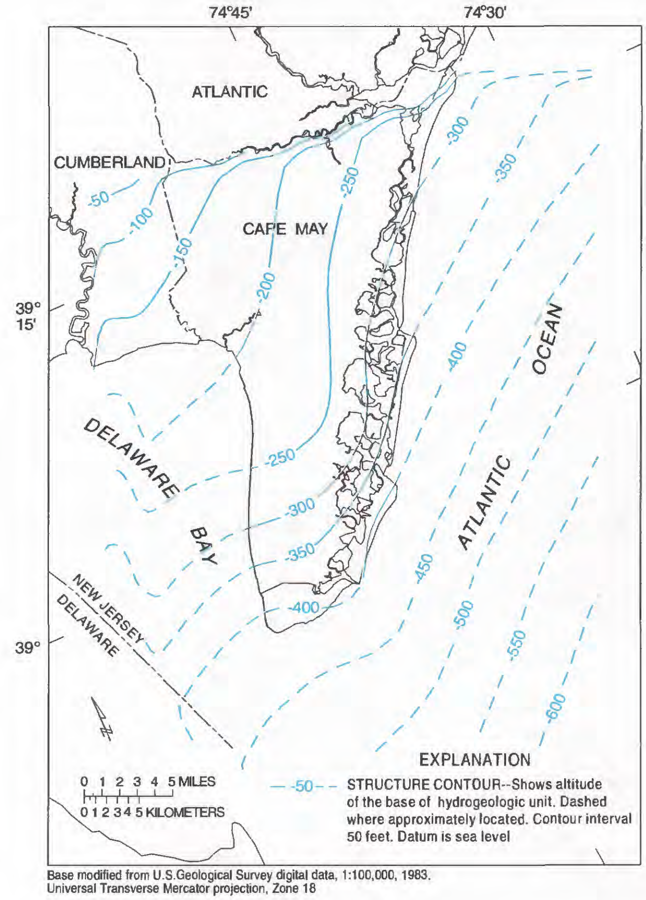


Figure 7. Altitude of the base of the Cohansey aquifer.

purposes, is collected by means of sanitary sewers, conveyed to wastewater-treatment plants, and discharged to ocean outfalls. Domestic wastewater is discharged locally to septic systems. The water discharged to the ocean is lost from the ground-water system, thereby reducing the overall storage in the system. The water is replaced partly by increased downward leakage to the confined aquifers. However, saltwater also encroaches and replaces the freshwater, particularly in the southern half of the Cape May peninsula.

Flow System

Cape May County covers 263 mi^2 and can be subdivided into four main regions: upland (108 mi^2), freshwater wetland (55 mi^2), tidal wetland (75 mi^2), and barrier island (25 mi^2). Tidal and nontidal areas are separated by the upper wetlands boundary (Robert Cubberly, New Jersey Department of Environmental Protection, written commun., 1993). Extensive tidal marshes border the lower reaches of the Tuckahoe River and Dennis Creek (fig. 10). Tidal fluctuations in water levels in the unconfined aquifer range from as much as 6 ft at the shore to near zero a few hundred feet inland. Tidal fluctuations in water levels in the confined aquifers are about half those in the unconfined aquifer at corresponding locations.

The shallow aquifer system at inland locations in Cape May County is recharged by infiltration of precipitation to the water table. The recharge area excludes land area covered by surface-water bodies, which carry the precipitation directly offshore. All of

Table 2. Reported hydraulic properties of aquifers and confining units of Cape May County, New Jersey

[Locations shown in figure 1; estimates from specific-capacity data; --, data not available or not applicable; ft/d, foot per day; ft^2/d, foot squared per day]

Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storage coefficient	Porosity	Type of data	Location	Reference
			Holly Beach water-bearing zone			
2,005	--	0.17	--	Estimate	Countywide	Gill (1962, p. 55)
--	--	--	0.3	Laboratory test	Swainton	Chirlin and Assoc. (1992, p. 13)
--	0.1-73	--	--	Aquifer test	Swainton	Chirlin and Assoc. (1992, p. 12)
--	8-60	--	--	Slug test	Swainton	Chirlin and Assoc. (1992, p. 12)
3,008	60	--	--	Aquifer test	Rio Grande	Roy F. Weston (1965, p. 7)
			Estuarine sand aquifer			
2,592-2,678	8-28	--	--	Slug test	Swainton	Chirlin and Assoc. (1992, p. 12)
9,158-11,430	152-286	.0004-.0007	--	Aquifer test	Cape May Court House	J.G. Rooney (U.S. Geological Survey, written commun., 1968, p. 9)
2,674-5,348	--	--	--	Estimate	Cape May peninsula	Gill (1962, p. 55)
			Cohansey aquifer			
9,193-13,132	131-168	.00007-.0008	--	Aquifer test	Marmora	Sevee and Maher Eng. (1990, p. 36)
--	176	--	--	Laboratory test	Marmora	Sevee and Maher Eng. (1990, p. 27)
--	102-140	--	.34-.40	Laboratory test	Pierces Point	Gill (1962, p. 51)
--	70-82	--	.32-.39	Laboratory test	Burleigh	Gill (1962, p. 51)
5,348-11,631	119-257	.0002-.003	--	Aquifer test	Rio Grande	Gill (1962, p. 49)
2,670	54	--	--	Aquifer test	Cape May	Schoor and Depalma (1992)
--	94-142	--	.32-.34	Laboratory test	Higbee Beach	Gill (1962, p. 51)
3,610-6,030	53-94	.0001-.0002	--	Aquifer test	Sewell Point	Gill (1962, p. 49)
8,422-9,639	132-150	.0002-.0005	--	Aquifer test	Cape May City	Gill (1962, p. 49)
--	46-64	--	.35-.37	Laboratory test	Cape May City	Gill (1962, p. 51)
			Estuarine clay confining unit			
--	.006-.01	--	--	Laboratory test	Swainton	Chirlin and Assoc. (1992, p. 12)
--	.1-.4	--	--	Aquifer test	Cape May Court House	J.G. Rooney (U.S. Geological Survey, written commun., 1968, p. 9)
--	.04-16	--	--	Laboratory test	Cape May Court House	J.G. Rooney (U.S. Geological Survey, written commun., 1968, p. 9)
--	.026	--	--	Laboratory test	Fishing Creek	Roy F. Weston (1965, p. 12)
			Clay overlying Cohansey aquifer			
--	1-2	--	--	Aquifer test	Marmora	Sevee and Maher Eng. (1990, p. 32)
--	.01-.1	--	--	Laboratory test	Woodbine	Camp Dresser and McKee (1988, p. 4-12)
--	.06	--	--	Laboratory test	Pierces Point	Gill (1962, p. 51)
--	.4	--	--	Laboratory test	Cape May City	Gill (1962, p. 51)

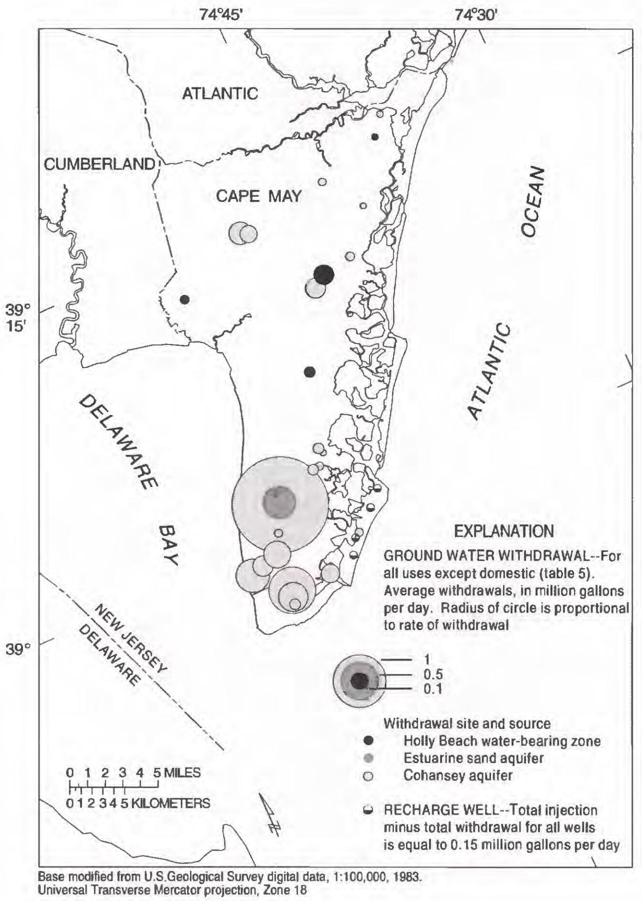


Figure 8. Well locations and withdrawals from the shallow aquifer system in 1989-90.

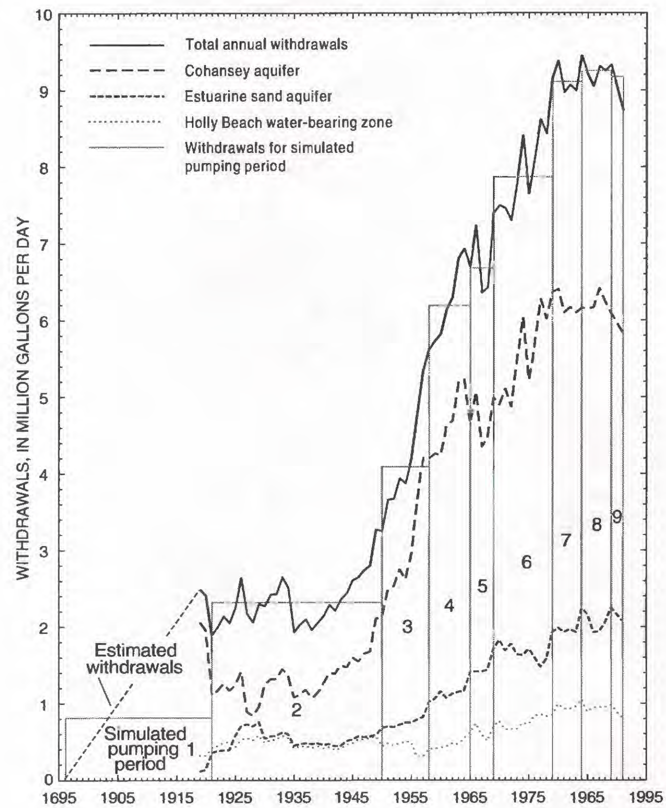
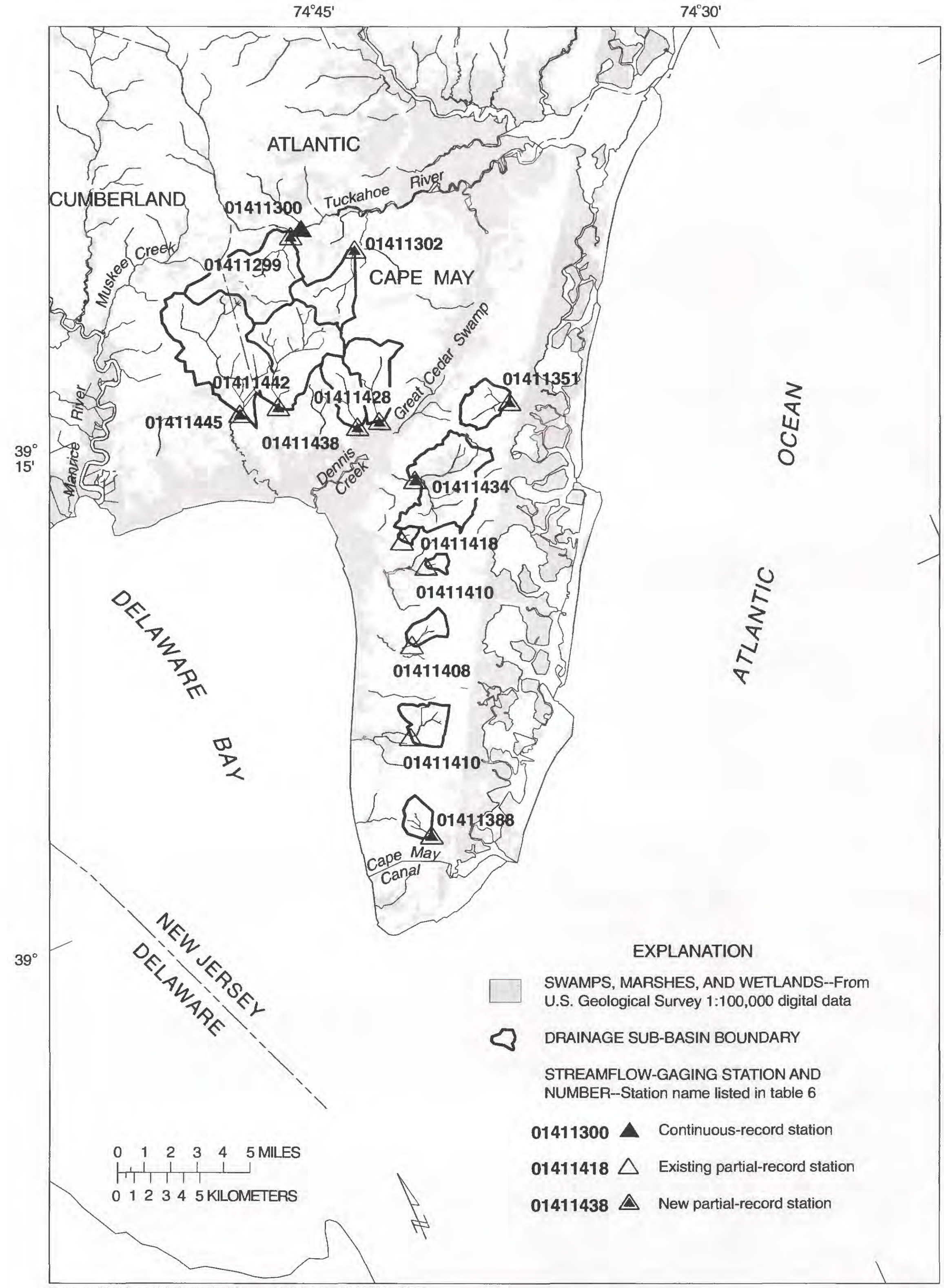


Figure 9. Estimated and simulated ground-water withdrawals in Cape May County from 1896 to 1990.

the recharge that enters the system first flows in the unconfined aquifer. Ground water that enters the system nearest to surface-water bodies follows the shallowest flow path and discharges to these bodies as base flow. Ground water that moves deeper within the unconfined aquifer but does not flow downward to the confined aquifers is discharged to low-lying streams, tidal wetlands, and the ocean.

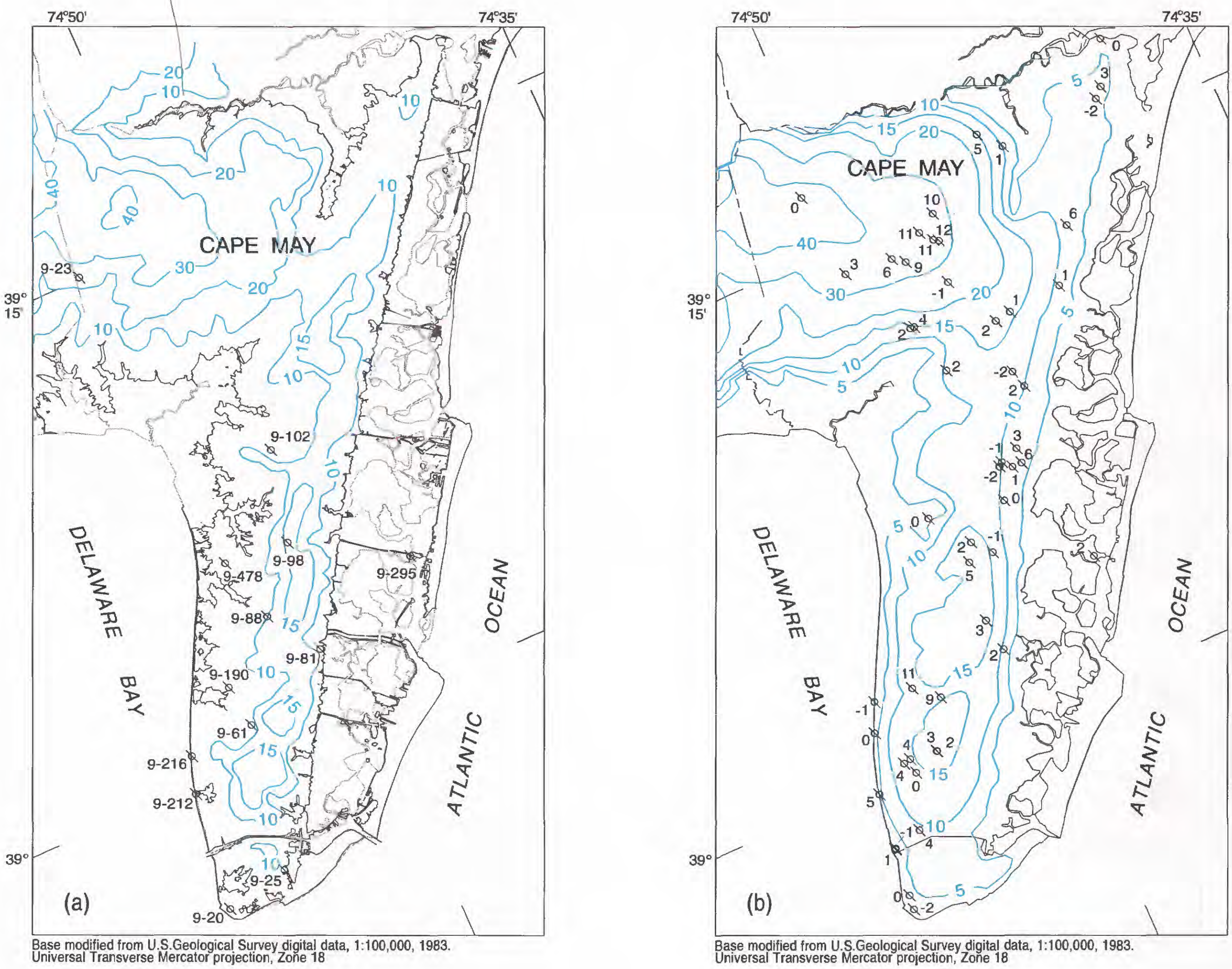
The Tuckahoe River and approximately 25 small streams are present in the county (fig. 10). The U.S. Geological Survey maintains a continuous-record streamflow-gaging station on the Tuckahoe River (01411300). Over the period of record (1969-93), mean annual streamflow at this station was 42.8 ft^3/s. Mean monthly minimum streamflow at this station was 22.7 ft^3/s in September and mean monthly maxmum streamflow was 67.6 ft^3/s in April. Only measurements from partial-record streamflow-gaging stations are available for 13 of the 25 small streams (Bauersfeld and others, 1993).

Low flow in the small streams was measured 11 times from September 1990 through March 1992 and was assumed to represent base flow. These flows were statistically correlated with the same-day flow in the Tuckahoe River (G.B. Carleton, written commun., 1994) by using the maintenance of variance extension, type 1 technique (Hirsch, 1982). The mean annual base flow of the Tuckahoe River was estimated to be 37.2 ft^3/s (G.B. Carleton, written commun., 1994) by using the sliding-interval technique (Pettyjohn and Henning, 1979). Mean annual base flow of small streams was estimated from mean annual base flow of the Tuckahoe River using the correlation equations.



Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

Figure 10. Surface-water features in the study area.



EXPLANATION

—10— MEASURED WATER-TABLE CONTOUR--Shows altitude of April 1991 water levels. Source of data is G.B. Carleton (U.S. Geological Survey, written commun., 1994). Contour interval 5 and 10 feet. Datum is sea level

—— UPPER WETLANDS BOUNDARY--Separates tidal and non-tidal areas. Source of data is Robert Cubberly (N.J. Department of Environmental Protection, written commun., 1993)

9-20 OBSERVATION WELL AND NUMBER--Hydrograph shown in figure 31

EXPLANATION

—10— SIMULATED WATER-TABLE CONTOUR--Shows altitude of average 1991 water levels. Contour interval 5 and 10 feet. Datum is sea level

1 OBSERVATION WELL--Number is head residual, in feet

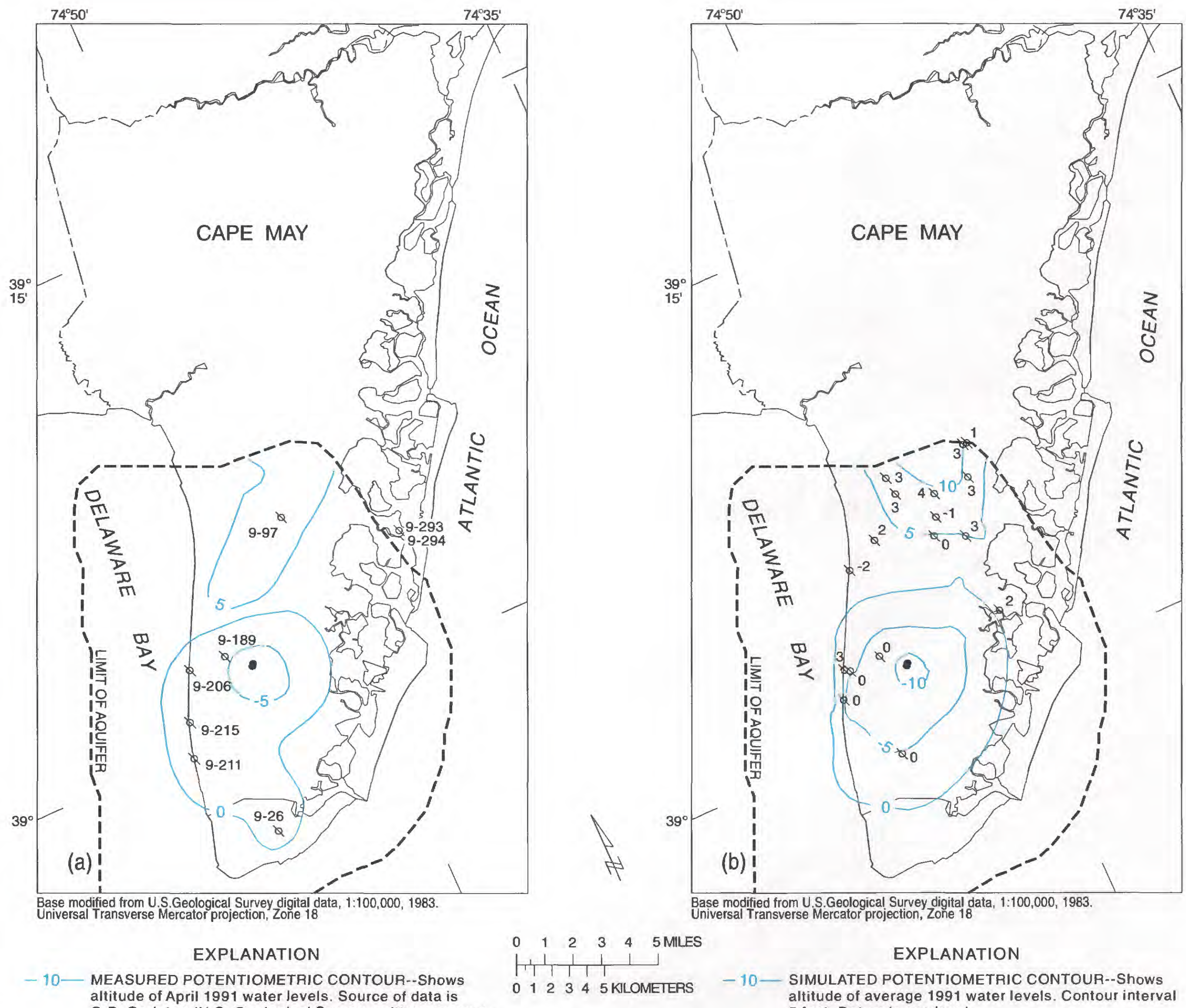
0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

Figure 11. Water table in the Holly Beach water-bearing zone based on: (a) water levels measured in April 1991 and (b) simulated average water levels in 1991.

Prior to the start of ground-water withdrawals in Cape May County in the late 1800's, water levels in each of the shallow aquifers stood above sea level. Water levels in the unconfined aquifer have declined locally since withdrawals began, whereas water levels in the confined aquifers have declined regionally.

Water levels in the unconfined aquifer (fig. 11a) depend strongly on land-surface topography. Gradients in the aquifer are steep northwest of Great Cedar Swamp (fig. 10), and flat on the peninsula. Water levels in the aquifer fluctuate as much as 5 ft seasonally, and are usually highest in April and lowest in Septem-



EXPLANATION

— 10 — MEASURED POTENTIOMETRIC CONTOUR--Shows altitude of April 1991 water levels. Source of data is G.B. Carleton (U.S. Geological Survey, written commun., 1994). Contour interval 5 feet. Datum is sea level

9-26 OBSERVATION WELL AND NUMBER--Hydrograph shown in figure 32

• WATER-SUPPLY WELL

EXPLANATION

— 10 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of average 1991 water levels. Contour interval 5 feet. Datum is sea level

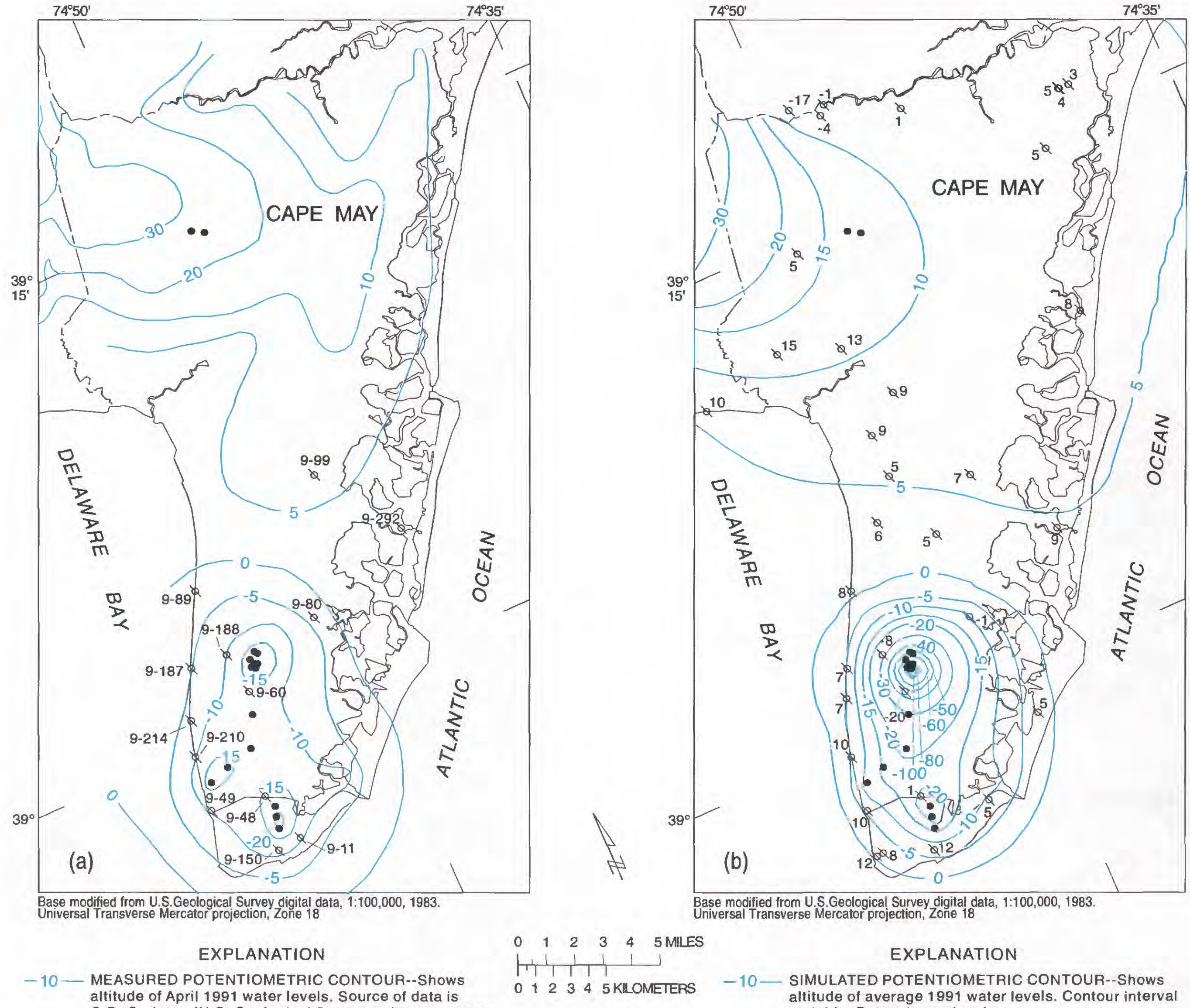
1 OBSERVATION WELL--Number is head residual, in feet

• WATER-SUPPLY WELL

Figure 12. Potentiometric surface in the estuarine sand aquifer based on: (a) water levels measured in April 1991 and (b) simulated average water levels in 1991.

ber. Construction of the Cape May Canal in the 1940's has dewatered the aquifer locally and has affected water levels.

Prior to ground-water withdrawals, the estuarine sand aquifer was recharged from the overlying Holly Beach water-bearing zone along the centerline of the peninsula. The location of the recharge area varied with seasonal and climatic changes. Ground water then flowed downgradient toward offshore areas and discharged upward along the saltwater-freshwater boundary. Ground-water withdrawals from this aquifer and the underlying Cohansey aquifer have lowered water



EXPLANATION

—10— MEASURED POTENTIOMETRIC CONTOUR--Shows altitude of April 1991 water levels. Source of data is G.B. Carleton (U.S. Geological Survey, written commun., 1994). Contour interval 5 and 10 feet. Datum is sea level

9-48 OBSERVATION WELL AND NUMBER--Hydrograph shown in figure 33

• WATER-SUPPLY WELL

EXPLANATION

—10— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of average 1991 water levels. Contour interval variable. Datum is sea level

1 OBSERVATION WELL--Number is head residual, in feet

• WATER-SUPPLY WELL

Figure 13. Potentiometric surface in the Cohansey aquifer based on: (a) water levels measured in April 1991 and (b) simulated average water levels in 1991.

levels in this aquifer below sea level in the southern half of the peninsula (fig. 12a). Natural flow directions in this area have reversed and are now toward shore. A local cone of depression has formed at the Rio Grande well field. Only north of this well field have water levels changed little over time. Current flow patterns also indicate that seawater may be recharging the aquifer in its outcrop area in the Delaware Bay. Gradients in the aquifer are shallower than those in the Holly Beach water-bearing zone. Water levels in the aquifer fluctuate as much as 20 ft seasonally, and the fluctuations are greatest at major withdrawal locations.

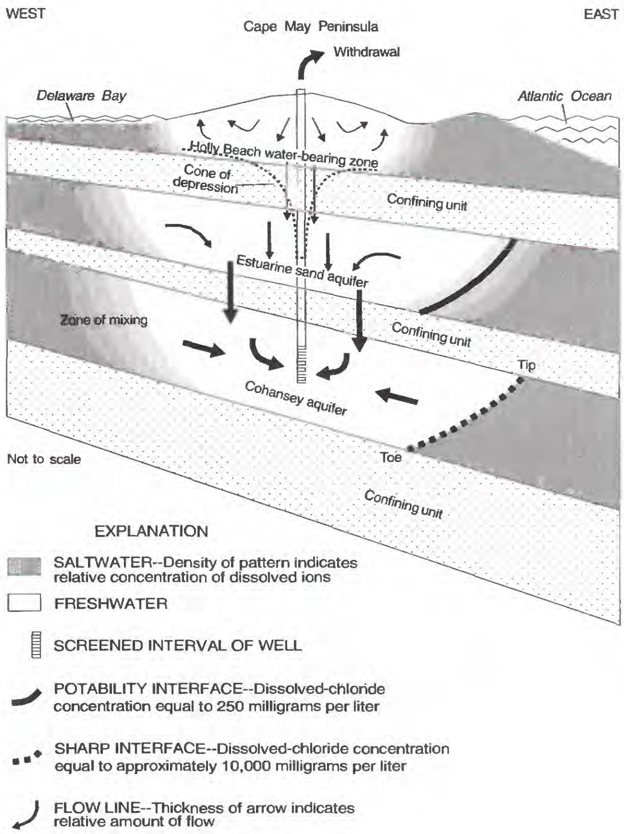


Figure 14. Diagram of the shallow aquifer system on the Cape May peninsula, New Jersey.

On the peninsula, predevelopment flow patterns in the Cohansey aquifer were similar to those in the estuarine sand aquifer. Flow from the overlying aquifers recharged the aquifer along the centerline of the peninsula. Withdrawals from the Cohansey aquifer have increased downward flow by creating a regional cone of depression and three local cones of depression that are centered at the major withdrawal locations (fig. 13a). The area of lowered water levels likely extends offshore. Within the regional cone, water levels north of the Cape May Canal have continued to decline, whereas water levels south of the canal have recovered from lows measured in the 1960's. In the northern part of the county, ground water discharges naturally to the Tuckahoe River and offshore. Water levels in the Cohansey aquifer north of Cape May Court House (fig. 1) have not changed over time and resemble water levels in the unconfined aquifer. Gradients in the Cohansey aquifer are shallower than those in the unconfined aquifer in the northern part of the county and are similar to those in the estuarine sand aquifer on the peninsula. Water levels in the aquifer fluctuate as much as 30 ft seasonally.

Water Quality

Ground-water quality in Cape May County varies due to land-use practices and the proximity to saltwater, which are the main causes of contamination in the shallow aquifer system. Ground-water supplies not directly affected by these factors exist in a natural, pristine state. Natural ground water can contain sodium, chloride, iron, and manganese in concentrations that exceed drinking-water standards (New Jersey Administrative Code, 1990).

Effects of Saltwater Encroachment

A representative cross section through the shallow aquifer system on the Cape May peninsula is shown in figure 14. All three shallow aquifers of Cape May County are contaminated with saltwater. Saltwater encroachment probably began slowly with the Pleistocene sea-level rise. Encroachment increased when the first wells were drilled in the county and withdrawals caused ground-water levels to decline below sea level. Since the 1940's, saltwater contamination has forced the abandonment of many public supply wells (Lacombe and Carleton, 1992). Saltwater contamination is defined as the presence of dissolved chloride in concentrations at or greater than 250 mg/L (New Jersey Administrative Code, 1990). Sodium is a less reliable indicator of saltwater contamination in ground water because sodium concentrations can increase through cation exchange with confining-unit materials.

Saltwater encroachment in the unconfined Holly Beach water-bearing zone has affected only nearshore domestic wells (fig. 15a), whereas encroachment in the confined aquifers is more extensive. Coastal flooding can also introduce saltwater into the Holly Beach water-bearing zone in lowlying areas. In the estuarine sand aquifer, saltwater contamination is prevalent in the Villas area (fig. 1), where many domestic wells have been abandoned since 1965 (fig. 16a). Dissolved-chloride concentrations greater than 250 mg/L have also been measured in the aquifer in

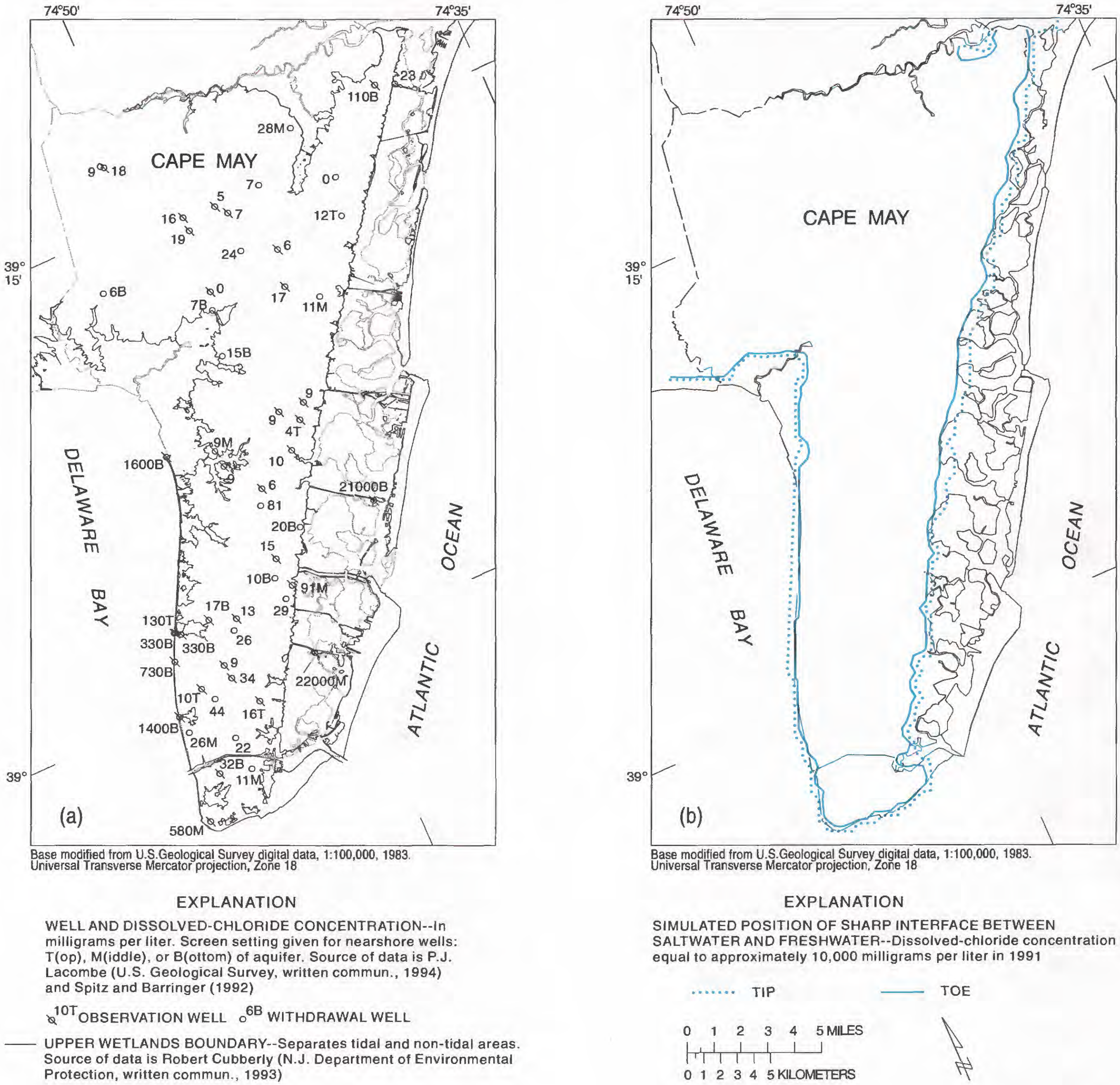


Figure 15. Water quality in the Holly Beach water-bearing zone based on: (a) recent measured dissolved-chloride concentrations and (b) simulated sharp-interface position between saltwater and freshwater in 1991.

isolated nearshore locations in other parts of the peninsula.

Saltwater encroachment has been widespread in the Cohansey aquifer (fig. 17a). Saltwater contamination has significantly affected the public supply wells belonging to Cape May City (fig. 1). Of the five remaining wells (9-12, 9-14, 9-27, 9-45, 9-43), three have been affected by saline water. This has forced Cape May City to purchase freshwater from Lower Township. Saltwater contamination also caused aban-

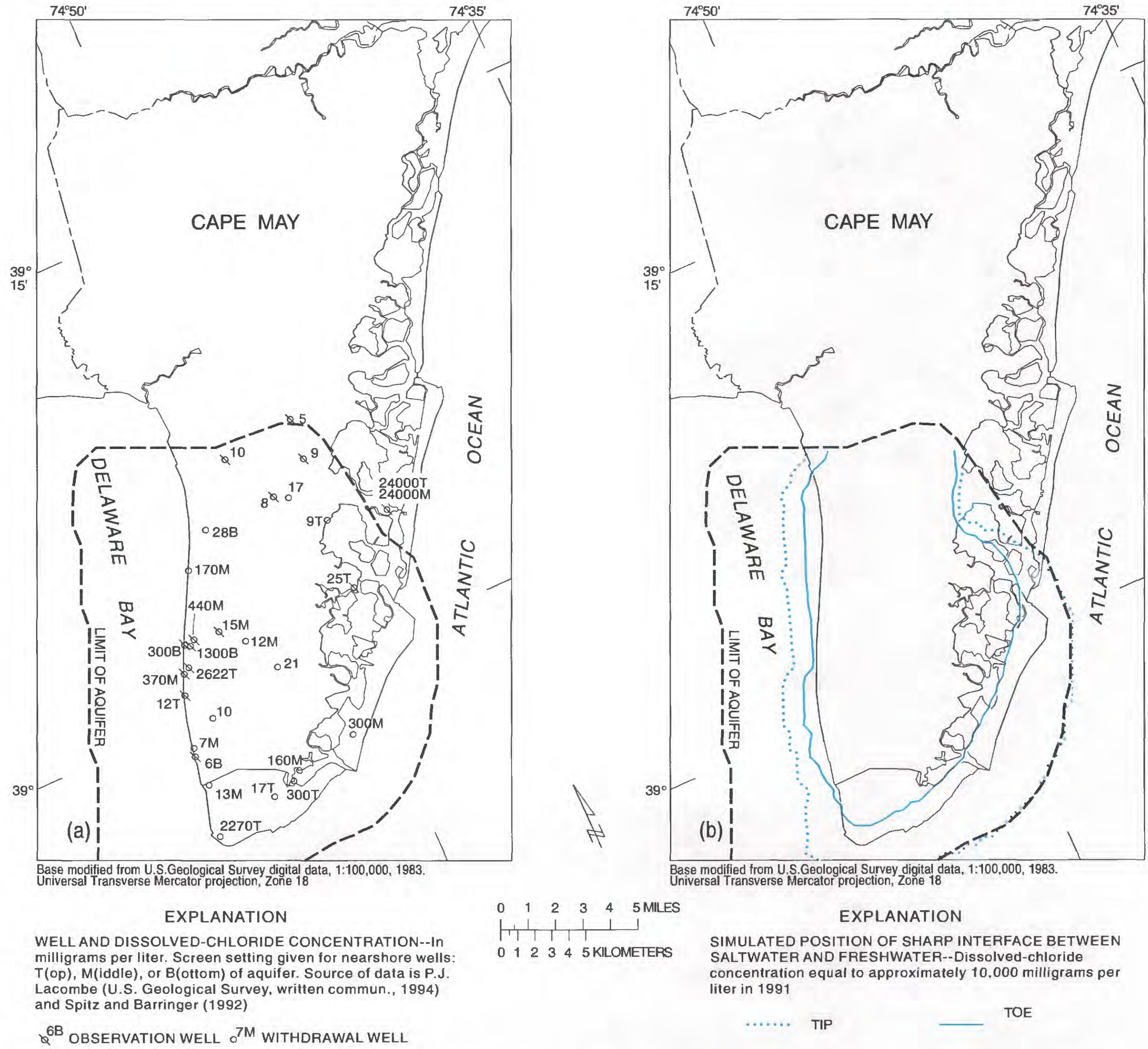


Figure 16. Water quality in the estuarine sand aquifer based on: (a) recent measured dissolved-chloride concentrations and (b) simulated sharp-interface position between saltwater and freshwater in 1991.

donment of the two public supply wells belonging to Cape May Point by 1972 (9-19, 9-21). Both Cape May Point and West Cape May purchase water from Cape May City. Near Sunset Beach, saltwater contamination affected the two wells belonging to Northwest Magnesite Company[1] by 1978 (9-29, 9-28). Increasing dissolved-chloride concentrations that are just below 250 mg/L were measured at the Delaware Bay shore west of the Rio Grande well field in 1994. In the eastern part of the county, chloride concentrations are greater than 250 mg/L beneath the barrier islands and

[1]The use of firm names in this report is for identification purposes only and does not impute responsibility for any present or potential effects on water resources in the study area.

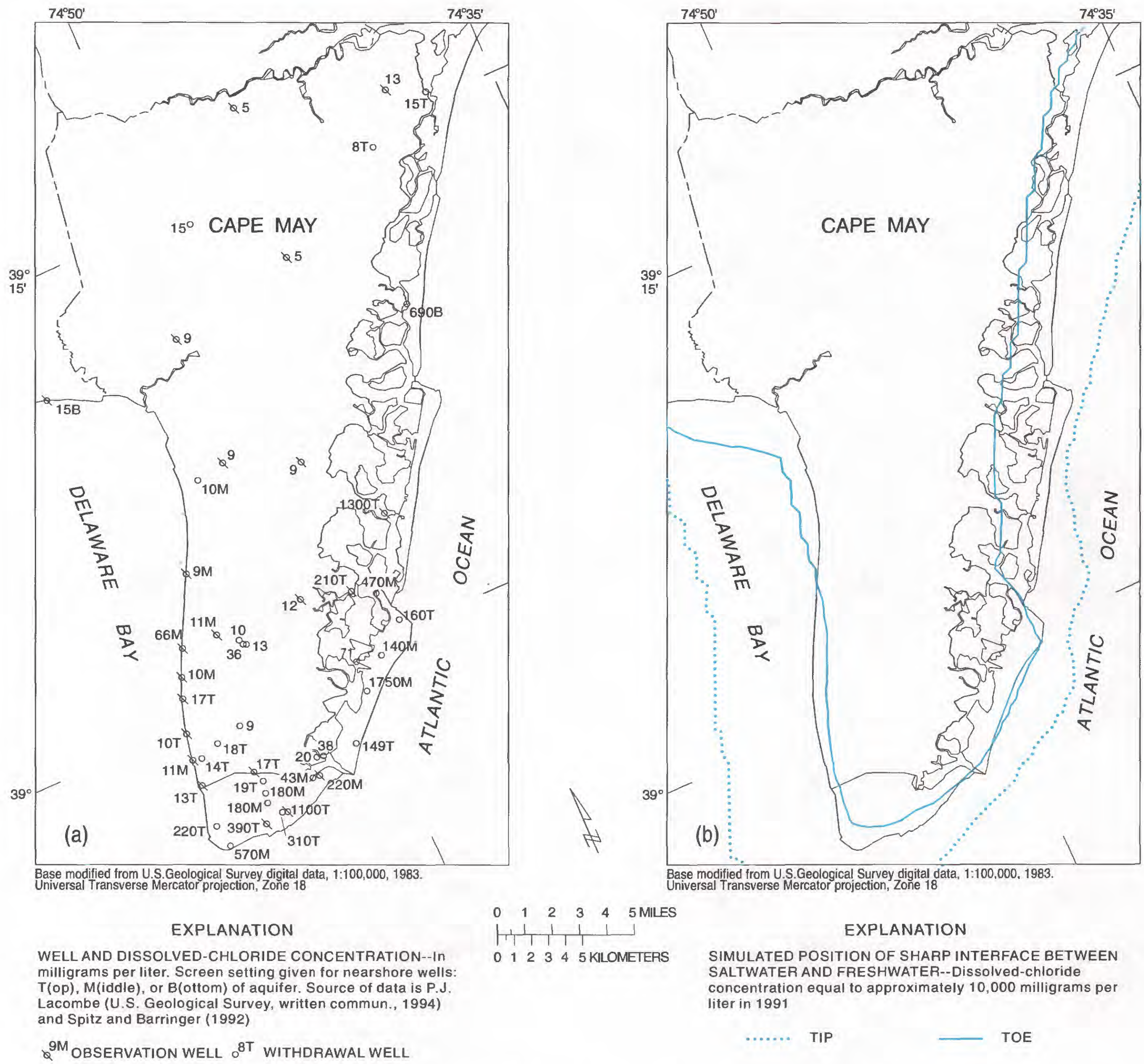


Figure 17. Water quality in the Cohansey aquifer based on: (a) recent measured dissolved-chloride concentrations and (b) simulated sharp-interface position between saltwater and freshwater in 1991.

part of the adjacent tidal wetlands. Saltwater upconing may have occurred at the Stokes Laundry well (9-182) in Wildwood Crest in 1989. No saltwater contamination has yet been found, however, in the Lower Township public supply wells.

Effects of Land-Use Practices

Ground water also can be contaminated as a consequence of land-use practices. This type of contamination has limited development of the unconfined aquifer for water supply. Runoff from nonpoint- and point-source contamination infiltrates to the unconfined aquifer. Sources of both nonpoint- and point-

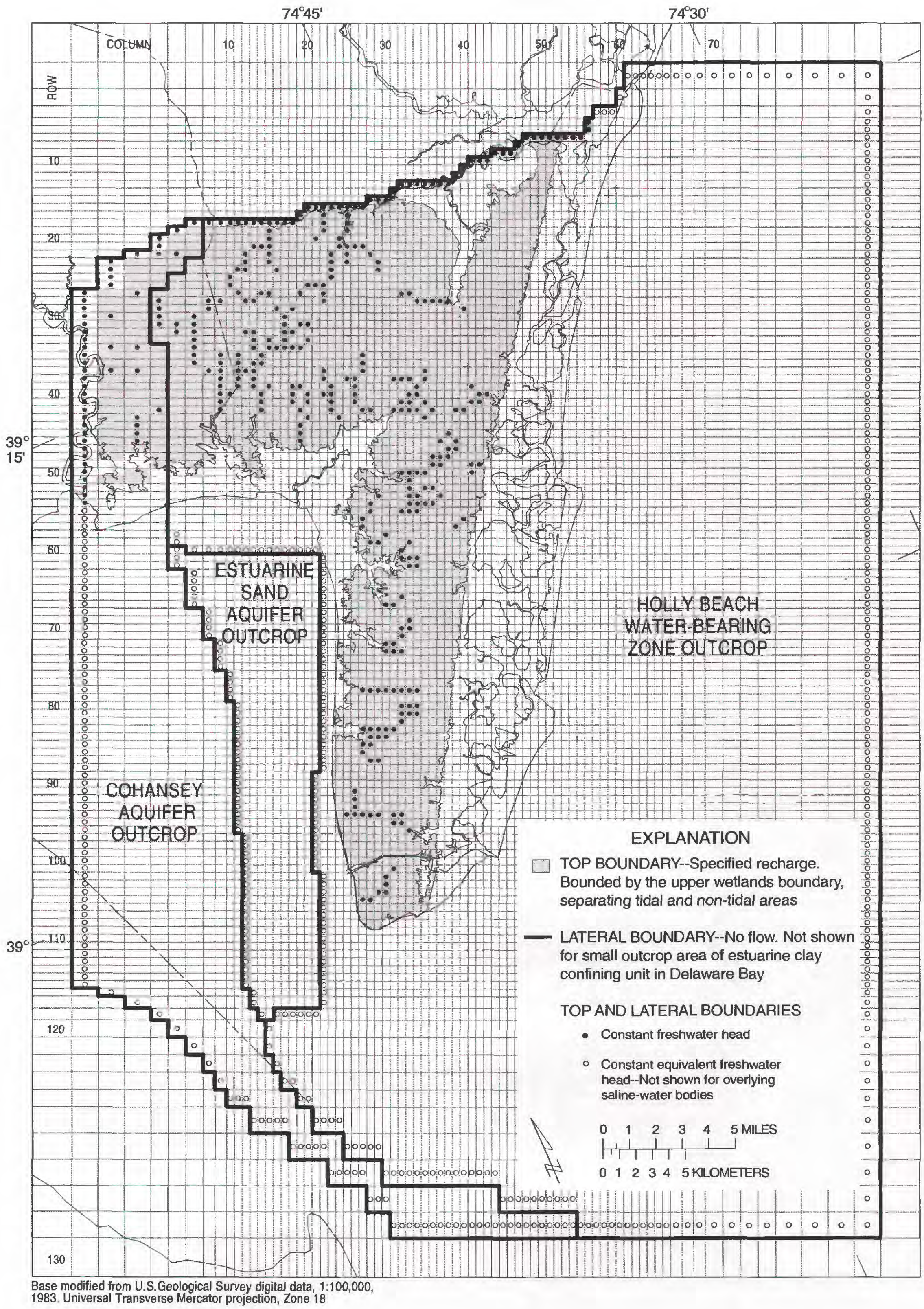


Figure 18. Model grid and boundary conditions, Cape May County, New Jersey.

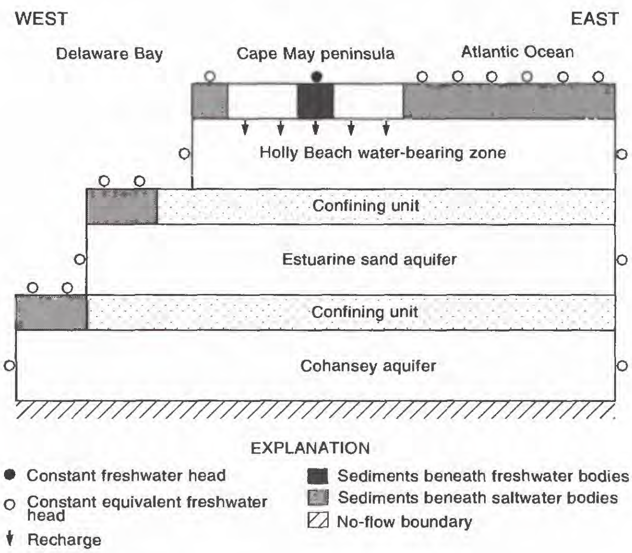


Figure 19. Schematic diagram along a row of the model through the Cape May peninsula.

source contamination are widespread in the county, particularly in the developed areas south of Great Cedar Swamp (fig. 10). A list of known sites in the county where contamination of soil or ground water is confirmed and is either undergoing or awaiting remediation is maintained by the NJDEP (New Jersey Department of Environmental Protection, 1994).

Nonpoint-source contamination is found in developed and agricultural areas. In developed areas, contamination is created by many sources; one example is domestic septic systems. In agricultural areas, contamination is caused by use of fertilizers and pesticides. Examples of point sources of contamination are hazardous-waste sites, landfills, underground storage tanks, industrial sites, and waste-treatment facilities. These sites typically cover an area of less than 5 acres each.

ANALYSIS OF GROUND-WATER FLOW AND SALTWATER ENCROACHMENT

The physical system at the interface between the saltwater and freshwater ground-water environments is complex and, therefore, is rarely simulated in terms of fully three-dimensional density-dependent miscible-fluid flow in a porous medium. Instead, appropriate simplifying assumptions are made to facilitate a reasonable and tractable approximation of the system that quantifies the relation between saline and fresh ground water. The two main numerical conceptualizations of saltwater-freshwater systems are the sharp-interface approach and the variable-density approach. The sharp-interface approach assumes that the system is composed of two completely immiscible fluids. The variable-density approach assumes that only one miscible fluid is transporting a solute, which affects the density and viscosity of the fluid. The variable-density approach also includes the effects of dispersion and chemical reactions associated with advective movement. If regional estimates of the location of saltwater are desired, the sharp-interface approach is most appropriate. If local estimates of dissolved-chloride concentrations in water are desired, the more complex, more restrictive, and less tractable variable-density approach is used.

The shallow-aquifer system of Cape May County was simulated by using the SHARP Fortran code (Essaid, 1990). SHARP is a quasi-three dimensional finite-difference code that simulates both freshwater and saltwater flow in layered coastal aquifers by coupling the two mathematical equations representing the freshwater and saltwater flow. The equations are coupled because the fluids share a boundary at the interface. The parabolic partial-differential equations are solved simultaneously for freshwater and saltwater head. Once the heads are calculated, the interface elevation is calculated by using the equation for continuity of fluid pressure at the interface.

Model Limitations and Assumptions

The limitations of any numerical analysis of a ground-water system affect the conclusions drawn about the system and the certainty of results of predictive simulations made with a calibrated model. Limitations fall into three categories: those due to characteristics of the data, those due to simplifications in the computer code, and those due to simplifications in the model formulation. Data limitations result from a lack of data--for example, on the location of saline ground water--or inaccuracy of data--for example, recharge and withdrawal estimates. A third type of data limitation is the error associated with field measurements.

Table 3. Values of hydraulic properties of aquifers and confining units used in the simulation of ground-water flow of Cape May County, New Jersey

[Values for onshore area only; --, data not available or not applicable; ft/d, foot per day; ft^2/d, foot squared per day; ft/d/ft, foot per day per foot]

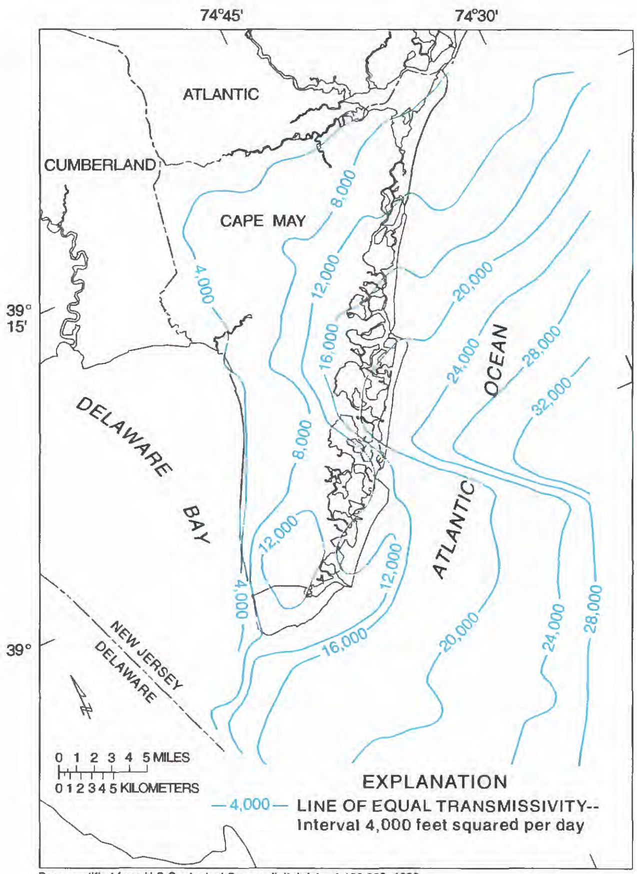
Transmissivity[1] (ft^2/d)	Hydraulic conductivity (ft/d)	Leakance[2] (ft/d/ft)	Storage coefficient[3]	Porosity
		Holly Beach water-bearing zone		
7,560-13,140	126-219	--	0.06	0.3
		Estuarine sand aquifer		
4,400-10,080	55-126	--	.0006	.3
		Cohansey aquifer		
2,610-13,050	18-90	--	.0004	.3
		Sediments beneath surface-water bodies		
--	4-8	.08-.16	--	--
		Estuarine clay confining unit		
--	.004	.000005	--	--
		Clay overlying Cohansey aquifer		
--	.002	.000008	--	--

[1]Calculated as hydraulic conductivity multiplied by average aquifer thickness.
[2]Calculated as vertical hydraulic conductivity (assumed to be one-tenth of hydraulic conductivity) divided by average confining-unit thickness (bed thickness beneath surface-water bodies is assumed to be 5 ft).
[3]Calculated as specific storage multiplied by average aquifer thickness.

The limitations and assumptions of the SHARP Fortran code, discussed in Essaid (1990), include its inability to explicitly represent flow in confining units, upconing of saltwater beneath well screens, and tidal effects. Discretization of the study area requires that the hydraulic properties, recharge, and streamflow within grid cells be approximated. Discretization creates an offset error between field measurements at actual well locations and simulated values at model nodes. In addition, more than one well can be simulated in a cell, thereby overestimating drawdown in that cell.

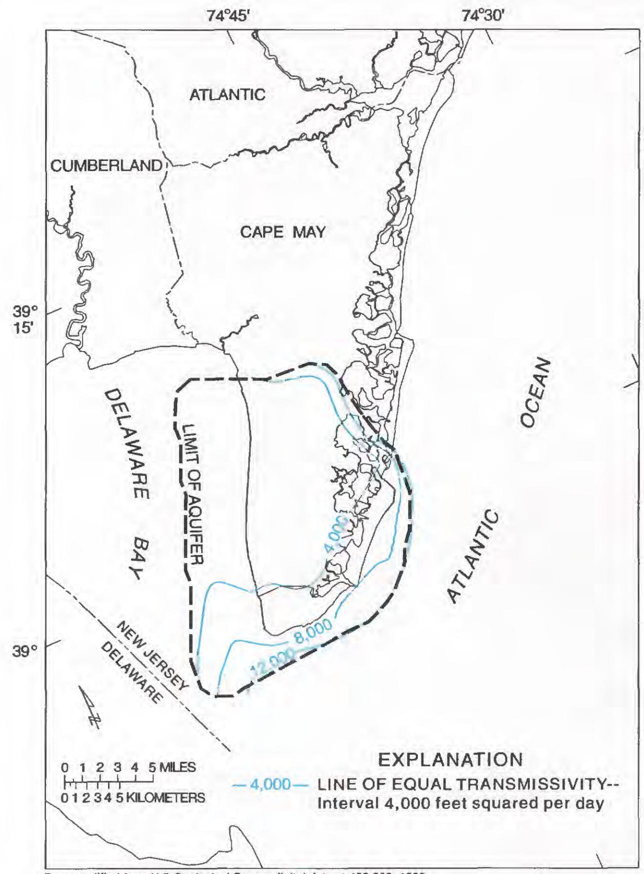
In the SHARP code, the mixing zone between freshwater and saltwater is assumed to be abrupt. This means that the interface that separates fresh ground water from saline ground water has no transition. In reality, the transition is gradual (fig. 14), and in Cape May County, the mixing zone can be several thousand feet wide, as indicated by measurements of chloride concentrations in ground water. This implies that dilute saline water, with a dissolved-chloride concentration greater than the 250-mg/L potability limit, is located landward of the simulated sharp interface. Because ground-water velocities within the mixing zone vary, simulated movement of the sharp interface can be much smaller than estimated movement of the "potability interface" (representing the approximate location of the 250-mg/L chloride concentration). Tracking of the movement of the potability interface in this study represents an improvement over tracking of the movement of the sharp interface in earlier studies (Spitz and Barringer, 1992; Spitz, 1996).

Furthermore, in the sharp-interface approach to numerical analysis of saltwater-freshwater systems,



Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

Figure 20. Transmissivity values used in the model for the Holly Beach water-bearing zone.



Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

Figure 21. Transmissivity values used in the model for the estuarine sand aquifer.

the width of the mixing zone is assumed to be small compared to the thickness of the aquifer. This assumption is violated in some areas of Cape May, where the mixing zone is more than a mile wide. The density gradient present over a wide transition (mixing) zone causes heads to be higher on the freshwater side of the sharp interface and the interface to be located farther seaward than would be the case if no mixing occurred. However, the density effect is small in locations where ground-water chloride concentrations are only a few thousand milligrams per liter (Reilly, 1993, table 18-3). Thus, model results are valid in most areas where saltwater encroachment is a concern.

Leakage in the Cape May model is chosen to be restricted (an option in the SHARP code), which prevents saltwater from leaking into the freshwater zone. This assumption is recommended for systems with considerable vertical leakage (Essaid, 1990, p. 56). Choosing this option counterbalances the farther inland simulated location of the saltwater in the SHARP code with complete mixing when compared to that in a variable-density code (Hill, 1988).

Finally, the shallow aquifer system is assumed to be composed of layered units. All aquifers are assumed to be isotropic, withdrawals are averaged over simulated pumping periods, and local-scale heterogeneities or short-term effects are not simulated.

Model Design

The shallow aquifer system of Cape May County was discretized by use of a model grid with 130 rows,

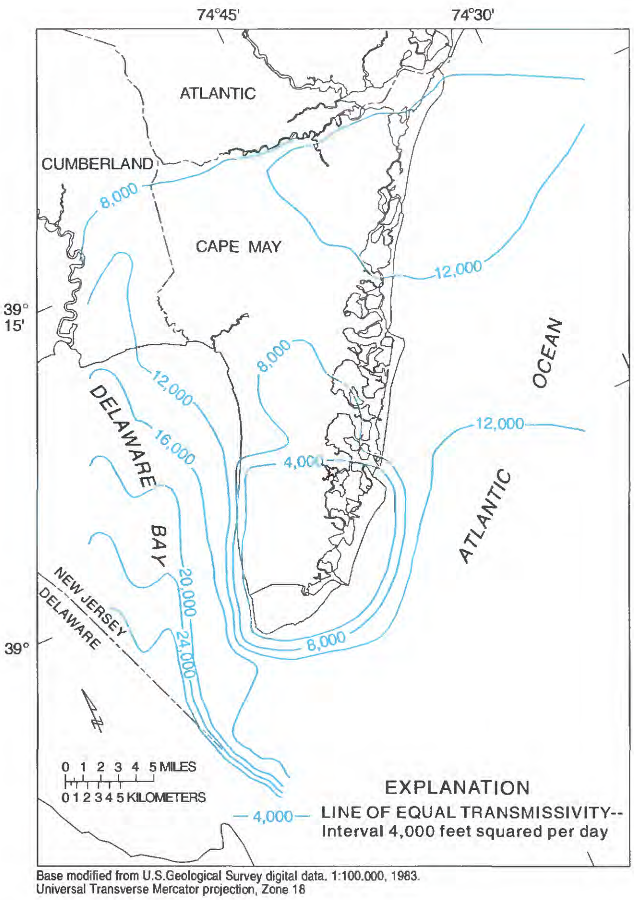


Figure 22. Transmissivity values used in the model for the Cohansey aquifer.

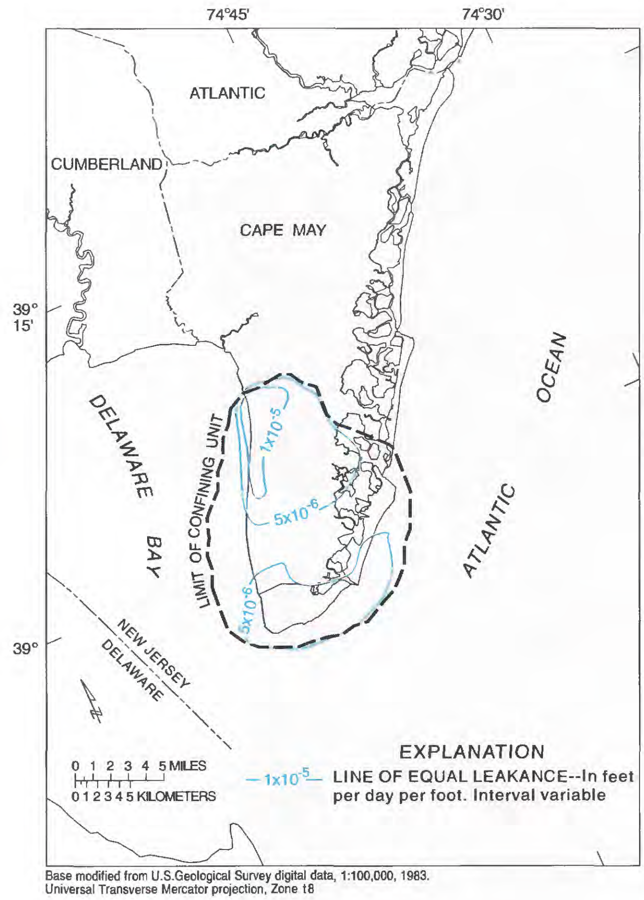


Figure 23. Leakance values used in the model for the estuarine clay confining unit.

78 columns, and 3 aquifer layers. Areal and cross-sectional views of the grid are shown in figures 18 and 19, respectively. Model boundaries were selected to coincide with natural hydrologic boundaries where possible or to be distant so as not to affect simulation results within the county border. Grid-cell size was chosen to be uniform over the county and minimum size (approximately 1,500 ft on a side) was limited by computing requirements. The smallest cell size was insufficient to simulate local ground-water flow patterns beneath the barrier islands. Time discretization is discussed in the transient calibration section of this report. Input data sets for the model were created by using three separate application programs of a geographic information system (GIS) to assign hydraulic properties, boundary conditions, and initial conditions.

Boundary Conditions

The top boundary of the model in areas with surface-water bodies is a constant-head boundary. In freshwater areas, the constant head is defined by topographic elevation. In saltwater areas, the constant head is defined by the equivalent freshwater head of saltwater, because of the density difference between the two fluids. Equivalent freshwater head is calculated as

$$h_f = z + \frac{\rho_w}{\rho_f} l$$

where h_f = equivalent freshwater head,

z = elevation above datum of the point representing the well screen,

ρ_w = density of the fluid in the well,

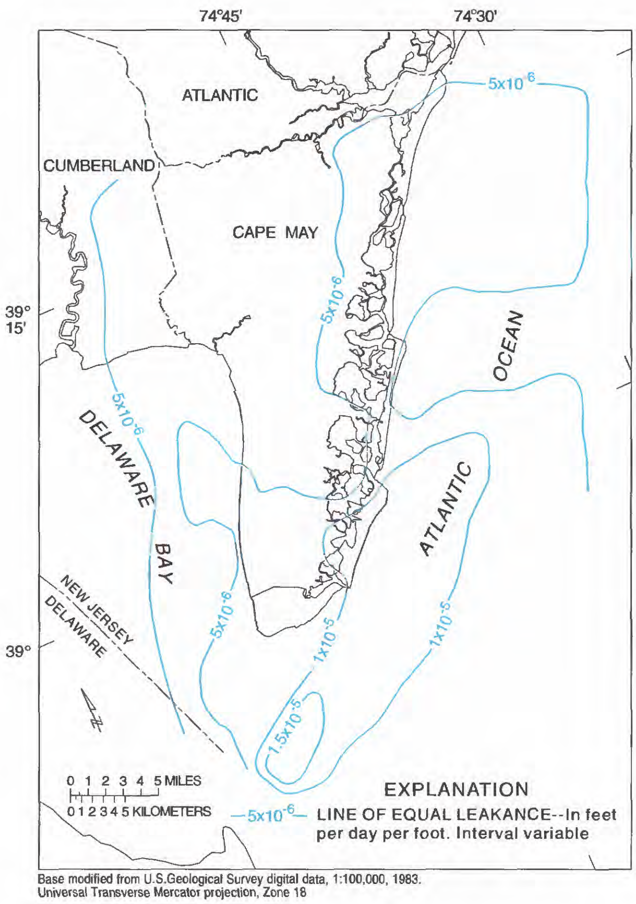


Figure 24. Leakance values used in the model for the confining unit overlying the Cohansey aquifer.

ρ_f = density of freshwater, and

l = vertical height of fluid in the well above the point representing the well screen.

The equation in this form is valid only for the determination of horizontal flow and when the heads are in wells screened at the same elevation (Reilly, 1993).

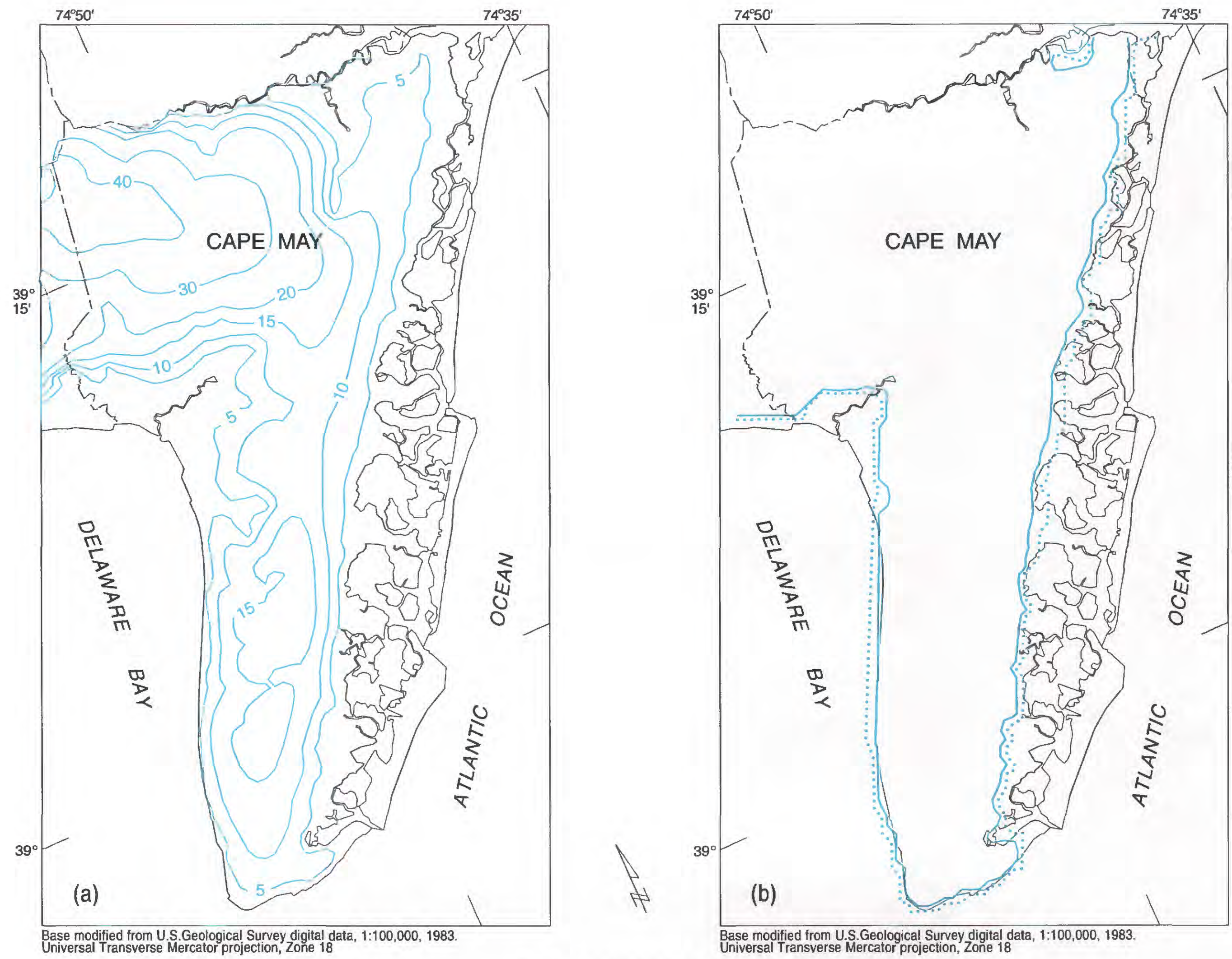
For constant-head boundaries, the flow between the constant head and the underlying aquifer is controlled by the leakance of the intervening bed material. Leakance is calculated from bed thickness and vertical hydraulic conductivity. Streambed leakance is calculated by using stream length and width in addition to these two parameters. Streams are estimated to average 0.5 ft in depth, 5 ft in width, and 5 ft in bed thickness on the basis of field observations (G.B. Carleton, written commun., 1994). Stream length is estimated by using a GIS.

The top boundary of the model in areas without surface-water bodies is the water table. The water table is a specified-flux boundary to which ground-water recharge is applied. Recharge also is applied to constant-freshwater-head boundaries. Recharge is estimated to be 16.6 in/yr from the water budget for the unsaturated zone developed by P.J. Lacombe (written commun., 1994); this amount is equal to precipitation (41.9 in/yr) minus the sum of evapotranspiration (22.4 in/yr) and direct runoff (2.9 in/yr).

The bottom boundary of the model is a no-flow boundary representing the thick confining unit beneath the Cohansey aquifer. Lateral boundaries of the model in areas representing the Maurice River, Muskee Creek, and Tuckahoe River (fig. 10) are defined as constant-freshwater-head boundaries. These boundaries receive no recharge. Lateral boundaries of the model in areas representing the Delaware Bay and Atlantic Ocean are defined by an equivalent freshwater head. Initial conditions of the model consist of freshwater heads and saltwater-freshwater-interface elevations. Interface elevations are chosen so that the initial calculated saltwater heads are zero.

Hydraulic Properties

The hydraulic properties of aquifers and confining units used in the model are listed in table 3. The values used in the simulations are generally within the range of reported values (table 2) for onshore areas. The simulated hydraulic conductivities of the Holly Beach water-bearing zone are higher than reported values mainly as a result of insufficient allotment of freshwater-discharge areas in the model. An incomplete GIS data base on wetlands at the time of model construction precluded discretization of all freshwater wetlands in the model. The absence of some freshwater wetlands impeded discharge from the unconfined aquifer, resulting in the need for a high simulated value for aquifer hydraulic conductivity and stream-bed hydraulic conductivity (8 ft/d), and a low simulated value for recharge (15 in/yr). A lower simulated recharge is reasonable given that evapotranspiration from wetlands is usually higher than that from uplands. The simulated value of streambed hydraulic conductivity is within the range of reported values for unconsolidated streambed sediments (Vogel and Reif, 1993, table 12).



EXPLANATION

—10— SIMULATED WATER-TABLE CONTOUR--Shows altitude of predevelopment water levels. Contour interval 5 and 10 feet. Datum is sea level

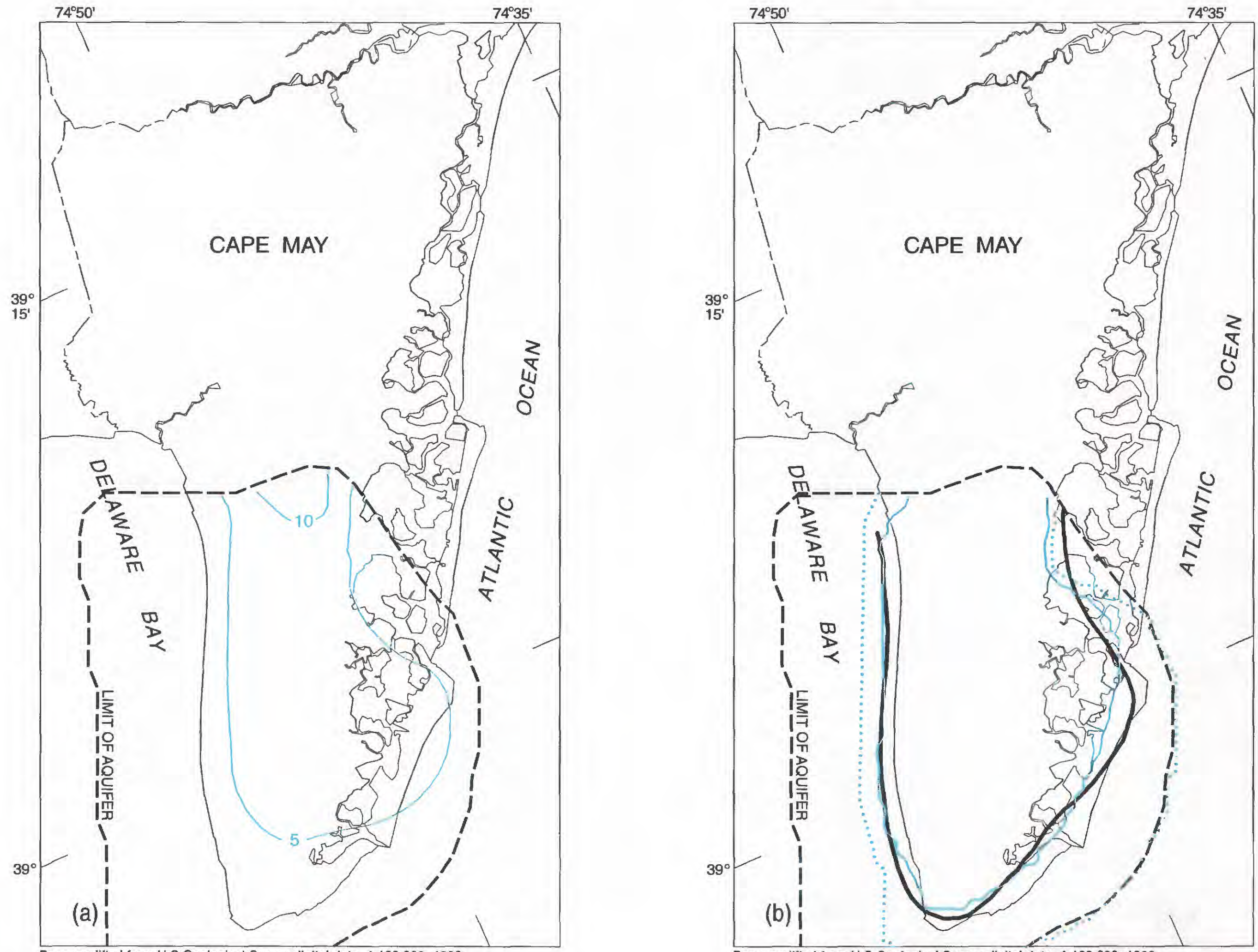
EXPLANATION

SIMULATED POSITION OF SHARP INTERFACE BETWEEN SALTWATER AND FRESHWATER--Dissolved-chloride concentration equal to approximately 10,000 milligrams per liter in predevelopment

······· TIP ——— TOE

Figure 25. Holly Beach water-bearing zone showing: (a) simulated predevelopment water table and (b) simulated predevelopment sharp interface between saltwater and freshwater.

A zone of composite hydraulic conductivity based on the hydraulic conductivities of the Holly Beach water-bearing zone and the estuarine sand aquifer was assigned to these units in the southeastern offshore part of the study area because of the lack of data on the hydrogeologic framework in this area. The offshore southeastern extent of the estuarine clay confining unit (fig. 3) was also moved landward in order to calibrate the location of saline ground water in the confined aquifers in Cape May City. This modification is considered reasonable given the well-documented saltwater-encroachment problem in the area. Outcrop areas of the estuarine clay confining unit and the estuarine sand aquifer in the Delaware Bay also were modified slightly during calibration. The leakance of the estuarine clay in this area was increased in order to calibrate the location of saline ground water in the confined aquifers in Villas.



Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

EXPLANATION

10 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of predevelopment water levels. Contour interval 5 feet. Datum is sea level

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

EXPLANATION

SIMULATED POSITION OF SHARP INTERFACE BETWEEN SALTWATER AND FRESHWATER--Dissolved-chloride concentration equal to approximately 10,000 milligrams per liter in predevelopment

······· TIP ——— TOE

——— MEASURED POSITION OF POTABILITY INTERFACE--Dissolved-chloride concentration equal to 250 milligrams per liter in the middle of the aquifer in predevelopment. Source of data is Lacombe and Carleton (1992)

Figure 26. Estuarine sand aquifer showing: (a) simulated predevelopment potentiometric surface and (b) measured and simulated predevelopment locations of saline ground water.

The simulated hydraulic conductivities of the estuarine sand and Cohansey aquifers were lowered in order to reproduce the measured cones of depression and locations of saline ground water in these aquifers. The hydraulic conductivity of the intervening confining unit was also lowered. A second hydraulic conductivity zone was assigned in the Cohansey aquifer to represent the lower reported values south of Rio Grande and the increased confinement by the estuarine clay. Revision to the representation of the structure of the base of the Cohansey aquifer, which involved lowering the base of the aquifer in areas several miles offshore (P.J. Lacombe, written commun., 1994), was made after the model was constructed. An thickness for the Cohansey aquifer in these areas would reduce both the slope of the saltwater-freshwater interface

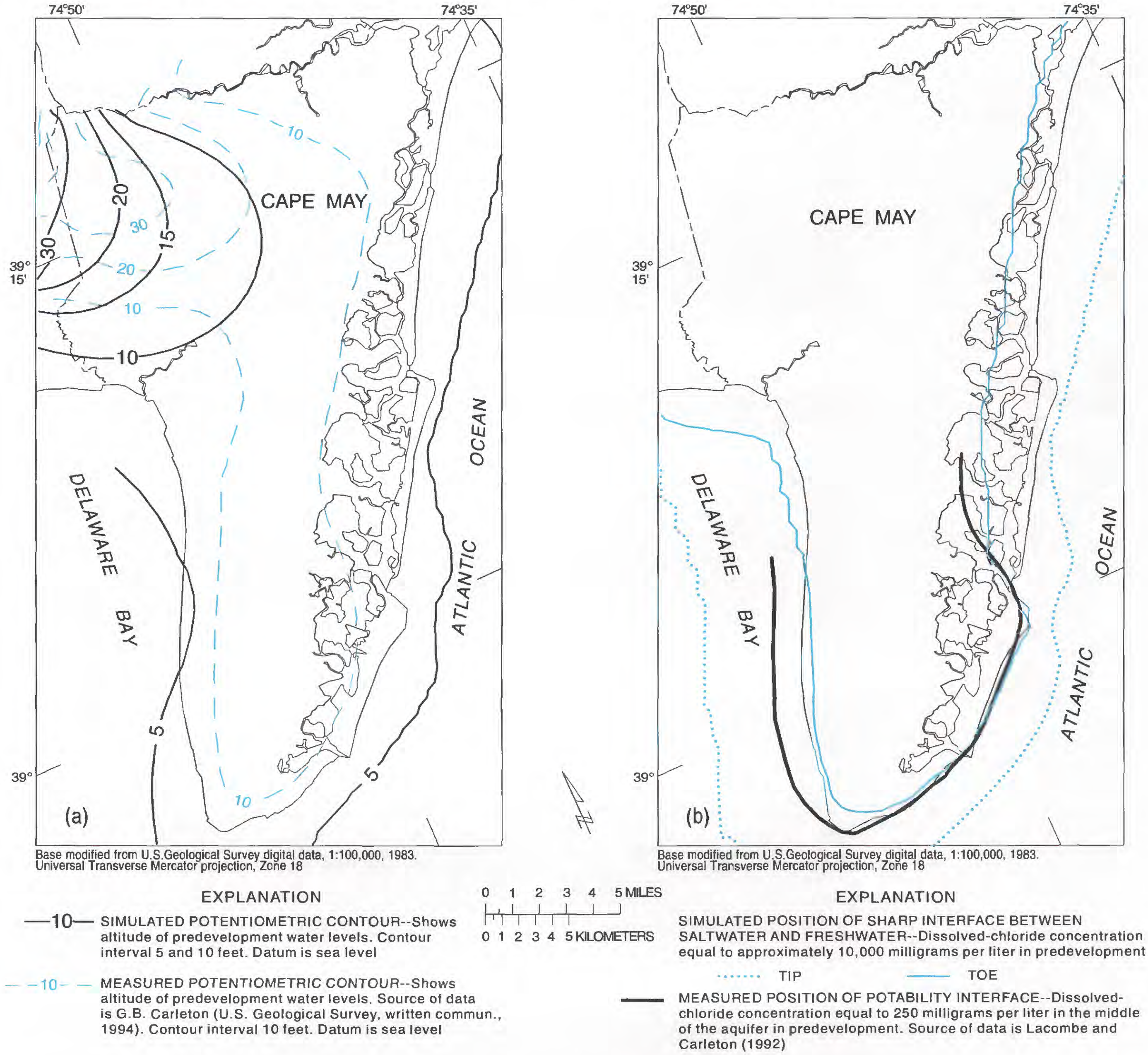
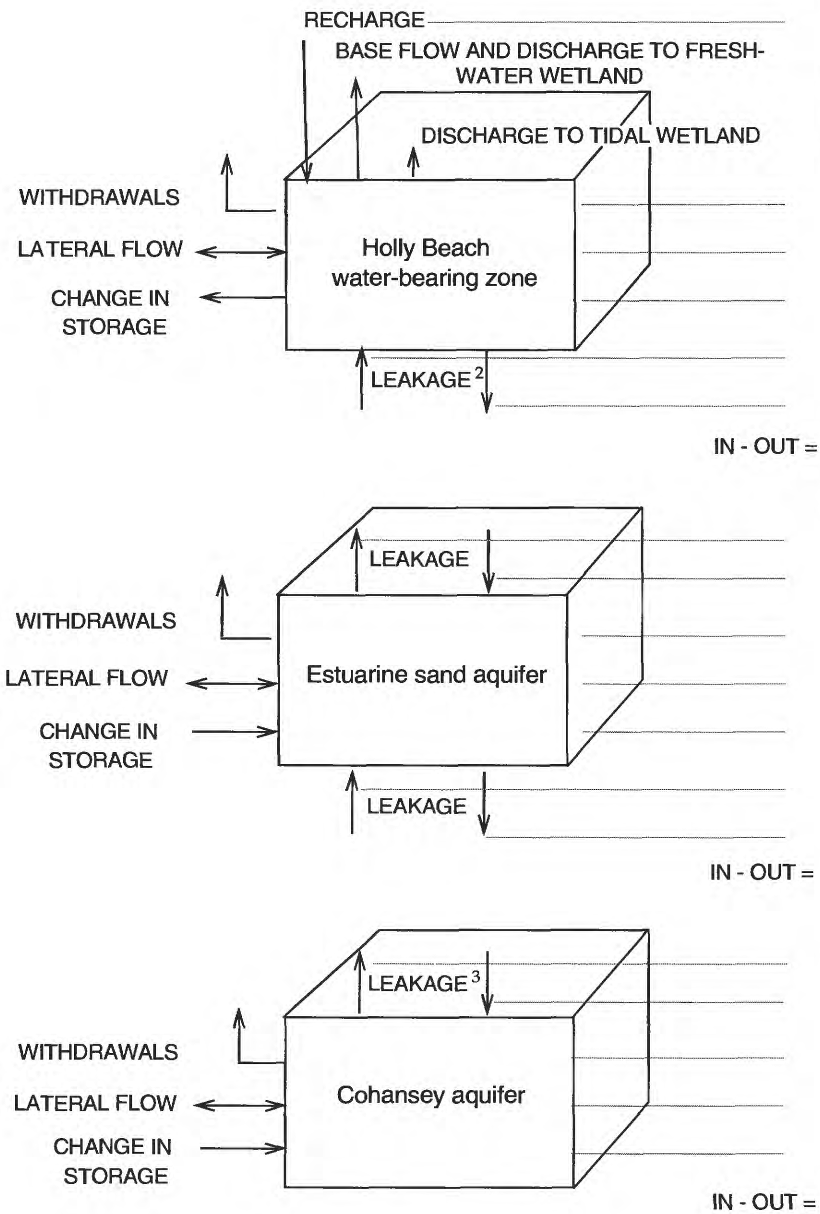


Figure 27. Cohansey aquifer showing: (a) measured and simulated predevelopment potentiometric surfaces and (b) measured and simulated predevelopment locations of saline ground water.

increased thickness for the Cohansey aquifer in these areas would reduce both the slope of the saltwater-freshwater interface and the simulated rate of saltwater encroachment. Simulated hydraulic conductivities of the Cohansey aquifer and the two confining units are lower than reported values. It is reasonable that hydraulic conductivities in regional-scale simulations are lower than those determined from local-scale measurements (Navoy and Carleton, 1995, p. 60).

Areal values for transmissivity of the simulated aquifers are shown in figures 20 through 22. Values of transmissivity are higher in downdip areas where the



	Predevelopment		1991	
	Estimated[1]	Simulated	Estimated[1]	Simulated
	129.2	120.4	129.2	120.4
		-32.7		-32.9
	-127.6		-121.	
		-75.2		-74.6
	0.	0.	-1.4	-.8
	- - -	-10.4	- - -	-9.8
	0.	-.2	0.	-.1
	0.	.9	0.	.8
	-.8	-1.7	-4.7	-2.4
IN - OUT =	.8	1.1	2.1	.6
	-.5	-1.	0.	-.8
	.8	1.7	6.	2.4
	0.	0.	-2.7	-2.2
	- - -	-.8	- - -	.9
	0.	0.	.3	.3
	0.	.1	0.	0.
	-.3	0.	-3.6	-1.1
IN - OUT =	0.	0.	0.	-.5
	-1.1	-.1	0.	-.1
	.3	.5	4.7	1.7
	0.	0.	-6.	-5.9
	- - -	-.5	- - -	2.2
	0.	.1	.3	.6
IN - OUT =	-.8	0.	-1.	-1.5

EXPLANATION

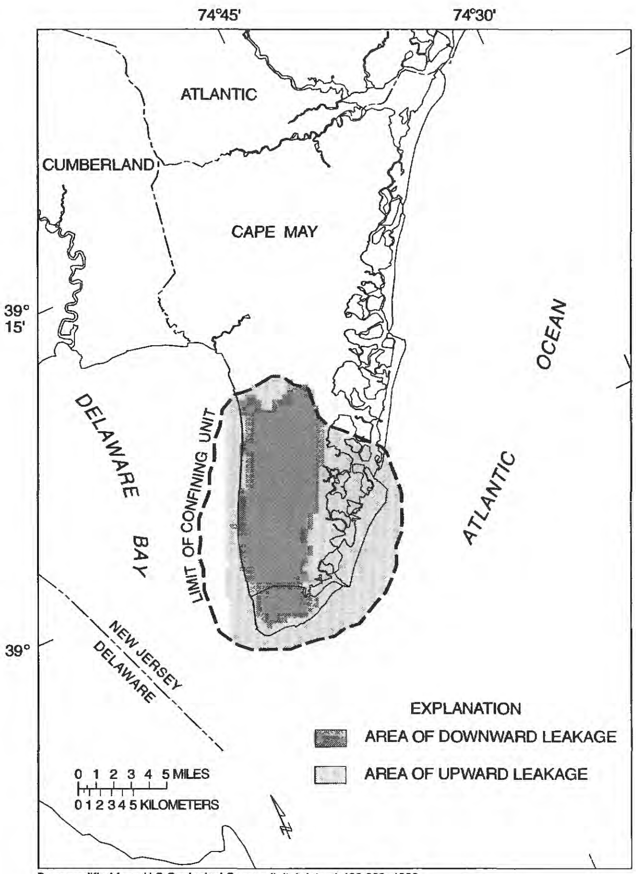
⟶ INFLOWS AND OUTFLOWS OF WATER--In million gallons per day

- - - DATA NOT AVAILABLE OR NOT APPLICABLE

Positive values indicate water entering an aquifer and negative values indicate water leaving an aquifer, except for CHANGE IN STORAGE, for which positive values indicate water released from storage and negative values indicate water added to storage.

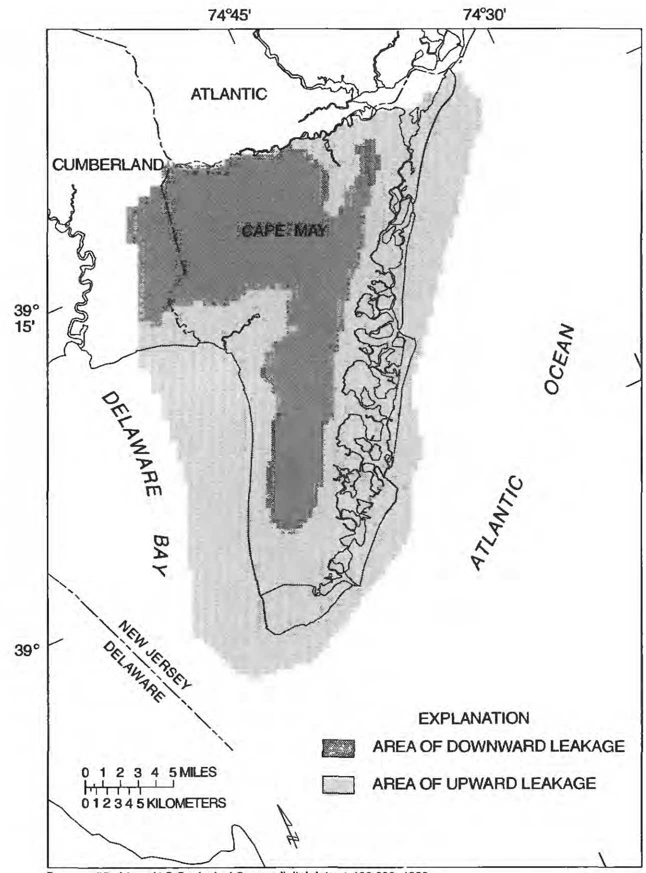
[1]Modified from P.J. Lacombe (U.S. Geological Survey, written commun., 1994).
[2]Excluding leakage to Cohansey aquifer on mainland.
[3]Excluding leakage from Holly Beach water-bearing zone on mainland.

Figure 28. Estimated and simulated ground-water budgets under predevelopment and 1991 conditions, Cape May County, New Jersey.



Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

Figure 29. Direction of simulated predevelopment leakage through the estuarine clay confining unit.



Base modified from U.S.Geological Survey digital data, 1:100,000, 1983.
Universal Transverse Mercator projection, Zone 18

Figure 30. Direction of simulated predevelopment leakage through the confining unit overlying the Cohansey aquifer.

aquifers thicken and lower in areas with more confinement. Areal values of leakance for the simulated confining units are shown in figures 23 and 24. Values of leakance are lowest in areas where confining-unit thickness is highest (figs. 3 and 5).

Steady-State Calibration of Predevelopment Conditions

The model of the shallow aquifer system of Cape May County was calibrated in two phases. First, a steady-state calibration of ground-water flow under predevelopment conditions was made. Next, a transient calibration incorporating ground-water withdrawals from 1896 to 1990 was done. Freshwater heads and saltwater-freshwater-interface positions from the predevelopment simulation were used as initial conditions in the transient simulation. Steady-state conditions were assumed to be met when the change in storage for each of the aquifers was less than 0.01 ft^3/s. These conditions were achieved by using a 1,400-year simulation, with a maximum time step of 15 years. Because of the lengthy computation time of the model, the simulation parameter for solution convergence closure was set to 0.75 ft. Although parameter values for a steady-state solution were used (Essaid, 1990, p. 53), the interface continued to move slowly onshore at the end of the simulation.

The calibration criteria for the steady-state simulation were to match the measured predevelopment water levels, the estimated predevelopment ground-water budget, and the measured predevelopment location of saline ground water. The availability of measured predevelopment data was limited. Calibration

Table 4. Simulated travel times for leakage across confining units in the vicinity of major well fields, Cape May County, New Jersey

[Travel time in years; positive flow is downward, negative flow is upward]

Location	Predevelopment	1991
Estuarine clay confining unit		
Rio Grande	142	50
County Airport	288	134
Lower Township wells	454	200
Cape May City	415	213
Clay overlying Cohansey aquifer		
Rio Grande	776	3
County Airport	7,648	26
Lower Township wells	-334	44
Cape May City	-740	64

targets were to match measured water-levels within 15 ft; ground-water flows and the areal configuration of saline ground water were evaluated subjectively. The 15-ft-head-difference calibration target is considered reasonable for a regional-scale simulation (Navoy and Carleton, 1995, p. 53). The accuracy of the predevelopment calibration was limited by the paucity of available data, particularly for the regional delineation of the saltwater-freshwater-interface. As a result of some of the limitations and assumptions inherent in the model discussed above, the model is better calibrated in some areas than in others.

Flow System

Simulated ground-water levels in the shallow aquifer system under predevelopment conditions are shown in figures 25a through 27a. Measured ground-water-level data were available only for the Cohansey aquifer. The match between measured and simulated water levels in this aquifer is within the calibration target of 15 ft. The simulated water levels and gradients in the other aquifers are representative of predevelopment flow patterns described earlier.

The estimated and simulated predevelopment fresh-ground-water budgets are shown in figure 28. Both budgets are for the saturated ground-water zone within the county border. The match between the estimated and simulated budgets is good; the main difference is the distribution of discharge from the unconfined aquifer. Because the model does not simulate all freshwater wetlands, some ground water instead discharges laterally to offshore areas. Also, recharge is greater in the estimated budget than in the simulated budget, so flows are higher.

The direction of simulated predevelopment leakage of ground water from the Holly Beach water-bearing zone across the estuarine clay to the estuarine sand aquifer is shown in figure 29. The direction of simulated predevelopment leakage from the estuarine sand aquifer across the confining unit to the Cohansey aquifer is shown in figure 30. The figures were developed by rerunning the calibrated model with the SHARP complete mixing option for leakage between the saltwater and freshwater zones. Leakage between the aquifer and overlying constant heads in aquifer outcrop areas is not shown. Leakage directions correspond to predevelopment flow patterns discussed earlier. The time of travel for ground-water leakage across the confining beds is greater than 140 years at selected locations (table 4). Travel time is calculated using the equation

$$t = d/v = d/[Q/(n_e A)]$$

where v = ground-water velocity,
d = thickness of confining unit,
Q = vertical flow through cell,
n_e = effective porosity of confining unit, and
A = cell area.

The assumed effective porosity for silt and clay confining units is 7 percent (Roscoe Moss Company, 1990, p. 7).

Location of Saline Ground Water

The simulated positions of the tip and toe of the sharp interface between saltwater and freshwater under predevelopment conditions are shown in figures 25 through 27b. The tip represents the intersection of the interface with the top of the aquifer, whereas the toe represents the intersection of the interface with the bottom of the aquifer (fig. 14). The simulated interface represents ground water with dissolved-chloride concentrations of approximately 10,000 mg/L

(50-per cent concentration interface). The potability interface shown in figures 26b and 27b is defined on the basis of dissolved-chloride concentrations equal to 250 mg/L in water from the middle of the aquifer. Because few measurements of the predevelopment dissolved-chloride concentrations in the shallow aquifer system are available, these locations of saline ground water are highly speculative; however, the simulated interface positions are consistent with the available measurements.

Transient Calibration of Pumping Conditions

Nine pumping (stress) periods were used to simulate pumping conditions from January 1, 1896, to January 1, 1991. Ground-water withdrawals are simulated as annual rates averaged over a pumping period. Simulated withdrawals are shown in figure 9. The average withdrawals for pumping period 1 are estimated to be half the withdrawal rate in 1920. Ten time steps with a time-step multiplier of 1.2 were used for each period. Maximum time-step size reached 3 years at the end of the longest period. Simulated domestic withdrawals from 1921 to 1990 (table 5 were estimated from the self-supplied population and a per capita water use of 65 gallons per day (G.B. Carleton, written commun., 1993). For recharge wells, the amount injected minus the amount withdrawn was simulated.

Calibration criteria for the transient simulation were to match long-term water-level hydrographs and measured water levels in 1991; to match the estimated ground-water budget in 1991, including base flow to streams; and to be consistent with the chronological progression of contamination of ground water by chloride and the areal distribution of chloride-contaminated ground water in 1991. The specific calibration targets were to match hydrographs and water levels within 15 ft. The ground-water budget, base flow to streams, saltwater encroachment, and location of saline ground water were assessed on a qualitative basis.

Changes in the Flow System

Measured water levels in the Holly Beach water-bearing zone in April 1991 and locations of wells with hydrographs are shown in figure 11a; simulated water levels for January 1, 1991 (representing annual average conditions), and locations of observation wells used to calculate head residuals for the aquifer are shown in figure 11b. Average annual conditions are assumed to occur after recovery of water levels from the effects of heavy pumping in the summer, but before natural recovery of water levels in the spring. Review of long-term hydrographs for the aquifer indicates that annual average water levels are approximately 1 ft lower than water levels measured in April 1991. Therefore, a comparison of measured water levels in April 1991 to the simulated annual average water levels, accounting for the 1-ft difference, shows that the calibration is within the target of 15 ft.

The root mean square error (RMSE) between measured and simulated water levels (heads) is calculated as

$$RMSE = \left[\left(\sum_{i=1}^{n}\left(h_{m_i} - h_{s_i}\right)^2\right)/n\right]^{0.5}$$

where h_m = measured head,
h_s = simulated head,
i = summation index, and
n = number of comparisons.

The RMSE at the observation wells shown in figure 11b is 3.7 ft. Figure 31 shows the comparison between measured and simulated hydrographs for the aquifer. The transient effect on the Holly Beach water-bearing zone is flattened as a result of the vertical axis interval. The match for all of the wells is within the calibration target. Comparison of simulated water levels in figure 11b with simulated water levels under predevelopment conditions in figure 25a demonstrates the small change in water levels over time in the aquifer.

Measured water levels in the confined estuarine sand aquifer in April 1991 and locations of wells with hydrographs are shown in figure 12a; simulated water levels in January 1, 1991 (representing annual average conditions), and locations of observation wells used to calculate head residuals for the aquifer are shown in figure 12b. Review of long-term hydrographs for the aquifer indicates that annual average water levels are approximately 2 ft lower than water levels measured

Table 5. Simulated domestic ground-water withdrawals from 1921 to 1990, Cape May County, New Jersey

[Model grid shown in fig. 18; withdrawals from the estuarine sand aquifer are 100-percent consumptive; withdrawals from the Holly Beach water-bearing zone are 20-percent consumptive]

Layer	Row	Column	Withdrawals, in million gallons per day							
			1921-49	1950-57	1958-64	1965-68	1969-78	1979-83	1984-88	1989-90
			Holly Beach water-bearing zone							
3	10	50	0.002	0.002	0.003	0.004	0.006	0.008	0.010	0.012
3	12	50	.002	.002	.003	.004	.006	.008	.010	.012
3	14	49	.006	.006	.008	.011	.018	.025	.031	.036
3	17	48	.002	.002	.003	.004	.006	.008	.010	.012
3	22	47	.004	.004	.006	.008	.012	.016	.021	.024
3	26	46	.002	.002	.003	.004	.006	.008	.010	.012
3	30	45	.004	.004	.006	.008	.012	.016	.021	.024
3	37	44	.009	.011	.012	.014	.018	.021	.024	.026
3	41	38	.009	.011	.012	.014	.018	.021	.024	.026
3	42	28	.005	.005	.006	.007	.009	.010	.012	.013
3	46	30	.005	.005	.006	.007	.009	.010	.012	.013
3	46	40	.009	.011	.012	.014	.018	.021	.024	.026
3	56	29	.016	.021	.030	.039	.048	.056	.064	.070
3	60	35	.016	.021	.030	.039	.048	.056	.064	.070
3	64	35	.033	.041	.060	.078	.096	.112	.128	.140
3	69	31	.016	.021	.030	.039	.048	.056	.064	.070
3	78	36	.016	.021	.030	.039	.048	.056	.064	.070
3	91	31	.004	.007	.016	.025	.041	.054	.061	.066
3	92	29	.004	.007	.016	.025	.041	.054	.061	.066
		Total	.160	.200	.290	.380	.510	.620	.720	.790
			Estuarine sand aquifer							
2	63	23	.008	.010	.015	.019	.024	.028	.032	.035
2	68	40	.016	.021	.030	.039	.048	.056	.064	.070
2	69	37	.016	.021	.030	.039	.048	.056	.064	.070
2	70	39	.016	.021	.030	.039	.048	.056	.064	.070
2	72	24	.008	.010	.015	.019	.024	.028	.032	.035
2	73	37	.016	.021	.030	.039	.048	.056	.064	.070
2	79	36	.016	.021	.030	.039	.048	.056	.064	.070
2	80	28	.016	.021	.030	.039	.048	.056	.064	.070
2	80	37	.033	.041	.060	.078	.096	.112	.128	.140
2	81	24	.016	.021	.030	.039	.048	.056	.064	.070
2	84	35	.033	.041	.060	.078	.096	.112	.128	.140
2	85	24	.004	.007	.016	.025	.041	.054	.061	.066
2	86	24	.004	.007	.016	.025	.041	.054	.061	.066
2	86	35	.008	.014	.031	.050	.081	.108	.122	.132
2	87	24	.004	.007	.016	.025	.041	.054	.061	.066
2	88	24	.004	.007	.016	.025	.041	.054	.061	.066
2	89	24	.004	.007	.016	.025	.041	.054	.061	.066
2	92	31	.004	.007	.016	.025	.041	.054	.061	.066
2	93	29	.004	.007	.016	.025	.041	.054	.061	.066
2	95	24	.004	.007	.016	.025	.041	.054	.061	.066
2	96	24	.004	.007	.016	.025	.041	.054	.061	.066
2	96	25	.004	.007	.016	.025	.041	.054	.061	.066
2	97	25	.004	.007	.016	.025	.041	.054	.061	.066
2	98	33	.004	.007	.016	.025	.041	.054	.061	.066
2	99	31	.004	.007	.016	.025	.041	.054	.061	.066
		Total	.250	.360	.600	.840	1.190	1.480	1.680	1.830

in April 1991. A comparison of measured and simulated water levels, accounting for the 2-ft difference, shows that the match is within the calibration target, and the location and extent of the cone of depression at the Rio Grande well field are reproduced. The RMSE between measured and simulated water levels at observation wells in the aquifer is 1.8 ft. Figure 32 shows the measured and simulated hydrographs for the aquifer. The match for all of the wells is within the calibration target. Comparison of simulated water levels in figure 12b with simulated water levels under predevelopment conditions in figure 26a demonstrates the drawdown in water levels due to withdrawals.

Measured water levels in the confined Cohansey aquifer in April 1991 and locations of wells with hydrographs are shown in figure 13a; simulated water levels in January 1, 1991 (representing annual average conditions), and locations of observation wells used to calculate head residuals for the aquifer are shown in figure 13b. Review of long-term hydrographs for the aquifer indicates that annual average water levels are approximately 6 ft lower than water levels measured in April 1991. A comparison of measured and simulated water levels, accounting for the 6-ft difference, shows that the match is satisfactory, but not within the calibration target at all locations. The configuration of simulated water levels in the northern part of the county is different from that of measured water levels, probably as a result of underrepresentation of freshwater wetlands in the model and the low calibrated leakance value for the confining unit overlying the Cohansey aquifer.

The RMSE between measured and simulated water levels at observation wells in the aquifer is 7.5 ft; the match between measured and simulated water levels at most of the observation wells falls within the calibration target of 15 ft. The location and areal extent of the three measured local cones of depression in the southern half of the peninsula (fig. 13a) also are simulated accurately. Eight of the 13 simulated hydrographs for the aquifer (fig. 33) match the measured hydrographs within the calibration target, and 4 of the 5 that fall outside the target match within 20 ft. The hydrographs for which the match is poorest are from the wells located nearest the cones of depression. More specifically, the simulated hydrographs are too low at Rio Grande and too high at Cape May City compared to measured hydrographs. Calibration discrepancies at these wells are likely the result of (1) error from the coarseness of the model grid and time-step size; (2) error in water-level measurements made in withdrawal wells before the wells had fully recovered from pumping; (3) error due to inaccuracies in withdrawal data; and (4) error associated with the low calibrated hydraulic conductivity for the aquifer in the southern half of the peninsula, resulting in simulated drawdown that is greater than the measured drawdown. Comparison of simulated water levels in figure 13b with simulated water levels under predevelopment conditions in figure 27a confirms the decrease in water levels in the aquifer due to withdrawals.

The simulated fresh-ground-water budget for the shallow aquifer system in 1991 is shown in figure 28. The match between the estimated and simulated budgets is good. In addition to the smaller surficial discharge noted earlier for the simulated predevelopment budget, the simulated budget also has less downward leakage to the confined aquifers than the estimated budget. This reduction in recharge to the deeper supply wells in the simulated budget is compensated for by increased lateral flow from offshore areas.

As a result of ground-water development, downward leakage to the confined aquifers has increased significantly. The recharge area of the confined aquifers also has increased, whereas the recharge area of the unconfined aquifer has decreased. A comparison of simulated leakage in 1991 (figs. 34 and 35) to simulated leakage under predevelopment conditions (figs. 29 and 30) shows that the area of downward leakage through the confining units has increased, whereas the area of upward leakage has decreased. Leakage in 1991 was simulated by rerunning the calibrated model with the SHARP complete-mixing option for leakage. At the withdrawal centers, travel time for leakage across the confining unit overlying the Cohansey aquifer has been dramatically reduced (table 4); travel time across the estuarine clay confining unit has been reduced by more than half.

Estimated and simulated annual average base flows for the last pumping period are compared in table 6. Base-flow data were available for 13 of the 23 streams simulated by the model. Most of the differences between estimated and simulated base flows are acceptable given the lack of data on individual stream characteristics, the inability to simulate all freshwater wetlands, and the focus of the study on the confined

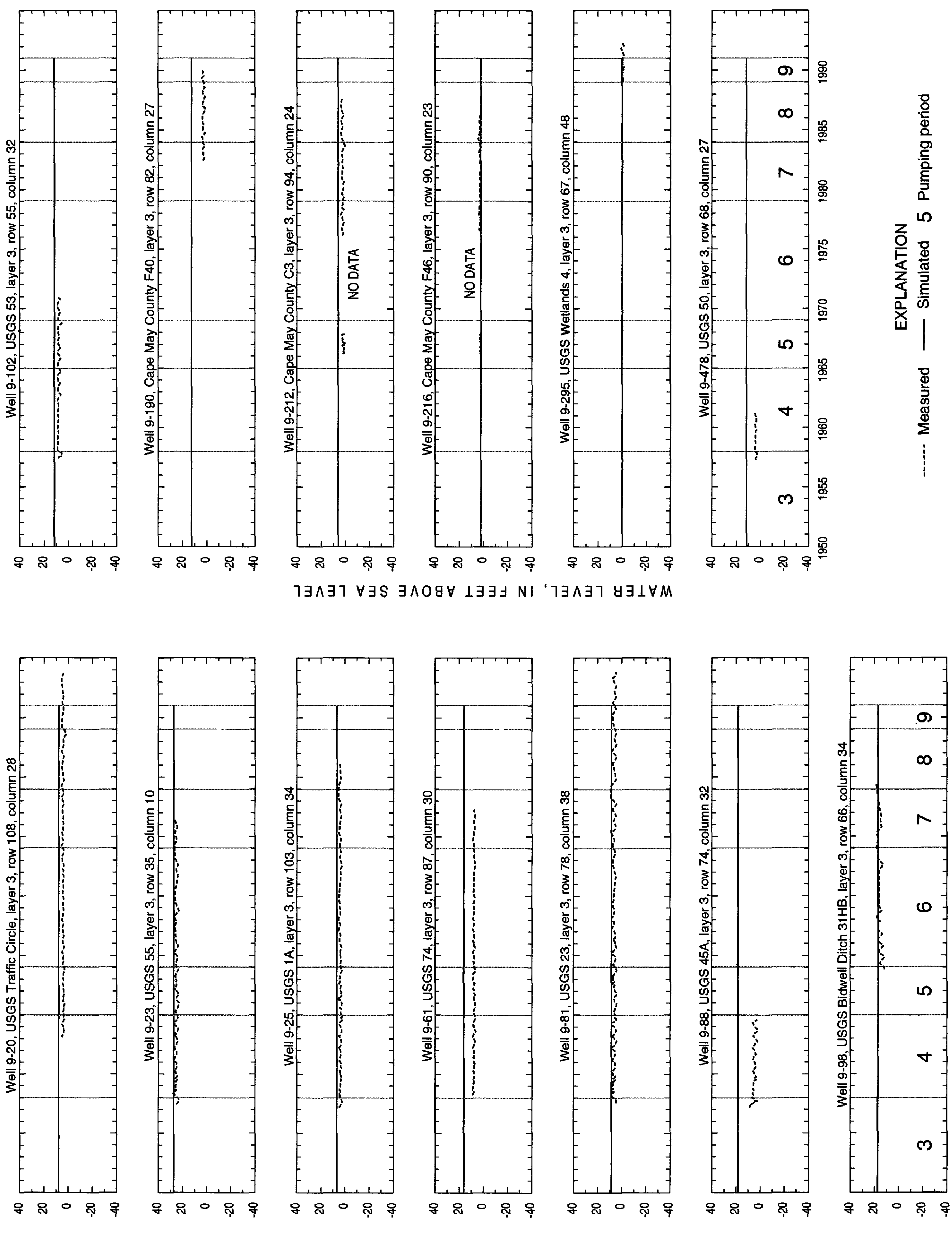


Figure 31. Measured and simulated hydrographs of water levels in wells in Cape May County, New Jersey, in the Holly Beach water-bearing zone.

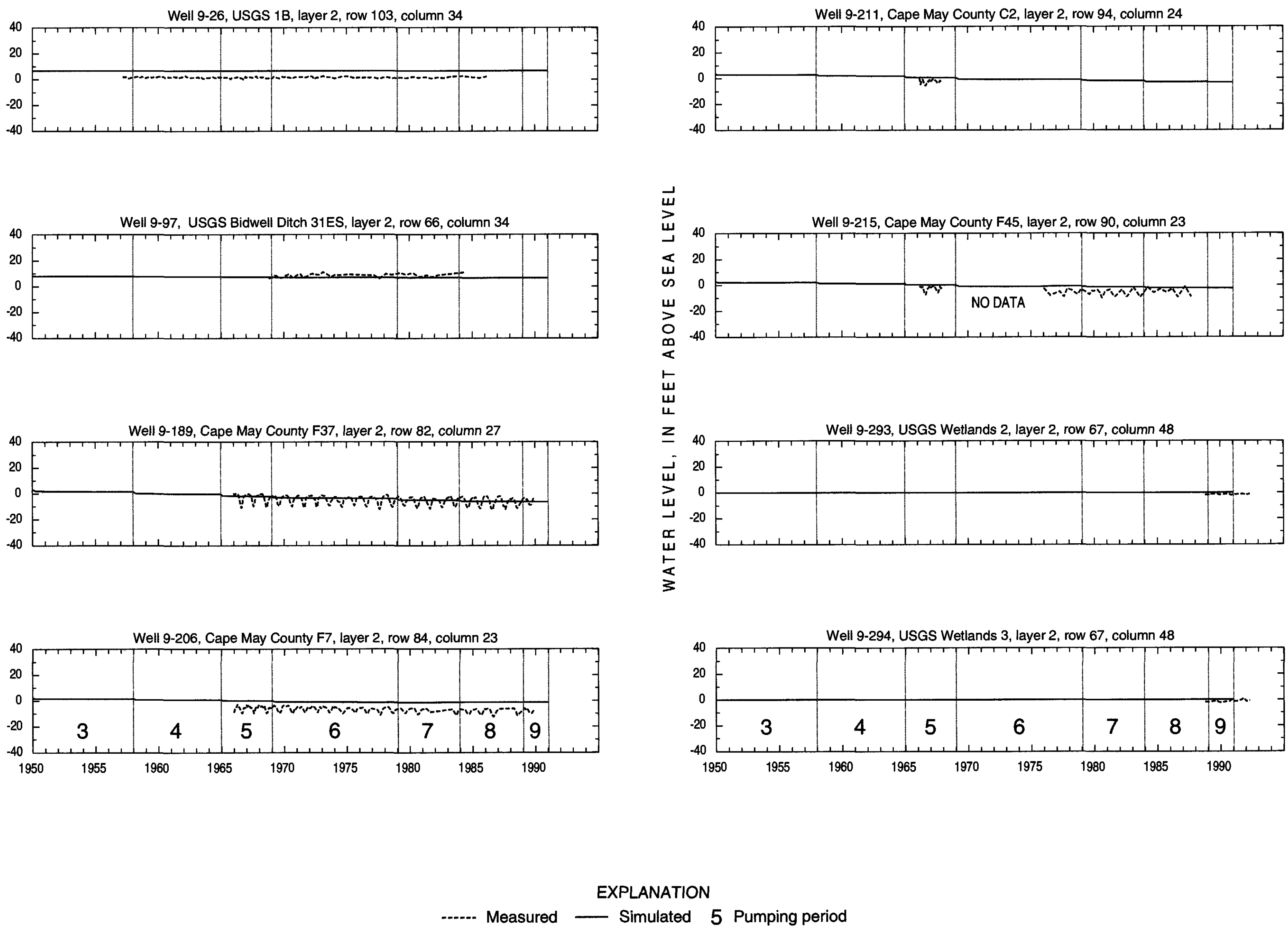


Figure 32. Measured and simulated hydrographs of water levels in wells in Cape May County, New Jersey, in the estuarine sand aquifer.

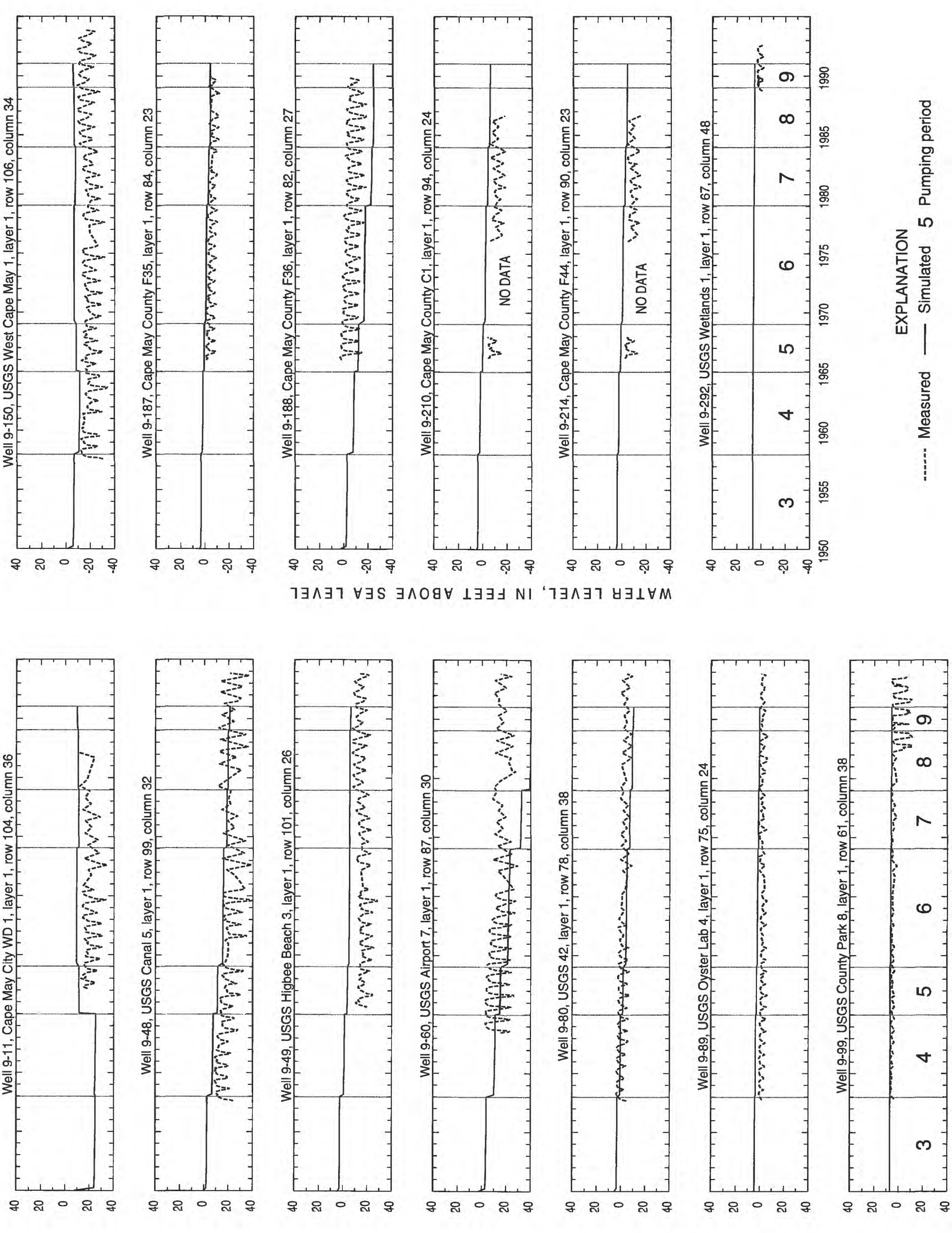


Figure 33. Measured and simulated hydrographs of water levels in wells in Cape May County, New Jersey, in the Cohansey aquifer.

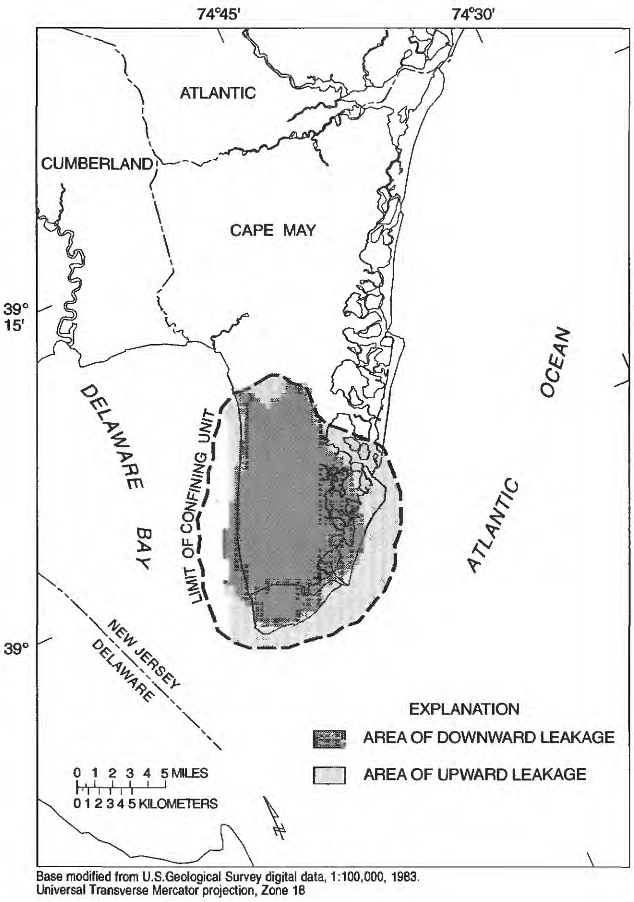


Figure 34. Direction of simulated leakage through the estuarine clay confining unit, 1991.

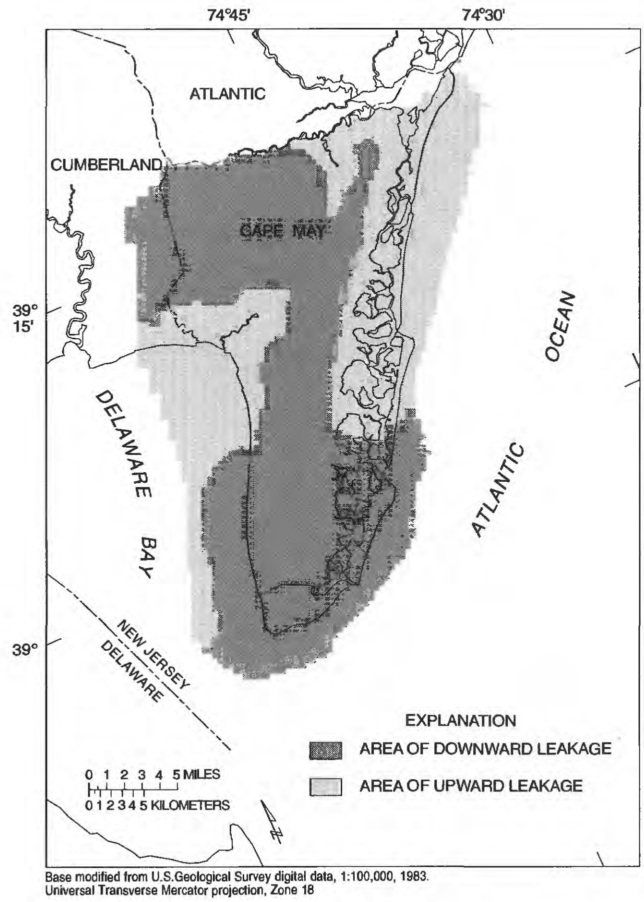


Figure 35. Direction of simulated leakage through the confining unit overlying the Cohansey aquifer, 1991.

aquifers. The largest differences are for Sluice Creek, West Creek, Mill Creek at Magnolia Lake, and Tarkiln Brook. The first three basins are considered to have the poorest measurement stations and the largest associated measurement error (G.B. Carleton, oral commun., 1994). Sluice Creek Basin, for which the difference is largest, also has the poorest base-flow correlation and a higher percentage of wetlands than the Tuckahoe River index basin. The difference for Tarkiln Brook is likely the result of the basin's location in an area in which the model was not rigorously calibrated.

Saltwater Encroachment

Dissolved-chloride concentrations in water samples from the Holly Beach water-bearing zone indicate that the potability interface (representing the 250-mg/L chloride concentration) is currently located near the western coast of the county and at the western end of the back bays, as shown in figure 15a. Most of the samples were collected during 1989-92 (P.J. Lacombe, written commun., 1994). The location of the well screen in the aquifer is provided to help define the vertical extent of the area in which chloride concentrations exceed 250 mg/L. The lack of sufficient data in most areas on the configuration of the mixing zone between freshwater and saltwater make rigorous calibration of the position of the sharp interface between saltwater and freshwater difficult. The simulated positions of the tip and toe (fig. 14) of the sharp interface in 1991 are shown in figure 15b. (Recall that the simulated sharp interface represents the location at which the dissolved-chloride concentration of the ground

Table 6. Estimated and simulated base flow, Cape May County, New Jersey

[Location of stations shown in fig. 10 and listed in order from north to south; USGS, U.S. Geological Survey; ft^3/s, cubic foot per second]

Streamflow-gaging station name	USGS station number	Estimated base flow (ft^3/s)[1]	Simulated base flow (ft^3/s)[2]	Difference (ft^3/s)
Tarkiln Brook	01411299	6.5	5.3	1.2
Mill Creek near Steelmantown	01411302	3.4	4.1	-.7
Mill Creek at Magnolia Lake	01411351	3.0	.6	2.4
East Creek	01411442	8.1	8.1	0.
West Creek	01411445	13.5	15.5	-2.0
Dennis Creek at Dennisville	01411428	4.3	3.5	.8
Dennis Creek near North Dennis	01411438	2.6	3.2	-.6
Sluice Creek	01411434	11.0	3.7	7.3
Goshen Creek	01411418	.2	.1	.1
Bidwell Creek	01411410	.3	.1	.2
Dias Creek	01411408	.9	1.5	-.6
Fishing Creek	01411400	1.6	2.1	-.5
Mill Creek at Cold Spring	01411388	.9	.3	.6

[1]From base-flow correlation with the Tuckahoe River (1990-92).
[2]Pumping period 9 (1989-90).

water is approximately 10,000 mg/L.) Given these considerations, the calibration of the model parameters has resulted in a acceptable fit between the measured and simulated locations of saline water in the aquifer. The position of the simulated interface is consistent with the dissolved-chloride-concentration measurements. The mixing zone in the Holly Beach water-bearing zone is very narrow as determined on the basis of both measured and simulated data, and is vertical in aspect.

Dissolved-chloride concentrations in water samples from the estuarine sand aquifer indicate that the potability interface is currently located onshore at Villas and the southeastern part of the peninsula (fig. 16a). The simulated positions of the tip and toe of the sharp interface between saltwater and freshwater in 1991 are shown in figure 16b. The calibration of the model parameters has resulted in an acceptable fit between the measured and simulated location of saline water in the aquifer. The simulated interface is farther onshore than the potability interface in the southeastern part of the peninsula. The simulated interface is less sloped in aspect in the estuarine sand aquifer than in the unconfined aquifer, in part as a result of confinement by the estuarine clay. However, in the outcrop area of the estuarine clay, the simulated interface in the aquifer is more sloped as a result of the increased leakance applied.

Dissolved-chloride concentrations in ground-water samples from the Cohansey aquifer indicate that the potability interface is currently located onshore at Cape May City, at Cape May Point, and north of Wildwood (fig. 17a). The simulated positions of the tip and toe of the sharp interface between saltwater and freshwater in 1991 are shown in figure 17b. The calibration of the model parameters has resulted in an acceptable fit between the measured and simulated locations of saline water in the aquifer. The simulated interface is farther onshore than the potability interface in the southwestern part of the peninsula. However, as in the estuarine sand aquifer, few of the measured wells are screened at the bottom of the aquifer. It is possible for the toe of the interface to move under the well screen and not contaminate the well with saltwater. The simulated interface is also farther onshore in Cape May City, possibly as a result of discretization effects.

Historical data on the encroachment of the potability interface toward Villas in the estuarine sand aquifer and toward Cape May City in the Cohansey aquifer are sufficient to be useful for model calibration. Few data are available for calibration of encroachment of the potability interface toward the Lower Township wells. Estimated and simulated encroachment of the potability interface from predevelopment to 1990 at the two locations is shown in figures 36 and 37 and listed in table 7. The locations of saline ground water shown in the figures were determined on the basis of dissolved-chloride concentrations greater than 250 mg/L. Values of estimated encroachment of the potability interface are conservative maximum values. Values of simulated encroachment of the potability interface are calculated from model intercell flows at the cell nearest the landward edge of saline ground water (landward of the simulated sharp interface) by using the following equation:

$$d = vt = [Q/(n_e A)]\,t$$

where v = ground-water velocity,

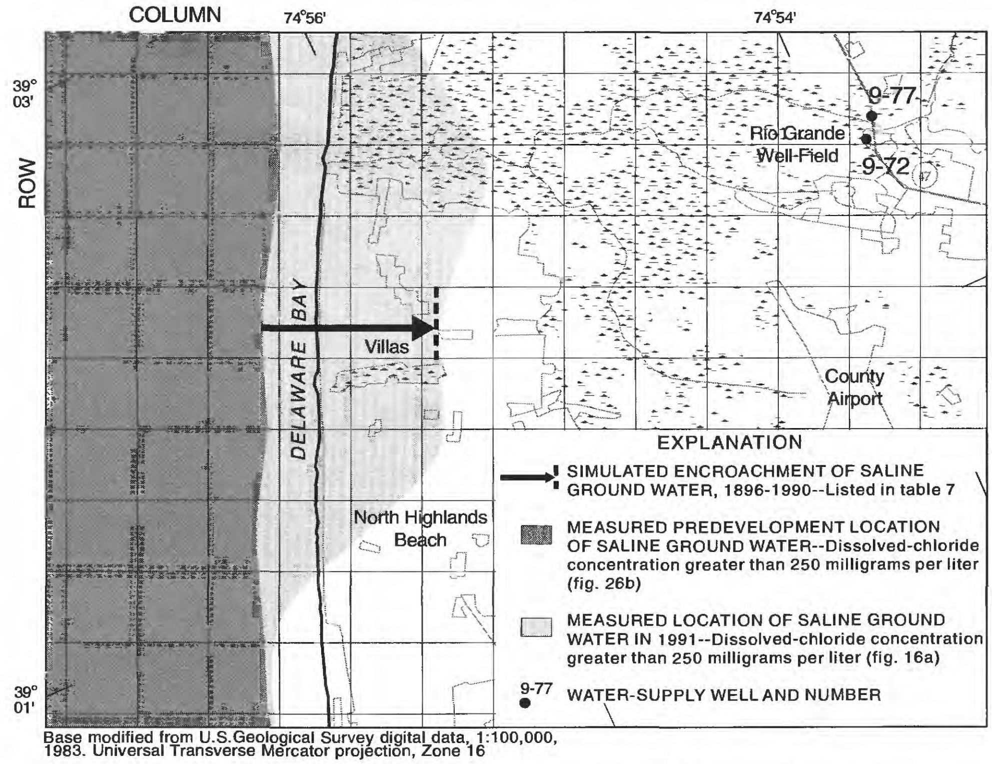


Figure 36. Estimated and simulated saltwater encroachment in the estuarine sand aquifer near Villas, New Jersey (Location shown in figure 1).

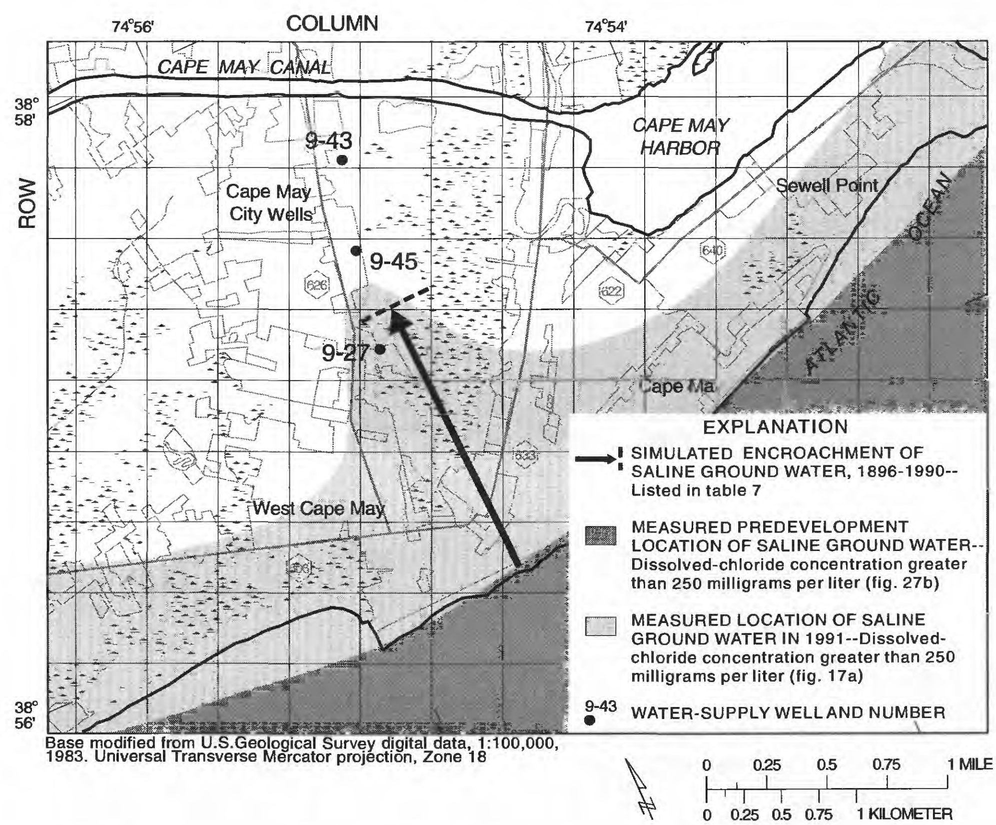


Figure 37. Estimated and simulated saltwater encroachment in the Cohansey aquifer near Cape May, New Jersey (Location shown in figure 1).

Table 7. Estimated and simulated saltwater encroachment near Villas and Cape May City, New Jersey

[Encroachment in feet; encroachment at Villas in estuarine sand aquifer (fig. 36); encroachment at Cape May City in Cohansey aquifer (fig. 37); ---, not applicable]

Period	Estimated encroachment	Simulated encroachment		
		porosity = 0.3	porosity = 0.15	porosity = 0.6
		Villas		
1950-57	140	50	100	30
1958-64	340	170	340	80
1965-68	820	180	350	90
1969-78	1,070	1,090	2,370	520
1979-83		810	1,580	370
1984-88	1,500	930	Saltwater past wells	470
1989-90		400	Saltwater past wells	200
Total	[1]3,870	3,630	---	1,760
		Cape May City		
1896-1920		430	600	160
1921-49	1,400	980	1,270	370
1950-57		1,650	2,590	860
1958-64	1,200	630	1,010	610
1965-68		340	660	100
1969-78	3,000	620	1,540	200
1979-83		500	1,880	120
1984-88		800	Saltwater past wells	190
1989-90	800	220	Saltwater past wells	20
Total	[2]6,400	6,170	---	2,630

[1]Estimated from decennial population data and dissolved-chloride-concentration data collected during 1985-89 (G.R. Webber, Cape May County Planning Board, written commun., 1989). Estimates based on the average of the velocities (125 ft/yr) of the 70-, 250-, 275-, 300-, and 900-mg/L chloride-concentration interfaces.

[2]Modified from Lacombe and Carleton (1992, table 1); first two periods estimated by using withdrawal history and decennial population data from 1930-50; last period estimated by using dissolved-chloride-concentration data collected during 1991-94.

t = time step,
Q = horizontal flow rate through cell face,
n_e = effective porosity of aquifer, and
A = cell-face area.

The effective porosity of gravel and coarse- to fine-grained sand aquifers is 30 percent (table 3). Direction of saltwater encroachment is calculated from the resultant flow vector in the two-dimensional areal plane. The difference between estimated and simulated encroachment at the two locations is less than 5 percent, although the rates of encroachment are different. The minor difference in encroachment could be a consequence of discretization, model limitations and assumptions used, uncertainty in local hydrogeologic conditions and withdrawal rates, uncertainty in the location of saline ground water and in flow-path direction, or well-interference effects. The average of the differences in encroachment at these two locations constitutes the calibration error band.

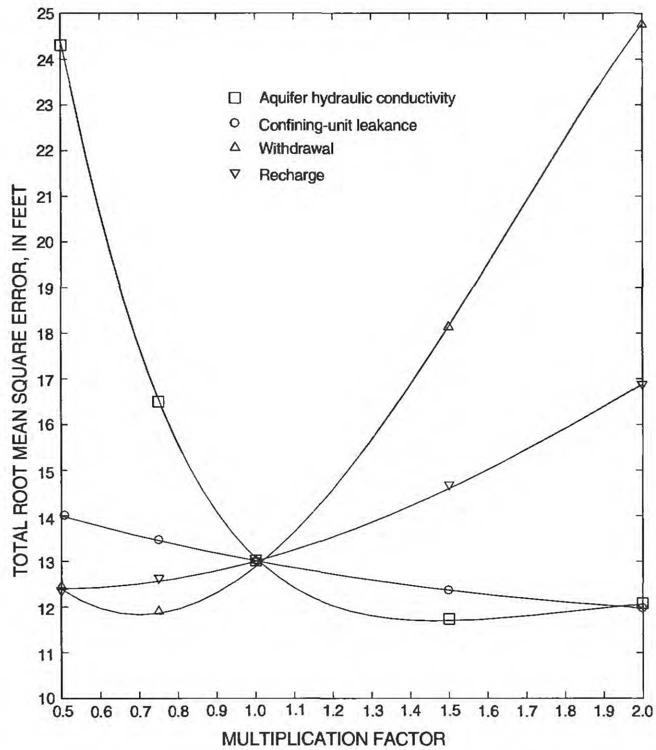


Figure 38. Sensitivity of simulated head to variations in the values of model parameters, Cape May County, New Jersey.

Sensitivity Analysis

The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model. This uncertainty is created by uncertainty in estimates of aquifer properties, hydrologic stresses, and boundary conditions. The sensitivity analysis is performed by systematically changing calibrated parameter values within a hydrologically reasonable range. Results are reported as the effects of the parameter changes on the goodness-of-fit of the calibrated solution. The more sensitive the solution is to the parameter changed, the more certain the calibration is with respect to that parameter. However, a different calibration could have different parameter sensitivities.

Results of a limited sensitivity analysis on the total RMSE of heads at observation wells in Cape May County is shown in figure 38. The values of calibrated aquifer hydraulic conductivity, confining-unit leakance, and recharge were tested in addition to those of the simulated withdrawals. Changes to hydraulic conductivity and leakance were applied to all appropriate hydrogeologic units. These parameters were varied over the whole model in a range from one-half to twice the calibrated value. Sensitivity testing of model discretization, boundary and initial conditions, spatial and temporal variations of parameters, and combinations of parameters were impractical in a simple analysis. Results show that the model was most sensitive to decreased hydraulic conductivity and increased withdrawals. The model was less sensitive to recharge and least sensitive to confining-unit leakance. Results of the analysis also indicate that hydraulic conductivity probably is not lower than calibrated values, whereas withdrawals and recharge probably are not higher than calibrated values.

Results of a limited sensitivity analysis on saltwater encroachment of the potability interface toward Villas in the estuarine sand aquifer and toward Cape May City in the Cohansey aquifer are shown in table 7. Changes to porosity were applied to all aquifers and over the whole model in a range from one-half to twice the calibrated value (0.3). Results of the analysis indicate that saltwater encroachment is very sensitive to porosity. The change in saltwater encroachment is directly proportional to the change in porosity with exceptions to this relation due mainly to the effects of spatial and temporal discretization. For example, withdrawal locations and withdrawal strength are related to grid-cell size and affect local flow gradients and rates.

Water-Supply-Development Simulations

Because Cape May County's water resources are limited, both short-term actions to address current problems and long-term actions to maintain a renewable supply are needed. In the short term, water-conservation techniques have been initiated (G.R. Webber, Cape May County Health Department, oral commun., 1994). In the long term, two possible water-supply-development alternatives were selected for testing with the Cape May model. The alternatives were designed in cooperation with State and county authorities (Thomas F. Beach, Remington & Vernick Engineers, written commun., 1994). Both alternatives involve significant use of the Cohansey aquifer. Ground-water development of the unconfined Holly Beach water-bearing zone was excluded because of

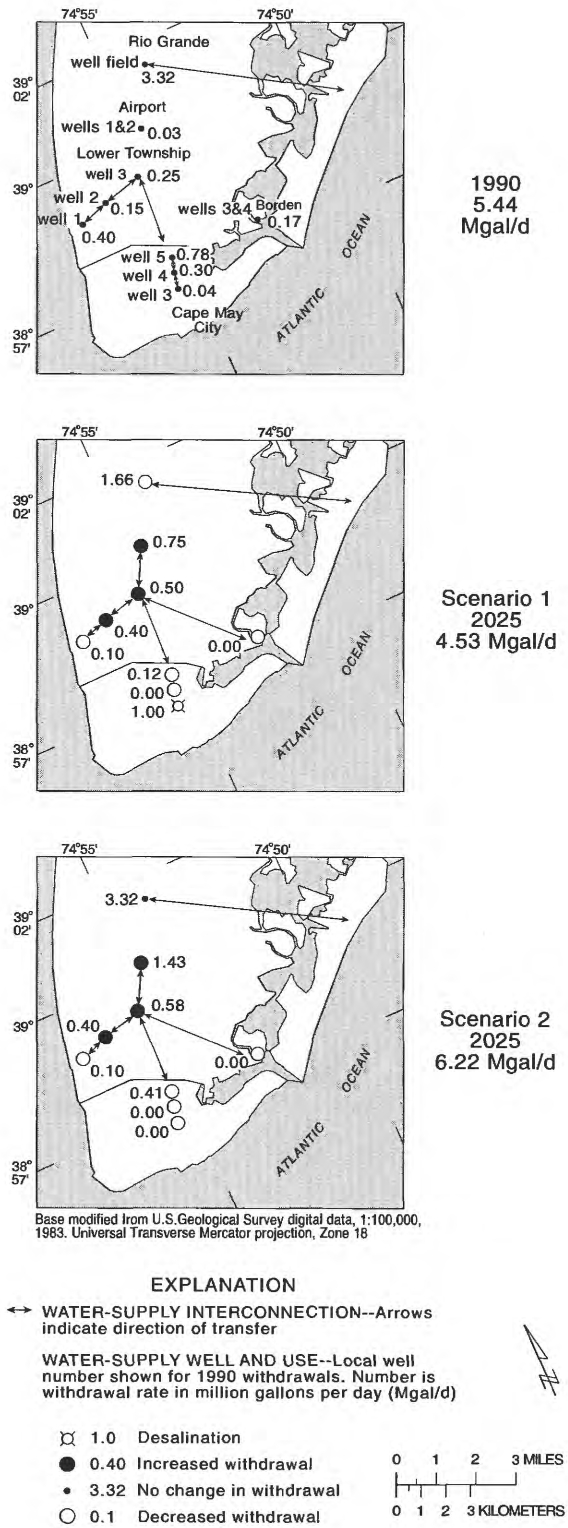


Figure 39. Description of the predictive scenarios, Cape May County, New Jersey.

cost, contamination, and environmental issues. The planning period for the two alternatives is 1995-2025.

Simulated ground-water withdrawals for the two alternatives are shown in figure 39 and listed in table 8. More specifically, the two alternatives involve the following conditions:

ALTERNATIVE 1	ALTERNATIVE 2
Decrease in withdrawals from Cohansey aquifer from 5.44 to 4.53 Mgal/d	Increase in withdrawals from Cohansey aquifer from 5.44 to 6.22 Mgal/d
Shift 1.66 Mgal/d withdrawals to deep aquifer system	No shift in withdrawals to deep aquifer system
Water-demand increase in Lower Township	Water-demand increase in Lower Township
Desalination of brackish withdrawals in Cape May City	Minor withdrawals in Cape May City
Some withdrawals relocated landward	Additional withdrawals relocated landward

A minor component of both alternatives was to also relocate withdrawals at the Borden seafood plant to the county airport wells. Current withdrawals for other uses were continued at 1991 rates. A modest increase (less than 20 percent) in water demand is expected for Cape May City and Wildwood (Rio Grande well field). However, withdrawals in Lower Township were increased according to population projections for 1990-2010 and a per capita water use of 100 gallons per day (Thomas F. Beach, Remington & Vernick Engineers, written commun., 1994). These estimates were further weighted by seasonality. The withdrawal estimates for Lower Township constitute a 90-percent increase in withdrawals by 2010. In alternative 2, the increase in water demand at Lower Township covers the reduction in withdrawals at Cape May City.

The alternatives do not include a consideration of well-field design; existing wells may or may not be capable of supplying the projected withdrawals. The alternatives pertain to the ground-water system only. Land development, water distribution, and other planning issues were not considered. The model does not include the deep aquifer system below the Cohansey aquifer; data have shown that withdrawals from the deeper aquifers do not influence water levels in the shallow aquifers (P.J. Lacombe, written commun.,

Table 8. Ground-water withdrawals for the water-supply-development alternatives, Cape May County, New Jersey

[USGS, U.S. Geological Survey; ---, not applicable]

Location	Local well number	USGS well number	Withdrawals, in million gallons per day						
			1991-94[1]	1995-99	2000-04	2005-09	2010-14	2015-19	2020-24
			Alternative 1						
Cape May City	3	9- 27	0.04	1.00	1.00	1.00	1.00	1.00	1.00
	4	9- 45	.30	0	0	0	0	0	0
	5	9- 43	.78	.12	.12	.12	.12	.12	.12
Borden Seafood	3	9- 42	.04	0	0	0	0	0	0
	4	9-183	.12	0	0	0	0	0	0
Lower Township	1	9- 52	.40	.10	.10	.10	.10	.10	.10
	2	9- 54	.15	.23	.31	.40	.40	.40	.40
	3	9- 57	.25	.34	.42	.50	.50	.50	.50
County Airport	1	9- 58	.02	.29	.33	.37	.37	.37	.37
	2	9- 59	.01	.29	.33	.37	.37	.37	.37
Rio Grande	well field	---	3.32	1.66	1.66	1.66	1.66	1.66	1.66
		Total	5.44	4.04	4.28	4.53	4.53	4.53	4.53
			Alternative 2						
Cape May City	3	9- 27	0.04	0	0	0	0	0	0
	4	9- 45	.30	0	0	0	0	0	0
	5	9- 43	.78	.41	.41	.41	.41	.41	.41
Borden Seafood	3	9- 42	.04	0	0	0	0	0	0
	4	9-183	.12	0	0	0	0	0	0
Lower Township	1	9- 52	.40	.10	.10	.10	.10	.10	.10
	2	9- 54	.15	.23	.31	.40	.40	.40	.40
	3	9- 57	.25	.42	.50	.58	.58	.58	.58
County Airport	1	9- 58	.02	.63	.67	.71	.71	.71	.71
	2	9- 59	.01	.63	.67	.71	.71	.71	.71
Rio Grande	well field	---	3.32	3.32	3.32	3.32	3.32	3.32	3.32
		Total	5.44	5.75	5.99	6.22	6.22	6.22	6.22

[1]Withdrawals are the same as for the last pumping period of the transient simulation (1989-90).

1994). Predicted water levels are accurate only to within the 15-ft calibration target discussed earlier.

Because of uncertainty in the interpretation of local hydrogeology, a shorter flow path could exist for saltwater to reach wells than can be determined on a regional scale. Therefore, saltwater could arrive at wells sooner than predicted. Saltwater also could reach wells sooner than predicted because the model does not include dispersion effects. For example, the assumption that the dissolved-chloride concentrations in the water withdrawn for reverse-osmosis (RO) operations are stable cannot be verified without a local-scale, variable-density-approach model. Predicted maximum encroachment of the potability interface is calculated from model intercell flows at the cell nearest the landward edge of saline ground water. This calculation is affected by the starting location and time step chosen. The offshore location of saline ground water is not certain; it could be nearer to the wells than estimated. A continued ground-water monitoring program in the county would protect against an unforeseen early arrival of the saline ground water as a result of these uncertainties.

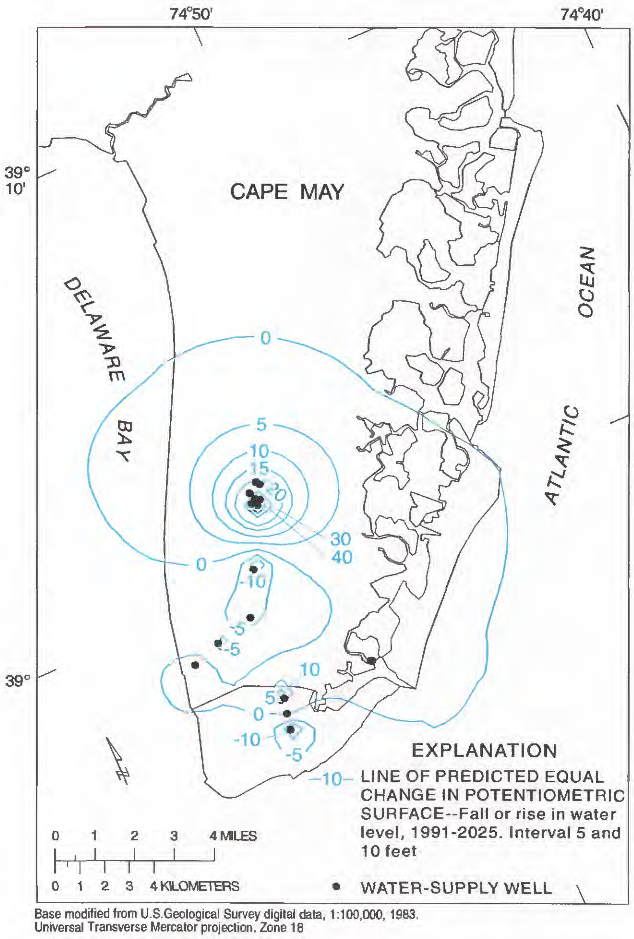


Figure 40. Predicted change in the potentiometric surface in the Cohansey aquifer for scenario 1.

Alternative 1

Water levels in the Holly Beach water-bearing zone and the estuarine sand aquifer did not change significantly over the planning period in the first alternative. The predicted change in water levels in the Cohansey aquifer in the first alternative is shown in figure 40. Water levels continued to decline near Cape May City. The most significant effect was the increase in water levels in the Cohansey aquifer centered at the Rio Grande well field. This increase, however, was derived at the cost of shifting half of the current withdrawals from the Cohansey aquifer to the upper aquifer of the Kirkwood Formation. Measured dissolved-chloride concentrations in wells screened in the upper aquifer of the Kirkwood Formation (P.J. Lacombe, written commun., 1994) indicate that ground water near Rio Grande well field is saline.

Table 9. Predicted saltwater encroachment during 1991-2025 in the Cohansey aquifer near major well fields,Cape May County, New Jersey

[Encroachment in feet; encroachment for alternative 1 shown in figs. 41-43; encroachment for alternative 2 shown in figs. 46-48; RO, reverse osmosis; ---, not applicable]

Period	Predicted encroachment	
	Alternative 1	Alternative 2
Rio Grande		
1995-2010	450	780
2010-25	380	870
Error band[1]	300	300
Total	1,230	1,950
County Airport		
1995-2010	420	620
2010-25	420	770
Error band	300	300
Total	1,140	1,690
Lower Township wells		
1995-2010	410	450
2010-25	560	640
Error band	300	300
Total	1,270	1,390
Cape May City		
1995-2010	Saltwater at RO well	530
2010-25	Saltwater at RO well	560
Error band	---	300
Total	---	1,390

[1]The average difference between measured and simulated encroachment near Villas (estuarine sand aquifer) and Cape May City (Cohansey aquifer) during the transient simulation (table 7).

Predicted saltwater encroachment in the Cohansey aquifer near the major well fields is shown in figures 41 through 43 and listed in table 9. The error band

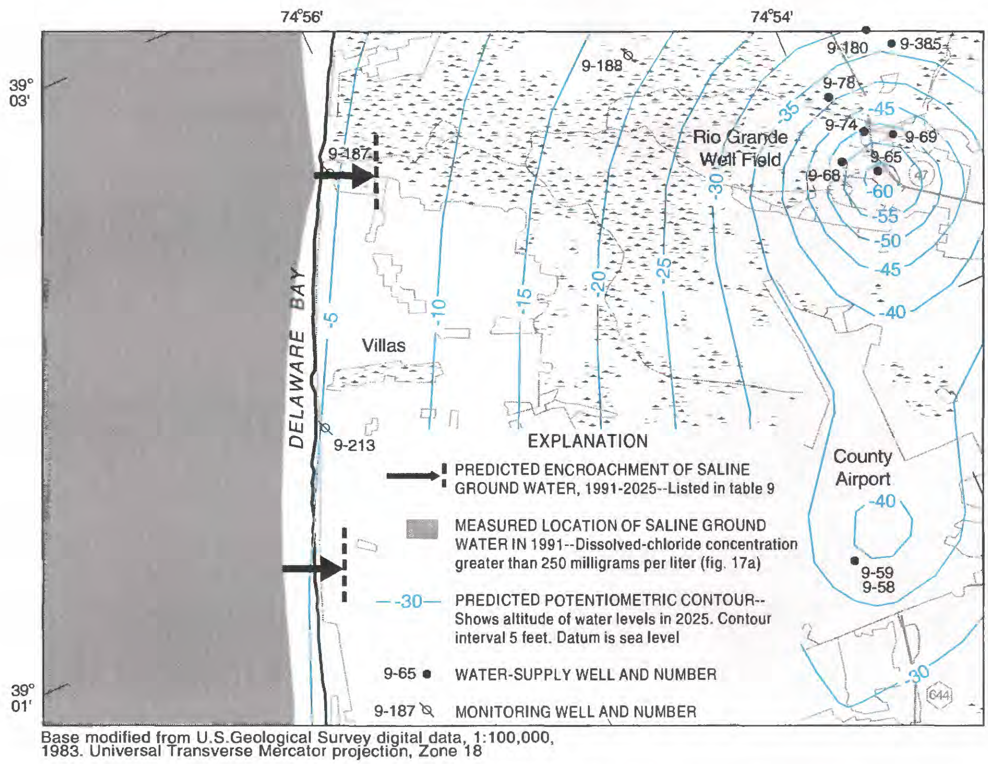


Figure 41. Predicted potentiometric surface and saltwater encroachment in the Cohansey aquifer for scenario 1 near Rio Grande (Location shown in figure 1).

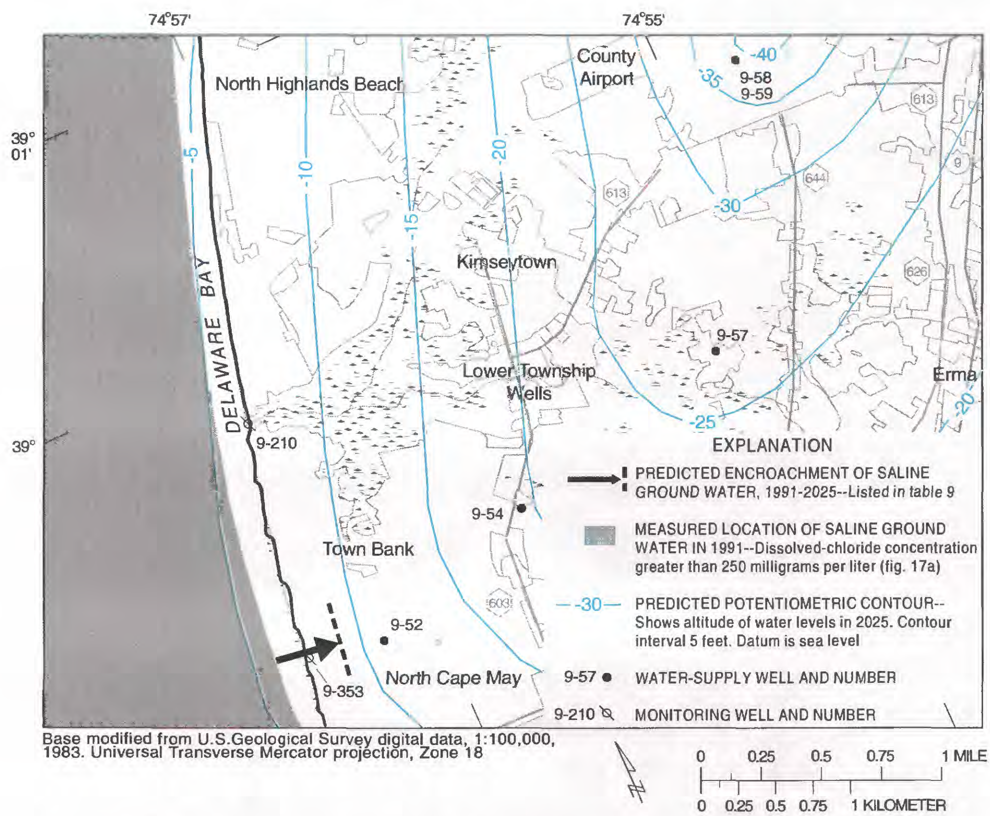


Figure 42. Predicted potentiometric surface and saltwater encroachment in the Cohansey aquifer for scenario 1 near Lower Township (Location shown in figure 1).

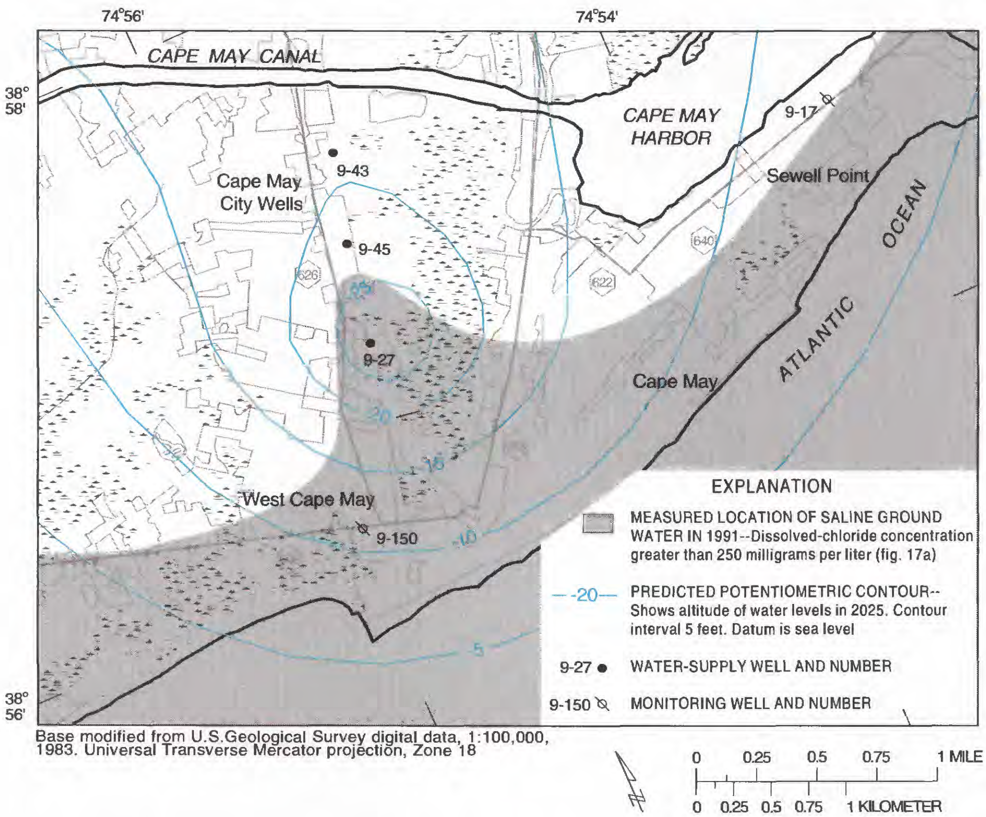


Figure 43. Predicted potentiometric surface and saltwater encroachment in the Cohansey aquifer for scenario 1 near Cape May City (Location shown in figure 1).

discussed earlier is included in the predicted encroachment because the calibrated model tends to underpredict encroachment. The error band also accounts for encroachment during 1991-94. Encroachment toward both the Rio Grande well field and the county airport (fig. 41) is approximately 1,200 ft during the planning period. Because of the lack of data on the current location of saline ground water near the Lower Township wells (fig. 42), the 1,300 ft of predicted encroachment could result in contamination of the well nearest the shoreline. This is a reasonable conclusion given the proximity of the well to the shoreline and the current high rate of withdrawal. In Cape May City (fig. 43), saltwater has reached the location of the supply well to be used for RO. On the basis of the shape of the simulated water-level surface in the Cohansey aquifer and absence of saltwater encroachment, the withdrawals at the RO well are predicted to stabilize the position of the potability interface in this area. This indicates that saltwater is not predicted to encroach toward supply wells located farther inland at Cape May City during the planning period.

Alternative 2

Water levels in the Holly Beach water-bearing zone did not change significantly over the planning period in the second alternative. Water levels in the estuarine sand aquifer (fig. 44) decreased slightly. Water levels in the Cohansey aquifer (fig. 45) decreased areally around the Rio Grande well field. Simulated flow gradients in alternative 2 generally are steeper than those in alternative 1. Water levels at Cape May City rose slightly as a result of the relocation of withdrawals out of this area.

Predicted saltwater encroachment in the Cohansey aquifer near the major well fields in this alternative is shown in figures 46 through 48 and listed in table 9. Encroachment toward all the withdrawal sites is greater than in alternative 1 because of the additional with-

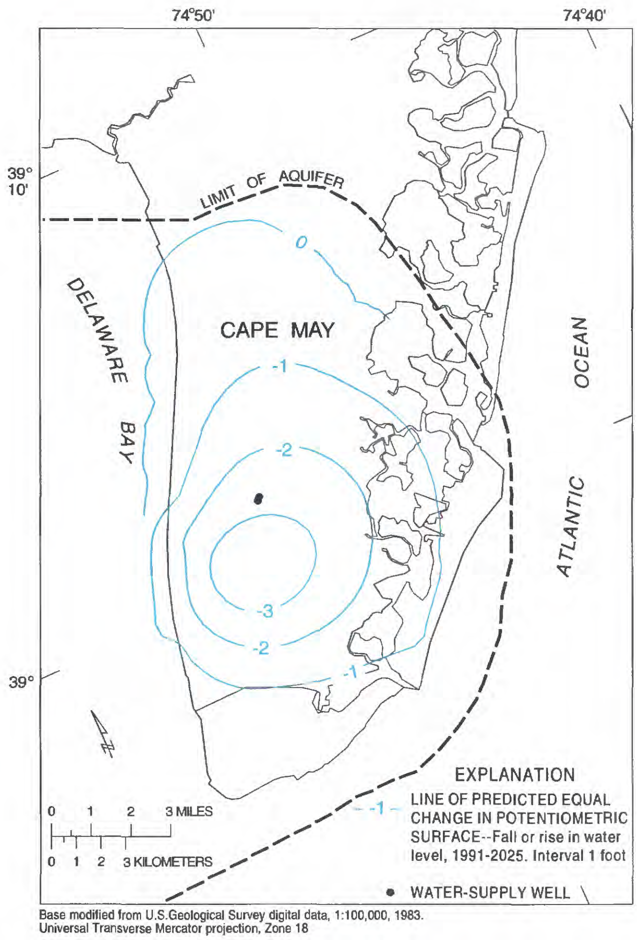


Figure 44. Predicted change in the potentiometric surface for scenario 2 in the estuarine sand aquifer.

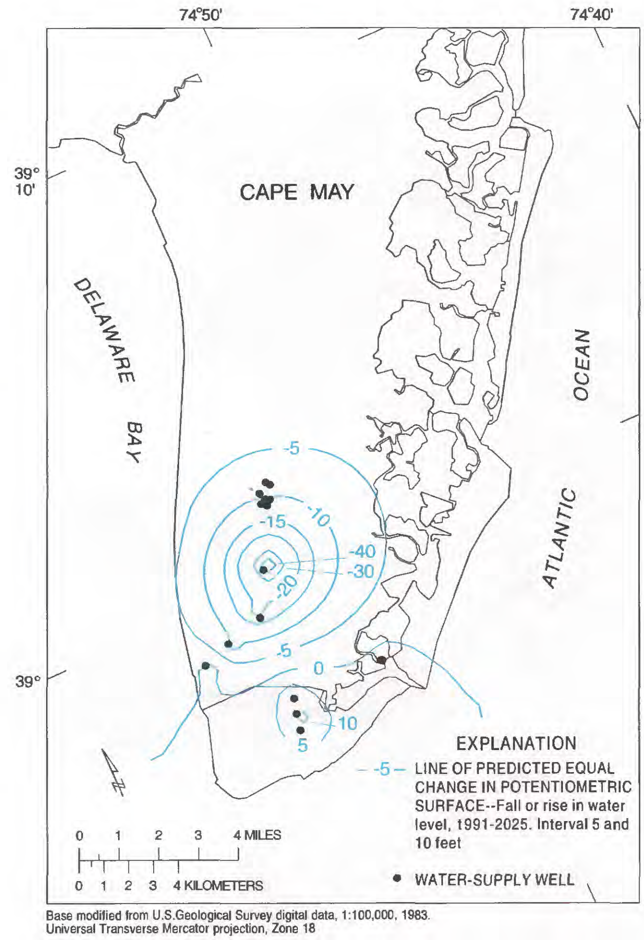


Figure 45. Predicted change in the potentiometric surface for scenario 2 in the Cohansey aquifer.

drawals. Nearly twice as much encroachment is predicted toward the Rio Grande well field. Encroachment toward the airport wells is increased by 50 percent, whereas encroachment toward the Lower Township wells is only slightly increased. At Cape May City, approximately 1,400 ft of saltwater encroachment is predicted, whereas no encroachment was predicted in alternative 1.

Use of Ground-Water Monitoring to Detect Saltwater Encroachment

Two types of monitoring wells are appropriate in coastal ground-water environments--outpost monitoring wells and upconing monitoring wells (Reilly, 1993, p. 465). Outpost wells are placed near the saltwater-freshwater transition in the aquifer used for water supply. These wells serve as an early-warning system for lateral saltwater encroachment, help to determine natural ground-water outflow and changes in outflow at the shoreline, and can be used to measure rates of encroachment of saltwater. Outpost well screens are set at the bottom of the aquifer, where the first signs of saltwater encroachment are found, and are short so that heads and dissolved-chloride concentrations can be defined accurately. If possible, groups of wells can be installed with screens set at different depths. The wells can be monitored continuously to account for tidal effects.

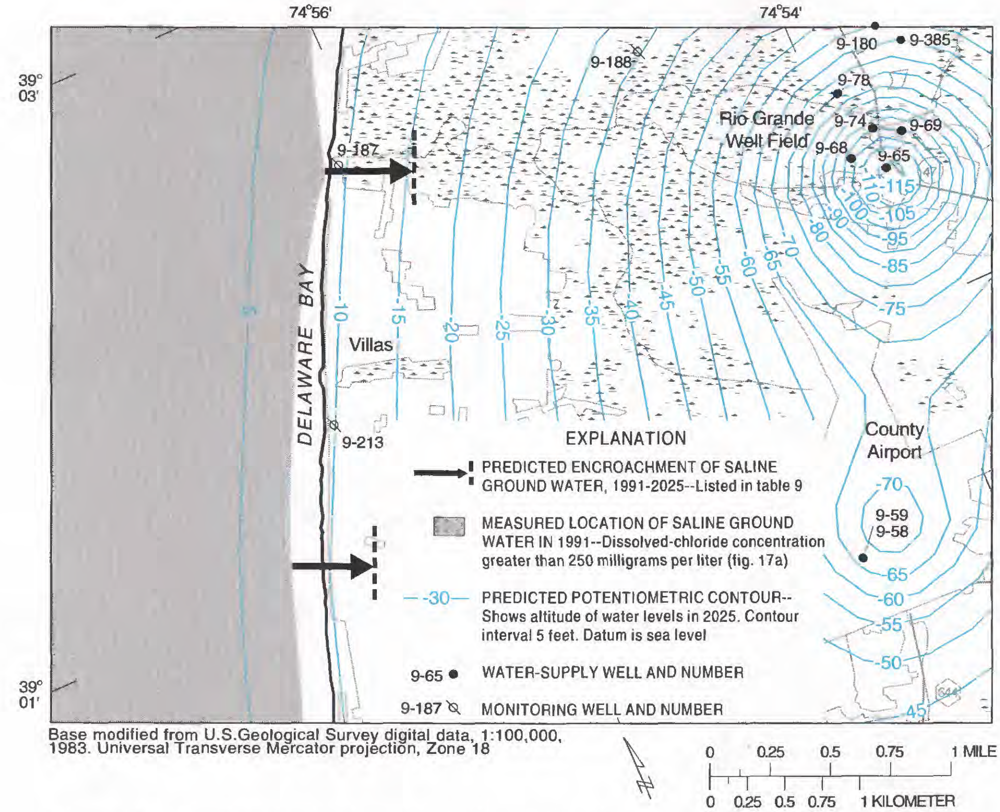


Figure 46. Predicted potentiometric surface and saltwater encroachment in the Cohansey aquifer for scenario 2 near Rio Grande (Location shown in figure 1).

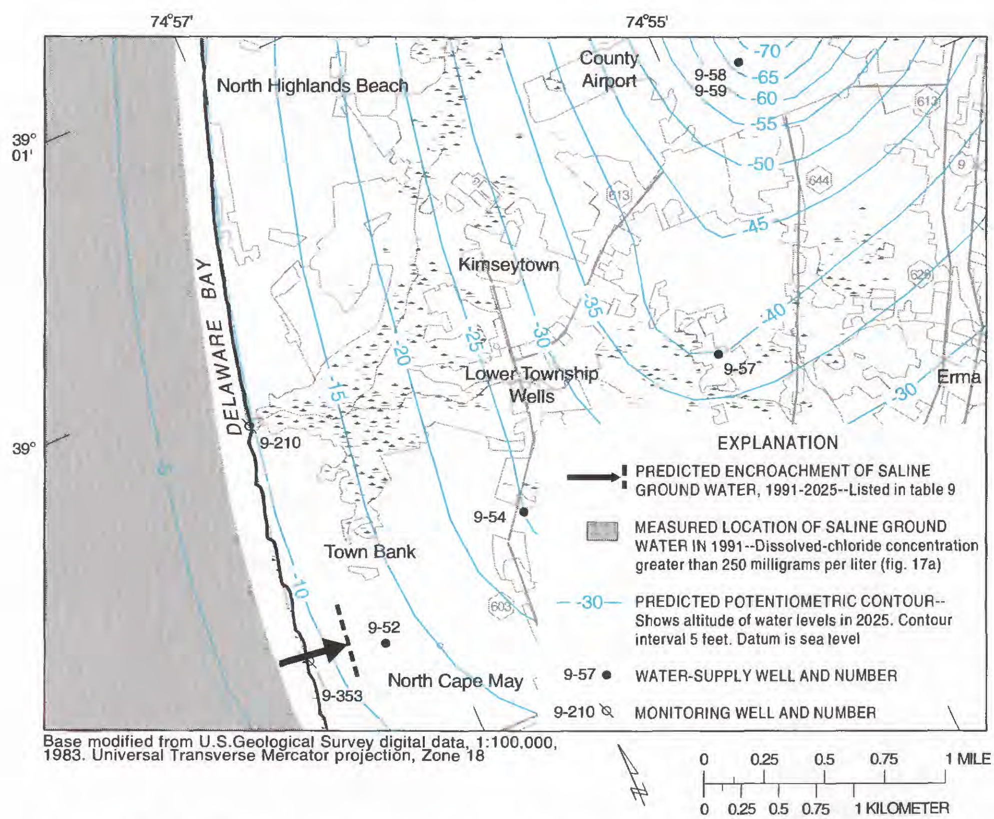


Figure 47. Predicted potentiometric surface and saltwater encroachment in the Cohansey aquifer for scenario 2 near Lower Township (Location shown in figure 1).

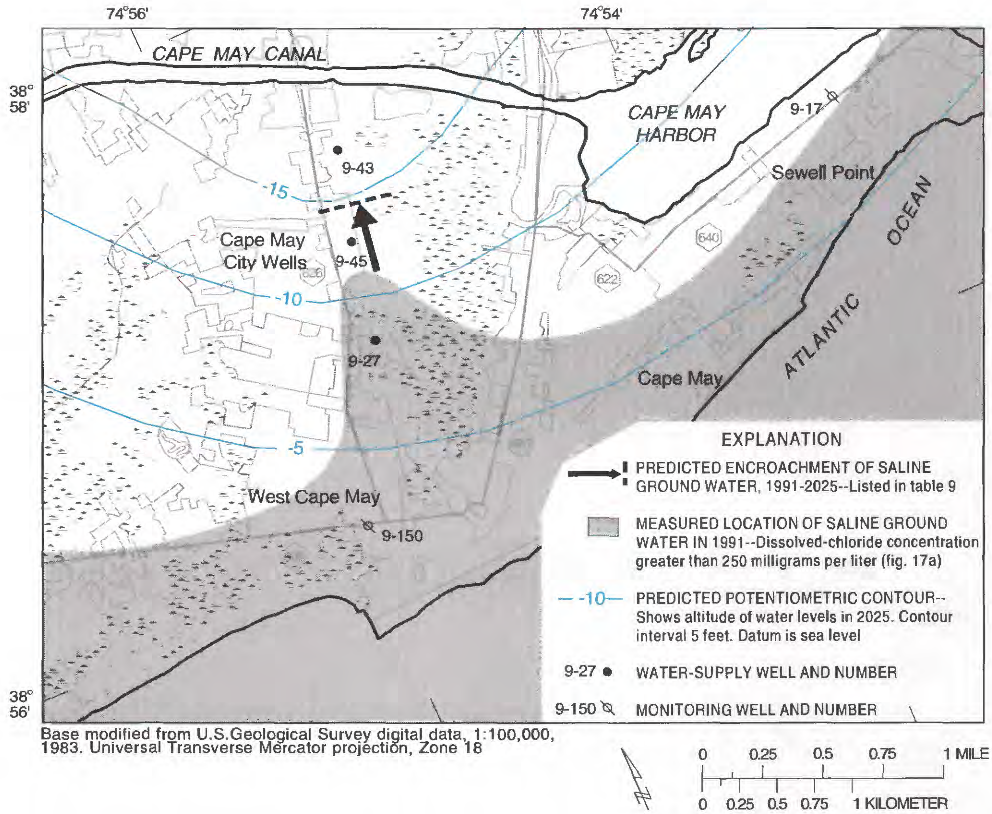


Figure 48. Predicted potentiometric surface and saltwater encroachment in the Cohansey aquifer for scenario 2 near Cape May City (Location shown in figure 1).

The ground-water system might be capable of sustaining an areal cone of depression, but head declines around an individual well can lead to the vertical encroachment, or upconing, of saline water into the well. In this instance, upconing monitoring wells are used. Screens in these wells are installed near and below (and possibly above) the depths of screens in supply wells to provide early detection of vertical saltwater encroachment. Use of these wells allows withdrawals to be adjusted to rates that do not cause upconing.

Finally, if the unconfined aquifer is to be developed for water supply, water-quality monitoring wells can also be used to detect any local contamination due to land use. These wells are installed near and upgradient from supply wells and are sampled regularly for appropriate contaminants. Well design is tailored to the individual site in order to monitor effectively for these contaminants.

SUMMARY AND CONCLUSIONS

Cape May County, the southernmost county in New Jersey, is on a natural peninsula that is virtually surrounded by saltwater, including the Atlantic Ocean and Delaware Bay. The potable-water supply of the county, nearly all of which comes from ground water, is limited by this proximity to saltwater. The shallow aquifer system provides about half the water supply; the other half comes from deeper aquifers. This report describes the results of a conceptual and numerical analysis of the shallow-ground-water resources of the county, with emphasis on the effects of saltwater encroachment on water supply.

The conceptual analysis of the saltwater-encroachment problem in the shallow ground-water system was conducted by investigating the hydrogeologic framework, water use, flow system, and water quality. The shallow aquifer system consists of the unconfined Holly Beach water-bearing zone and two confined aquifers, the estuarine sand and Cohansey aquifers, all of which are separated by confining units. Increased ground-water withdrawals from the shallow aquifer system in the southern half of the peninsula, mainly a result of the summer influx of tourists, have significantly altered natural ground-water flow patterns and threatened the water supply by drawing saltwater into the wells. Extensive cones of depression have formed in the confined aquifers. A similar problem is found in the deep aquifer system.

A numerical model of the shallow aquifer system in Cape May County was constructed and a quasi-three-dimensional finite-difference sharp-interface computer code was used to simulate ground-water flow and to predict saltwater encroachment under two water-supply-development alternatives. Simulation results and predictions are limited by data limitations and the assumptions inherent in the model. The model was calibrated to predevelopment and stressed (1896-1991) hydrologic conditions by comparing simulated heads with measured heads, simulated flows with estimated flows, and simulated saltwater encroachment with measured saltwater encroachment. Values of calibrated hydraulic properties were generally within the range of reported values. Simulation results were found to be most sensitive to aquifer hydraulic conductivity and withdrawals.

Two water-supply-development alternatives were simulated for the planning period 1995-2025 and involved only changes in the use of the Cohansey aquifer. Alternative 1 involved desalination of saline ground water (chloride concentration greater than 250 mg/L) at Cape May City and shifting half of the withdrawals at the Rio Grande well field from the Cohansey aquifer to the upper aquifer of the Kirkwood Formation. In addition, withdrawals for Lower Township were increased and most of the withdrawals from the well nearest the shoreline were relocated inland. Results of this simulation indicate that withdrawing saline water for desalination stabilizes the location of saltwater at Cape May City and significantly delays future encroachment to the Cape May City supply wells that are located farther inland. Shifting withdrawals at the Rio Grande well field to the deep aquifer system reduces the size of the cone of depression in the Cohansey aquifer centered at the well field.

Alternative 2 involved relocating most of the Cape May City withdrawals and withdrawals from the Lower Township well nearest the shoreline to inland locations. Results of this simulation show continued saltwater encroachment in Cape May City and toward the Rio Grande well field. Water levels in the cone of depression at Cape May City rise only slightly, whereas the cone of depression at Rio Grande is deepened. Because of the lack of data on the exact location of saline ground water seaward of the Lower Township supply wells, it is impossible to determine with certainty whether water in the well nearest the shoreline would be contaminated during the planning period in either of the alternatives.

These following general conclusions can be made about the shallow ground-water resources of Cape May County:

1. Significant saltwater encroachment in the Cohansey aquifer has affected Cape May City's water supply. Less encroachment is found at Wildwood, whereas encroachment toward Lower Township's water-supply wells has yet to be observed. Significant saltwater encroachment is found in the estuarine sand aquifer at Villas, near the Rio Grande well field. No significant encroachmen- has been observed in the little-used Holly Beach water-bearing zone.
2. Results of simulation of the alternatives in this study suggest that the withdrawals can be sustained over the 30-year planning period without significant saltwater contamination. Howeveı, the two alternatives involve only modest increases in withdrawals. Large increases in withdrawals or a continuation of the current withdrawal scheme would likely cause saltwater contamination of wells in Cape May City and Lower Township.
3. In addition to the alternatives tested above, water-conservation practices could help to lessen saltwater encroachment. Use of low-capacity wells spread far enough apart would help to create only small, non-overlapping cones of depression. Areal distribution of withdrawals would minimize the potential for upconing of saltwater in wells. Alternatively, installation of water-supply wells with screens set in the shallowest part of the aquifer and with high specific capacity would help to delay upconing of saltwater in the wells.
4. The freshwater supply of the county is finite and comes mainly from ground water, which originates as recharge from precipitation. Although the unconfined aquifer contains much of this freshwater, contamination as a result of land-use

practices prevents extensive use of the water from this aquifer. Most of the withdrawals from the shallow aquifer system are consumptive (water is ultimately discharged to the ocean through wastewater outfalls). The freshwater lost from the system is replaced partly by encroaching saltwater. Increased withdrawals and continued contamination due to land-use practices will exacerbate the water supply problem and threaten the limited supply. Continued monitoring of the resource by use of outpost and upconing wells would help to ensure early detection of saltwater encroachment.

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