GROUND-WATER HYDROLOGY AND SIMULATION OF SALTWATER ENCROACHMENT,

SHALLOW AQUIFER SYSTEM OF SOUTHERN CAPE MAY COUNTY, NEW JERSEY

By Frederick J. Spitz and Thomas H. Barringer

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4191

Prepared in cooperation with the

CITY OF CAPE MAY, CITY OF WILDWOOD, and the
TOWNSHIP OF LOWER MUNICIPAL UTILITIES AUTHORITY

West Trenton, New Jersey
1992

U.S. DEPARTMENT OF THE INTERIOR

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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
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[1] (ft^2/d)	0.0929	meter squared per day
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
million gallons per day (Mgal/d)	3875.	cubic meter per day
million gallons per year (Mgal/yr)	1,382,471.2	cubic meter per year

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

Abbreviated water-quality unit used in report: mg/L (milligram per liter).

[1] The unit for expressing transmissivity, reduced to its simplest terms form cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/day)/ft^2]ft$

GROUND-WATER HYDROLOGY AND SIMULATION OF SALTWATER ENCROACHMENT, SHALLOW AQUIFER SYSTEM OF SOUTHERN CAPE MAY COUNTY, NEW JERSEY

By Frederick J. Spitz and Thomas H. Barringer

ABSTRACT

Saltwater encroachment is occurring in the shallow aquifer system in the peninsula of Cape May County, New Jersey because of increasing withdrawals for public supply. This problem has necessitated the abandonment and sealing of formerly productive freshwater wells. The shallow aquifer system consists of three aquifers: a water-table aquifer (the Holly Beach water-bearing zone) and two confined aquifers--the estuarine sand and Cohansey. Some domestic wells located nearshore that are screened in the water-table aquifer have been affected by saltwater encroachment. Large withdrawals of water for public supply from the two confined aquifers at the Rio Grande, Cape May City, and Lower Township well fields have lowered ground-water levels below sea level in a large area of the peninsula and offshore, causing landward migration of saline ground water toward these well fields.

A computer model of the shallow aquifer system was constructed to improve understanding of the hydrogeology of, and saltwater encroachment in, the peninsula. The quasi-three-dimensional sharp-interface model is a discrete representation of the subsurface geometry, boundaries, and water transmitting characteristics of the system. Simulations of predevelopment (about 1890) and present (1989) hydrologic conditions were calibrated by comparison to measured hydrologic data and were used to define the distribution of flow and water levels within the system and the location and movement of the saltwater-freshwater interface.

Results of the simulations indicate that (1) the shallow aquifer system on the peninsula is recharged primarily by precipitation, whereas ground-water inflow from the northern part of the County is small; (2) under predevelopment conditions, only a small fraction of the water in the unconfined system leaked to the confined aquifers; (3) present (1989) withdrawals from the confined aquifers cause extensive drawdown in water levels that induces saltwater encroachment; and (4) the saltwater-freshwater interface in the Cohansey aquifer is onshore and near water-supply wells in Cape May City and near the shore west of the Lower Township and Rio Grande well fields.

The model also was used to evaluate the hydrologic consequences of five ground-water-development scenarios for the 1989-2049 planning period. The selected scenarios were (1) maintaining recent (1983-88) withdrawal rates and locations, (2) decreasing recent withdrawals by 25 percent, (3) increasing recent withdrawals by more than 80 percent, (4) aggregating withdrawals at recent rates at an enlarged well field at Rio Grande, and (5) increasing recent withdrawals by 100 percent and moving to new well fields that are inland and farther north on the peninsula. Model simulations of each scenario provided an estimate of the resulting change in ground-water levels, change in ground-water flow directions and rates, and movement of the saltwater-freshwater interface toward the major well fields. These results provide the hydrologic information required to design a water-supply-development strategy that would maintain the needed potable water for the planning period and a

monitoring program that would ensure early warning of impending saltwater encroachment, allowing sufficient time for development of an alternate supply.

The model approximates the interface as an abrupt (sharp) transition from freshwater to saltwater. In reality, the interface is a gradual transition that, on the basis of lines of equal chloride concentration interpreted from results of analyses of well water in Cape May County, probably is several thousand feet wide. Model predictions must be evaluated with the understanding that saline ground water is advancing faster in front of the simulated interface, where chloride concentrations are low, than at the simulated interface, where chloride concentrations are high. Consequently, the model yields much smaller estimates of interface movement than estimates made from dilute chloride concentrations measured at the front of the transition zone.

On the basis of model predictions, the saltwater-freshwater interface will advance more rapidly in the estuarine sand aquifer than in the Cohansey aquifer and because of the short travel time (on the order of a few years) through the confining unit separating the two aquifers, saltwater from the estuarine sand aquifer will contaminate wells screened in the Cohansey aquifer. Specifically, the simulation results predict that, if current pumping rates persist (scenario 1), the saltwater-freshwater interface will move approximately 400 feet in the Cohansey aquifer and more than 1,000 feet in the estuarine sand aquifer toward the Cape May City well field by the end of the planning period (2049). If pumping increases by 80 percent (scenario 3), the interface would move nearly 600 feet in the Cohansey aquifer and nearly 1,300 feet in the estuarine sand aquifer toward the well field. The proximity of the interface to these wells in 1989 indicates that the wells likely would be unsuitable for water supply by the end of the planning period.

The simulation results also predict that the saltwater-freshwater interface will move eastward toward the Lower Township well field most rapidly in the estuarine sand aquifer--by more than 1,200 feet during the planning period, if current pumping rates persist, and by about 2,800 feet with scenario 3. These results suggest that saline ground water will reach the westernmost well in this well field during the planning period. Model simulations, however, could not predict interface movement toward this well field in the Cohansey aquifer accurately.

Model predictions of the movement of the saltwater-freshwater interface toward the Rio Grande well field if current pumping rates persist are about 450 feet in the Cohansey aquifer and 700 feet in the estuarine sand aquifer. If pumping rates increase, as estimated in water-supply scenario 3, interface movement would exceed 600 feet in the Cohansey aquifer and more than 1,200 feet in the estuarine sand aquifer. Under either of these limiting circumstances, saltwater probably would not reach wells at this well field during the planning period because the well field is located about 2 miles inland, whereas the current position of the interface is near the shore in the estuarine sand aquifer and possibly even farther from the well field in the Cohansey aquifer.

Results of simulations of ground-water-supply development scenarios 2, 4 and 5 predict that reduction of withdrawals or relocation of pumpage areally to the center of the peninsula would delay saltwater encroachment. The ground-water-budget analysis indicates that relocation of withdrawals to the unconfined aquifer will reduce greatly landward movement of the saltwater-freshwater interface; however, the potential for contamination from human activities needs to be considered.

INTRODUCTION

Cape May County is the southernmost County in New Jersey (fig. 1). Saltwater encroachment is occurring in the shallow aquifer system in the peninsula of the County because increased withdrawals from water-supply wells has caused ground-water levels to drop below sea level. This has necessitated the abandonment and sealing of formerly productive freshwater wells. The shallow aquifer system consists of one surficial and two confined aquifers. Large withdrawals of water from the confined aquifers at the Rio Grande, Cape May City, and Lower Township well fields have lowered ground-water levels in a large area of the peninsula and part of the Delaware Bay and the Atlantic Ocean. This has caused landward migration of saline ground water toward these well fields. The water-table aquifer is the least developed of the three aquifers (fig. 2). Together, the shallow aquifer system provides about half of the County's industrial, domestic, irrigation, and public-supply water.

The number of permanent residents in the County, slightly more than 13,200 in 1900, was 93,000 in 1990. The 1989 summer population was estimated to be more than five times the size of the permanent population (Cape May County Planning Board, undated). The increase in the number of permanent-residents, augmented by the seasonal influx of tourists, has resulted in an increase in shallow-ground-water withdrawals from 4.22 Mgal/d in 1956 to 7.00 Mgal/d in 1986. The sharp increase in withdrawals after 1956 reflects an underestimation of withdrawals prior to that year because of the lack of data. Similarly, the apparent dip in withdrawals in the late 1980's reflects data deficiencies. The seasonal variation in pumpage is illustrated in figure 3.

The increase in consumptive withdrawals has led to a regionally lowered potentiometric surface in the confined aquifers in the southern part of the peninsula. The potentiometric surface represents the total hydraulic head in a confined aquifer as the height at which the water stands in cased wells. The water-table surface represents the total head in an unconfined aquifer (at atmospheric pressure). The extensive zone of lowered potentiometric head is thought to be caused by the merging of two local cones of depression around the Rio Grande and Cape May City well fields. This reduction in head has, in turn, affected ground-water quality in the region by enabling saline water to flow into withdrawal wells. Over time, some of these wells, such as the public-supply wells of the Cape May City Water Department, have been abandoned and replaced with others drilled farther inland to avoid the encroaching saltwater.

The permanent population of the County is expected to increase by 60 percent to approximately 160,000 by 2040. A 10-percent increase in summer population to approximately 660,000 is projected for that same period (Roger Tsao, New Jersey Department of Environmental Protection and Energy, written commun., 1989). Because water use is correlated with population, and to address local concern about saltwater encroachment, a 3-year study of the

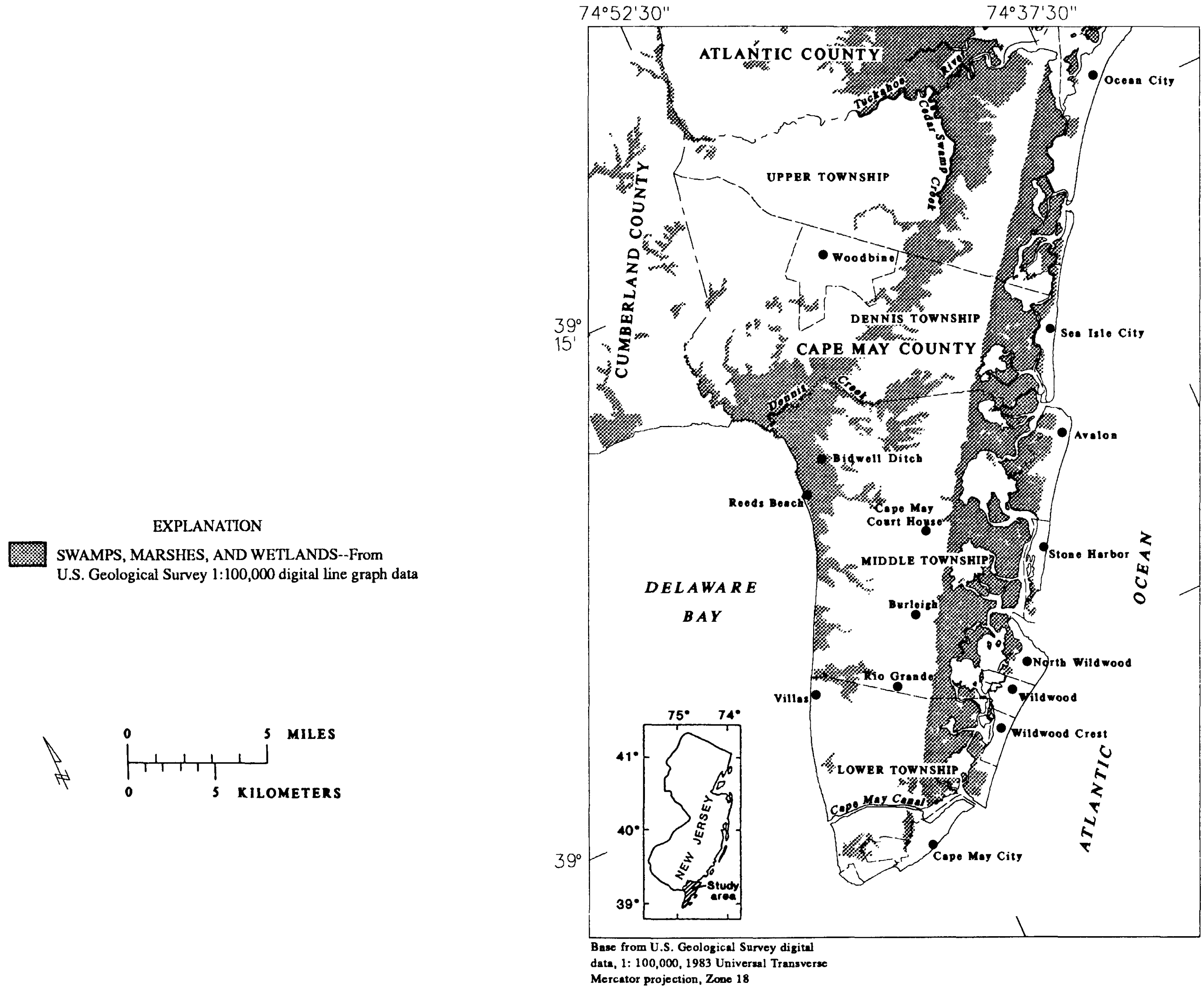


Figure 1.--Location of study area.

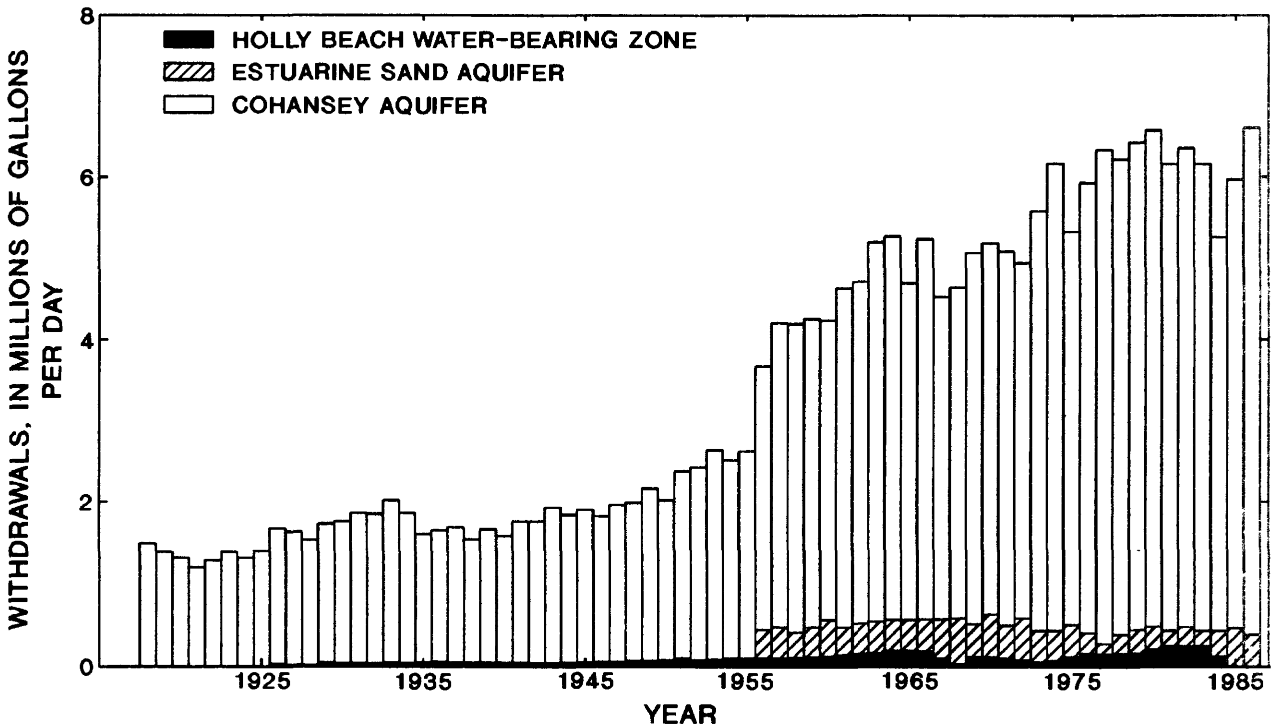


Figure 2.--Long-term pumping trends, by aquifer.

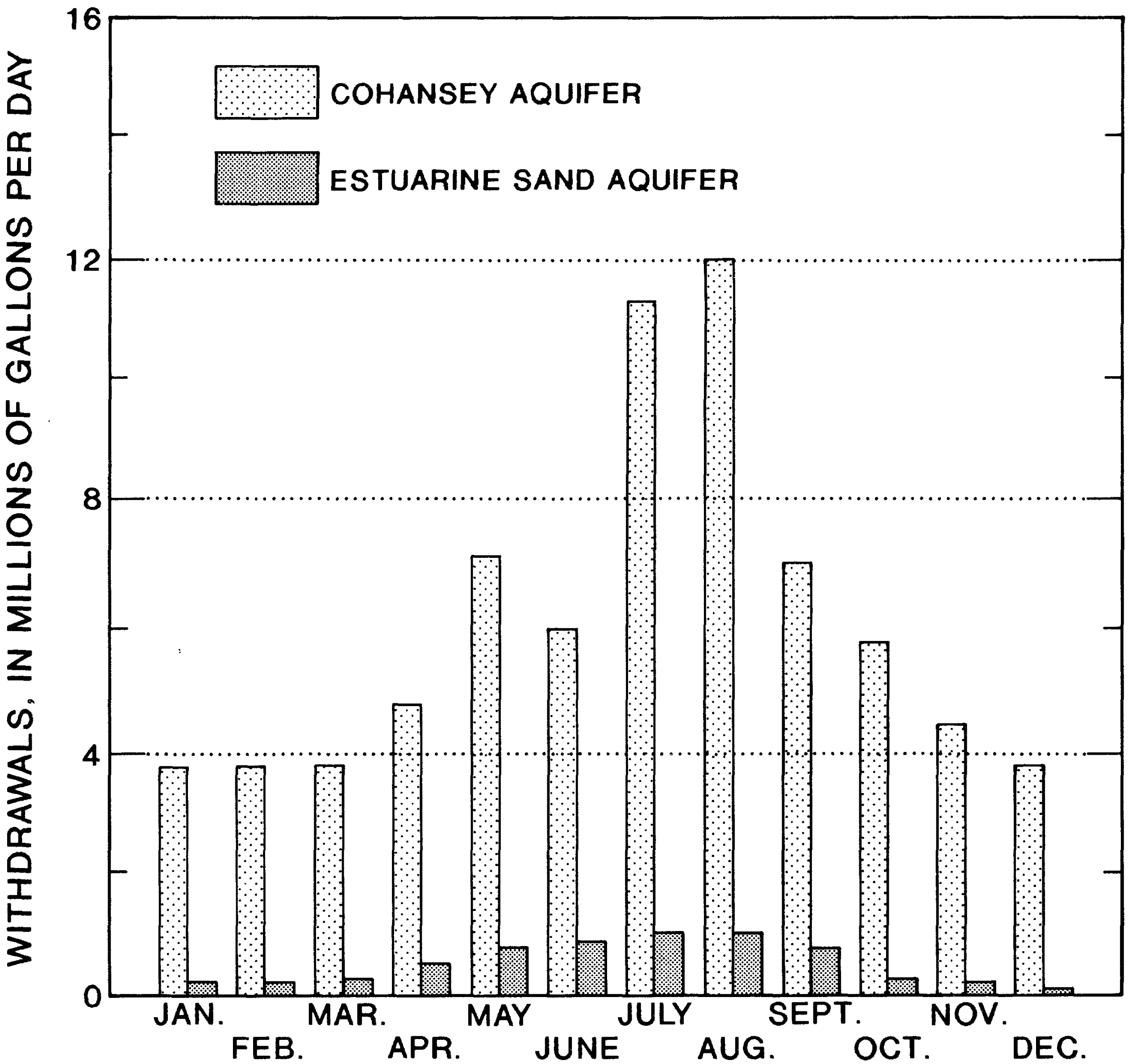


Figure 3.--Monthly variation in withdrawals by aquifer, 1986.

region's shallow aquifer system was begun in 1986 by the U.S. Geological Survey (USGS) in cooperation with the City of Cape May, City of Wildwood and the Township of Lower Municipal Utilities Authority.

As part of the study, a ground-water-flow model of the shallow aquifer system in the County was developed. The model was used to estimate the future availability of ground-water on the peninsula through a suite of scenarios developed to examine the shallow aquifer system's response to a variety of resource-development options. The planning period for these simulations is 60 years, to 2049. Results can be used by planners to identify an optimal resource-development strategy. This strategy will determine withdrawal rates and locations for the region's public-supply-well system that will meet water demand while limiting the extent of saltwater encroachment into the peninsula's aquifers.

Purpose and Scope

This report presents the results of an analysis of the shallow aquifer system of peninsular Cape May County, New Jersey. The objectives of this analysis were (1) to define the geometry of the ground-water system, the distribution of flow and water levels, and the configuration and movement of the saltwater-freshwater interface in each aquifer; (2) to evaluate the response of the ground-water system to withdrawal stresses; and (3) to present this hydrologic information in a manner that facilitates planning for long-term water-supply needs and design of a monitoring program that provides warning of saltwater contamination.

The report presents a description of the hydrogeologic framework of the shallow aquifer system, available ground-water-level and salinity data, and information on ground-water withdrawals. These data were used to construct a computer model that represents flow of fresh and saline ground water, which are separated by a sharp interface. The model was used to simulate predevelopment ground-water conditions and the response of the shallow aquifer system to withdrawals from approximately 1900 to present (1989). Simulation results were compared to measured hydrologic data.

The model also was used to predict the hydrologic response of the aquifer system to selected ground-water-development scenarios that are being considered by local planning agencies. The predicted change in ground-water levels, change in ground-water flow directions and rates, and movement of the saltwater-freshwater interface that results from each ground-water withdrawal scenario is presented.

Study Area

The Cape May peninsula (fig. 1) is a region of low topographic relief consisting of gently rolling plains with tidally influenced salt marshes and estuaries along its coast. The peninsula was created during the southward migration of the ancestral drainage channels beneath Delaware Bay during Pleistocene glacial and interglacial time (Knebel and Circe, 1988). An extensive swamp separates the peninsula from the mainland part of the County. Great Cedar Swamp, which contains Dennis and Cedar Swamp Creeks, diagonally bisects the County. Part or all of five first-order drainage basins are present in the study area: Cape May West, Cape May East, Tuckahoe River, Great Egg Harbor River, and Maurice River (R.D. Schopp, U.S. Geological Survey, written commun., 1989).

The peninsular part of the County is characterized by few streams and porous surficial sediments. Land-surface elevations range from sea level to slightly more than 20 ft above sea level along the longitudinal axis of the peninsula. Streams in the mainland part of the County are believed to be gaining (Gillespie and Schopp, 1982), where the land surface reaches an elevation slightly greater than 60 ft. The eastern coast consists of barrier islands that separate the Atlantic Ocean from an extensive estuarine complex. The western and southern coasts abut Delaware Bay and include areas of salt marsh. A canal connecting Delaware Bay to the Atlantic Ocean cuts across the tip of the peninsula. The floor of Delaware Bay typically is more irregular than is that of the Atlantic Ocean.

The County lies in the Coastal Plain physiographic province (Fenneman, 1946) and has a temperate climate. Mean precipitation ranges from 41 in/yr in the southern part of the peninsula to 45 in/yr in the northern part (R.D. Schopp, U.S. Geological Survey, written commun., 1987).

Approach

The shallow aquifer system was simulated by use of SHARP (Essaid, 1990a), a quasi-three-dimensional finite-difference computer model of freshwater and saltwater flow separated by a sharp interface in a layered coastal-aquifer system. The model was calibrated to predevelopment (about 1890) and present (1989) conditions by comparing simulated hydraulic heads in the three aquifers to water level data from the literature and from USGS data bases. Water-level hydrographs also were reproduced with the model. Because well-water chloride concentrations near the approximate 10,000-mg/L simulated concentration were rarely observed, extrapolations from lower concentrations were used to calibrate interface positions in the model. Hypothetical future withdrawal scenarios were tested with the model to investigate the consequences of continued pumpage at 1989 levels and of pumpage under various alternative circumstances. The predictive scenarios included increased and reduced pumpage and aggregation and relocation of production wells.

Previous Investigations

Cape May County's shallow aquifer system--including hydrogeology, aquifer and confining-unit properties, water levels, and chloride concentrations--have been evaluated in a number of studies. These studies are summarized in table 1, where they are divided into three categories: (1) county studies, (2) Coastal Plain studies, and (3) simulation studies. Interpretive studies and data-collection efforts most relevant to the present work are discussed briefly below.

Most data on the hydrogeology of the Cape May area were derived from well logs or from borehole- or surface-geophysical data. Gill (1962b) and Zapecza (1989) are the primary sources of information on Cape May County's hydrogeology. Schuster and Hill (in press), in a related ground-water study, also compiled data on withdrawals, and chloride concentrations and updated the hydrogeologic framework described by Gill (1962a). Sources of hydrogeologic data were supplemented by more recent borehole- or surface-geophysical surveys (S.K. Sandberg, New Jersey Department of Environmental Protection and Energy, written commun., 1989; P.J. Lacombe, U.S. Geological Survey, written commun., 1989).

Table 1.--Previous investigations of the shallow aquifer system, Cape May County

Reference	Area or subject
COUNTY STUDIES	
Cape May County Planning Board, 1982	Water supply
Epstein, 1988	Ground-water consumption and saltwater intrusion
Geraghty and Miller, 1971	Ground-water resources
Gill, 1962a	Ground-water resources, saltwater intrusion
Gill, 1962b	Well records and logs, stratigraphy
Roy F. Weston, 1967	Ground-water resources
Schuster and Hill, in press	Hydrogeology, ground-water withdrawals and saltwater intrusion
COASTAL PLAIN STUDIES	
Bauersfeld and others, 1989	Water resources data
Eckel and Walker, 1986	Aquifer water levels, 1983
Meisler, 1980	Delineation of salty ground water
Seaber, 1963	Chloride concentrations, 1923-61
Schaefer, 1983	Chloride concentrations, 1977-81
Vowinkel, 1984	Ground-water withdrawals, 1956-80
Vowinkel and Foster, 1981	Hydrogeologic conditions
Walker, 1983	Aquifer water levels, 1978
Zapecza, 1989	Hydrogeologic framework
Zapecza, Voronin, and Martin, 1987	Predevelopment aquifer water levels, withdrawals
SIMULATION STUDIES	
Martin, 1990	Ground-water flow, Coastal Plain
Meisler, 1985	Sea-level effects on saltwater-freshwater relations, Coastal Plain

Water levels in the shallow aquifer system were documented by Walker (1983) and by Eckel and Walker (1986). Additional water-level measurements for the County were made by the USGS during synoptic surveys in the summer and fall of 1988 (R. Rosman, U.S. Geological Survey, written commun., 1989). Data on ground-water withdrawal rates for the region were collated from USGS, New Jersey Department of Environmental Protection and Energy (NJDEPE), and local government records. Water chloride concentrations in wells screened in the shallow aquifer system documented by Gill (1962a) and Seaber (1963) were supplemented by subsequent measurements by the USGS and local government agencies (G.R. Webber, Cape May County Planning Board, written commun., 1989).

Well-Numbering System

A USGS well number consists of a county-code prefix followed by a unique sequence number for the well in that county. Cape May is represented by county code 9.

Acknowledgments

The authors thank the officials of the City of Cape May, City of Wildwood, and the Township of Lower Municipal Utilities Authority for their assistance in the study and in supplying withdrawal estimates. Thanks also are given to Elwood Jarmer and the Cape May County Planning Board personnel for their assistance in providing data and in helping to maintain the liaison among the parties involved. Our thanks also are extended to Dr. Hedeff Essaid of the USGS, the author of the SHARP computer model used in this work, for her continued assistance throughout the course of the study. For well-drilling and the provision of geophysical data and analysis, thanks are given to the New Jersey Department of Environmental Protection and Energy. The NJDEPE drilled a well nest west of Stone Harbor in 1988 to document the location of the saltwater-freshwater interface in that area. Finally, we thank the individuals and corporations in the County who gave USGS employees access to their wells to collect samples and make measurements.

GROUND-WATER HYDROLOGY

The hydrogeologic units in the study area are not necessarily identical to their associated geologic units. Geologic-unit designations are based on the geologic time in which the strata were deposited. Hydrogeologic-unit designations, however, are based on the water-bearing characteristics of the units (Zapecza, 1989, p. B7). Thus, the estuarine sand aquifer (table 2) may, for example, contain part of the Cohansey Sand geological stratum in peninsular Cape May County. In this report, all names refer to hydrogeologic unit unless otherwise indicated. Thus, the confining unit that separates the Cohansey and estuarine sand aquifers is the unit that separates them hydrogeologically.

Hydrogeologic Setting

The Coastal Plain physiographic province consists of layers of gravel, sand, silt, and clay that gently dip and thicken to the southeast. The shallow aquifer system of the Cape May consists of five hydrogeologic units, which are described below in order of increasing depth. The Holly Beach water-bearing zone, the surficial aquifer of the system, overlies the system's

Table 2.--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">System</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="2">Holocene</td><td rowspan="2">Beach and dune deposits</td><td rowspan="6">Holly Beach water-bearing zone</td><td>Beach and dune deposits</td><td rowspan="3">Holly Beach water-bearing zone</td></tr>
<tr><td>Intertidal sands</td></tr>
<tr><td rowspan="3">Pleistocene</td><td rowspan="3">Cape May Formation</td><td rowspan="3">Cape May Formation</td></tr>
<tr><td>Estuarine clay confining unit</td></tr>
<tr><td rowspan="2">Estuarine sand aquifer</td></tr>
<tr><td rowspan="4">Tertiary</td><td rowspan="4">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>Kirkwood Formation</td></tr>
</table>

two confined aquifers. On the peninsula, the estuarine clay underlies the Holly Beach water-bearing zone and confines the next deepest aquifer, the estuarine sand; both units are absent north of the peninsula. The estuarine sand aquifer is underlain by an areally extensive clay unit that confines the Cohansey aquifer (the deepest aquifer of the shallow aquifer system), which also is present throughout the County. These hydrogeologic units extend under Delaware Bay to the west and the Atlantic Ocean to the east and south.

The hydrogeologic framework represented by the model reflects data from the sources cited earlier, as revised by the incorporation of new data collected during the study. The chief adaptations to the hydrogeologic framework involved an extention of the northern limit of the confining unit overlying the Cohansey aquifer and an increase in the dip of the top of that unit in the southern part of the peninsula. Figure 4 represents the simulated hydrogeologic framework and accounts for the pinching out of hydrogeologic units in the mainland part of the County in figures 4c and 4d and the offset of the zero elevation contour with the County coastline in figure 4f. Similarly, the Holly Beach water-bearing zone is assumed to include the small amount of unsaturated zone material above the water table as well.

The unconfined Holly Beach water-bearing zone thickens to the east and is estimated to be 15 to 123 ft thick. In the southern part of the County, the Holly Beach water-bearing zone is composed of fine to coarse marine sands interspersed with gravel lenses. In the northeastern and barrier island areas, it consists of marine sands and beach and dune deposits. In the northwestern part of the County, it contains a mixture of sand and silty clay.

The Holly Beach water-bearing zone overlies the estuarine clay, a silty-clay confining unit, on the peninsula. The presence of interspersed lenses of sand and gravel cause this unit to be locally leaky. The thickness of the confining unit ranges from 12 to 102 ft and increases from northwest to southeast. The estuarine clay confines the estuarine sand aquifer. Based on data collected at the time of this study, both the estuarine sand aquifer and the estuarine clay confining unit pinch out in approximately the same location at the northern limit of the peninsula. The estuarine sand aquifer is from 20 to 163 ft thick and is made up of poorly sorted gravel, sand, and silty clay. The aquifer generally thickens to the east. It is highly permeable and thickest in the ancestral Delaware River channel and its tributary, which extend from Villas to Wildwood Crest (fig. 1) and from Reed's Beach to North Wildwood, respectively (Gill, 1962a). The channels were eroded into the Cohansey Sand geologic unit.

A clay confining unit separates the estuarine sand aquifer from the underlying Cohansey aquifer on the peninsula. This confining unit is 10 to 59 ft thick and is thinnest in the southern part of the peninsula, where it is also very leaky. Some investigators who have analyzed recent data question whether this confining unit consistently represents the top of the Cohansey aquifer (W.L. Newell, U.S. Geological Survey, oral commun., 1987). On the basis of geologic age, it lies within the Cohansey Sand at some locations. The Cohansey aquifer is estimated to be 30 to 229 ft thick and consists of a heterogeneous mix of fine gravel, sand, and silt, with thick, discontinuous clay wedges.

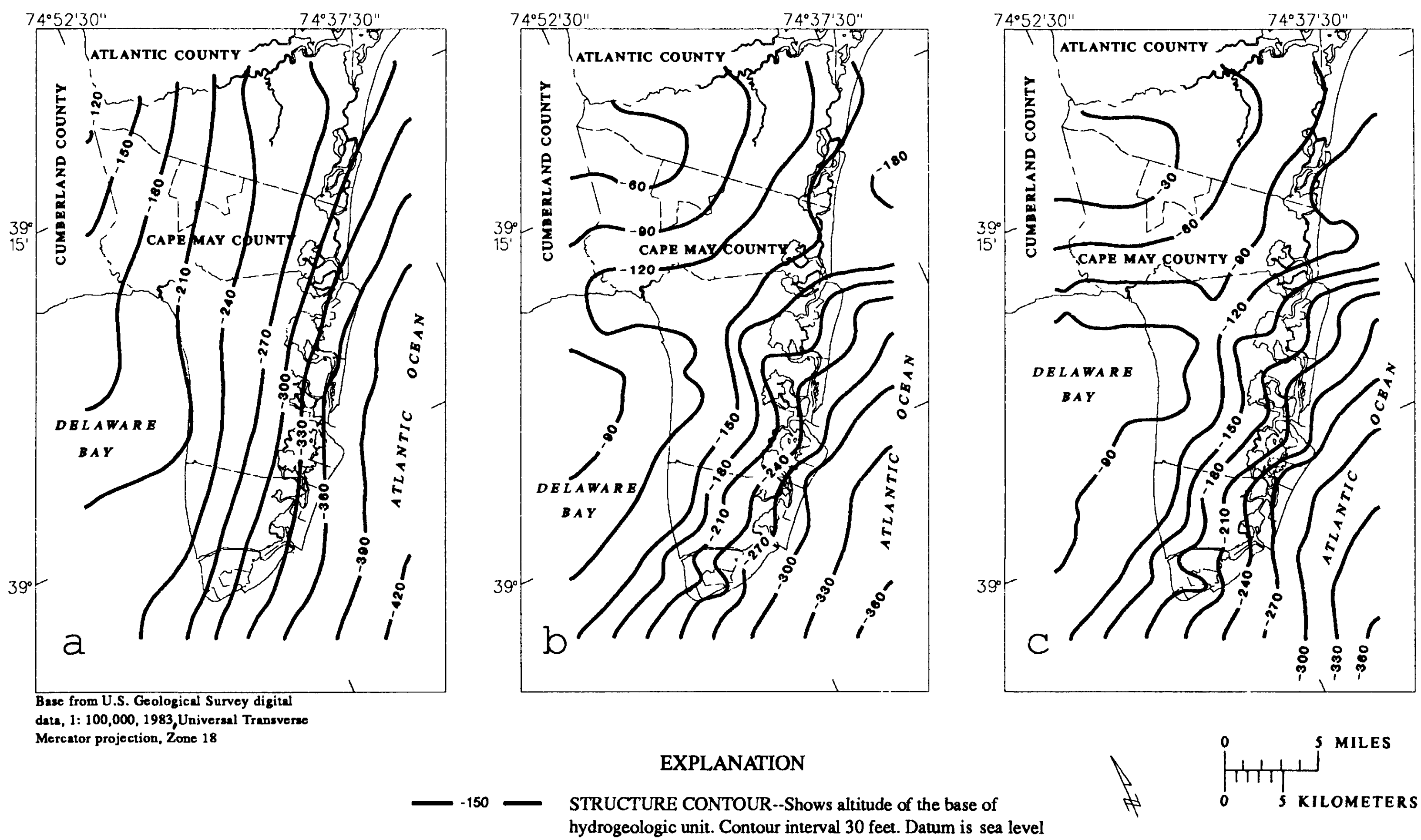
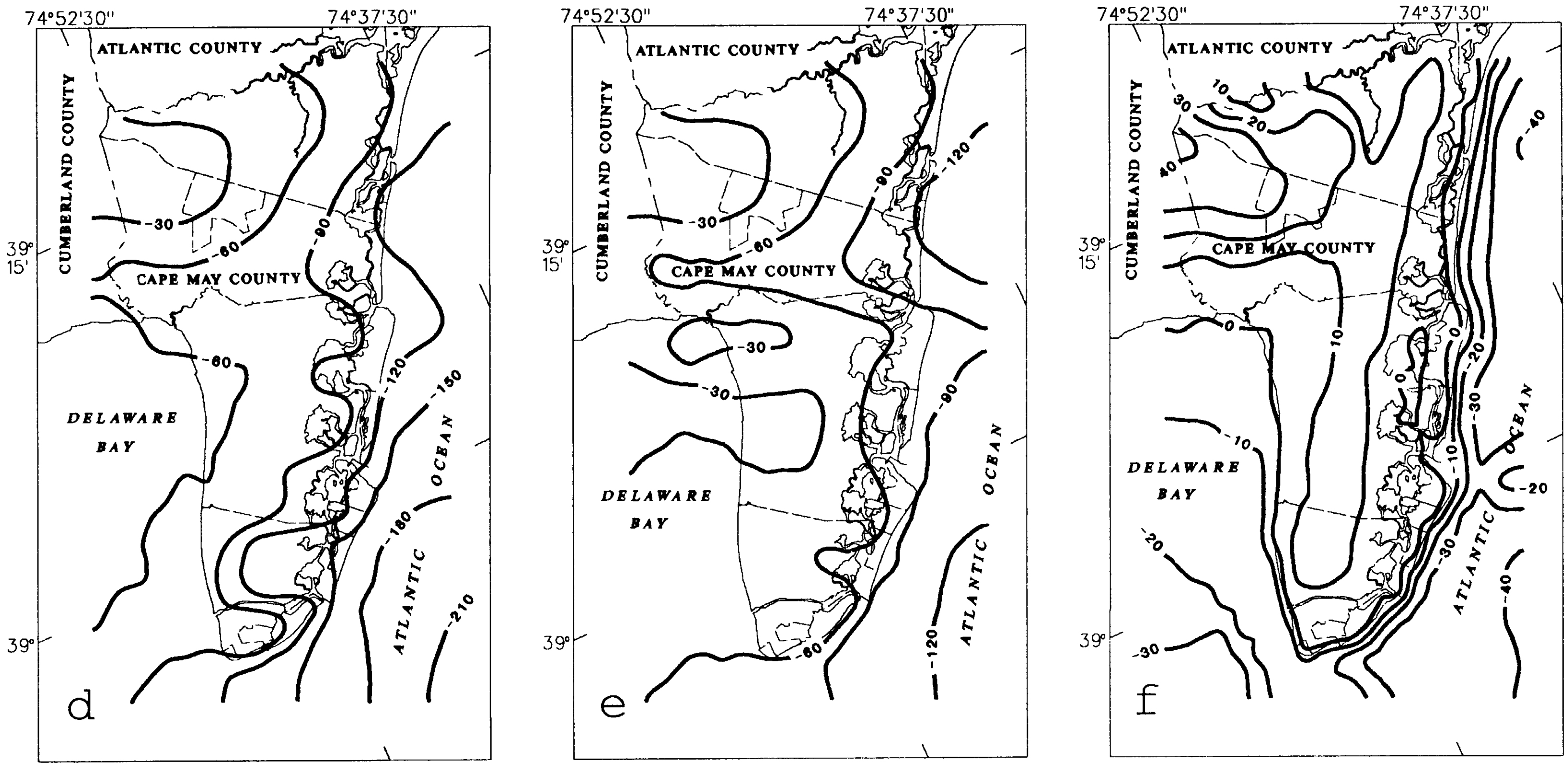


Figure 4.--Structure contours at the (a) base of the Cohansey aquifer, (b) base of the clay confining unit overlying the Cohansey aquifer, (c) base of the estuarine sand aquifer, (d) base of the estuarine clay confining unit, (e) base of the Holly Beach water-bearing zone, and (f) topographic and bathymetric contours for the land surface and offshore, respectively.



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

EXPLANATION

Figures 4d and 4e:

— -150 — STRUCTURE CONTOUR--Shows altitude of the base of hydrogeologic unit. Contour interval 30 feet. Datum is sea level

Figure 4f :

— 10 — TOPOGRAPIC/BATHYMETRIC CONTOUR--Shows altitude of land/bathymetric surface. Contour interval 10 feet . Datum sea level

Figure 4.--Structure contours at the (a) base of the Cohansey aquifer, (b) base of the clay confining unit overlying the Cohansey aquifer, (c) base of the estuarine sand aquifer, (d) base of the estuarine clay confining unit, (e) base of the Holly Beach water-bearing zone, and (f) topographic and bathymetric contours for the land surface and offshore, respectively--Continued.

The shallow aquifer system is separated from deeper aquifers by a continuous, tight, and areally extensive confining unit. This unit serves as a well-defined impermeable bottom boundary for simulation of the shallow aquifer system. The Kirkwood Formation includes the Rio Grande water-bearing zone, which is separated by an underlying confining unit from the more highly productive Atlantic City 800-foot sand aquifer. In southern Cape May County, saltwater has intruded farther into these deep aquifers than it has into the shallow aquifer system because of the naturally low freshwater heads that were present in the deep aquifers before pumping began.

Beneath the Atlantic Ocean and Delaware Bay, the hydrogeology was inferred from areas of better-known structure and coordinated with data from outside the study area (Schuster and Hill, in press). Offshore thicknesses of hydrogeologic units were assumed to be proportional to their thicknesses onshore. Thus, trends in structure and thickness observed in areas for which hydrogeologic-unit data are available were simply extended to areas for which there was little or no information.

Hydraulic Properties of Aquifers and Confining Units

The hydraulic characteristics of the units that comprise the shallow aquifer system are summarized in table 3. No new data on the hydraulic properties of aquifers and confining units were collected during this study. Several hydraulic characteristics were needed to satisfy the data requirements of the model: hydraulic conductivity, transmissivity, storage, vertical leakance, and porosity. The first two terms describe the rate at which water moves through an aquifer. Estimates of these properties can be obtained through a variety of methods. Values determined from results of aquifer tests are considered to be the most accurate of the commonly used methods (Driscoll, 1986, p. 76) because they represent aquifer properties averaged over a volume. The storage coefficient is the volume of water an aquifer releases from or takes into storage, whereas leakance describes the ease with which water flows through confining units. Porosity is the ratio of pore space to the total volume of an aquifer and is usually determined from laboratory tests.

Flow System Before Development and in 1989

Water recharges the shallow aquifer system chiefly by infiltration of precipitation into the Holly Beach water-bearing zone. Downward leakage from this aquifer recharges the confined estuarine sand and Cohansey aquifers. Idealized flow through the shallow aquifer system on the peninsula after development is shown in figure 5. Water discharges to streams, tidal estuaries, other wetlands, the Delaware Bay, and the Atlantic Ocean.

Gill (1962a) suggested a possible upward flow from the Cohansey aquifer to the estuarine sand aquifer during predevelopment (about 1890) on the peninsula based on water levels above sea level in early wells. However, because the data are few, this hypothesis is not confirmed. Schuster and Hill (in press) suggested that, downward flow from the Holly Beach water-bearing zone to the estuarine sand aquifer near Rio Grande (fig. 1) is a recent occurrence, produced by ground-water development. This hypothesis is based on ground-water age determined from tritium analyses that indicate the intervening confining unit impedes vertical flow.

Table 3.--Reported hydraulic properties of aquifers and confining units

[ft^2/d, feet squared per day; ft/d, feet per day; in/yr, inches per year; 1/d, per day; Cs, specific capacity test; Aq, aquifer test; Lab, lab test; - - -, no data or not applicable; <, less than; >, greater than; USGS, U.S. Geological Survey]

Aquifer	Transmissivity (ft2/d)	Horizontal hydraulic conductivity (ft/d)	Storage coefficient	Porosity	Type of data	Location	Reference
Holly Beach	2000	- - -	- - -	- - -	Cs	County	Gill (1962a)
	5200-7800	150	0.15	- - -	Model	County	Martin (1990)
		- - -	.17	- - -	Estimate	Cape May City	Gill (1962a)
Estuarine sand	9158-11430	152-286	.00043-.00073	- - -	Aq	Bidwell Ditch	J.G. Rooney (USGS, written commun., 1968)
	1694-5348	- - -	- - -	- - -	Cs	County	Gill (1962a)
Cohansey	7219	146	.0003	- - -	Aq/lab	North of canal	Gill (1962a)
	3610-6029	53-94	.00012-.00013	- - -	Aq/lab	South of canal	Gill (1962a)
		- - -	- - -	0.27-0.41	Lab	County	Gill (1962a)
	860-25900	178	.0001	- - -	Cs	Coastal Plain	Martin (1990)[1]
	<8000-11700	- - -	- - -	- - -	Model	Coastal Plain	Martin (1990)[1]

Confining unit	Leakance (1/d)	Vertical hydraulic conductivity (ft/d)	Type of data	Location	Reference
Sediments beneath surface-water bodies	- - -	- - -	Estimate	County	
	0.04	- - -	Model	Peninsula	Hill (1990)
Estuarine Clay	- - -	<0.01-0.04	Permeater	Bidwell Ditch	J.G. Rooney (USGS, written commun., 1968)
	.0000002-.5	- - -	Model	Peninsula	Martin (1990)
	.00004	- - -	Model	Peninsula	Hill (1990)
Clay overlying the Cohansey aquifer	- - -	>.008	Permeater	Reed's Beach	Gill (1962a)
	- - -	>.05	Permeater	Cape May City	Gill (1962a)
	.003	- - -	Model	Peninsula	Hill (1990)

[1]Values are for the combined Cohansey and estuarine sand aquifers.

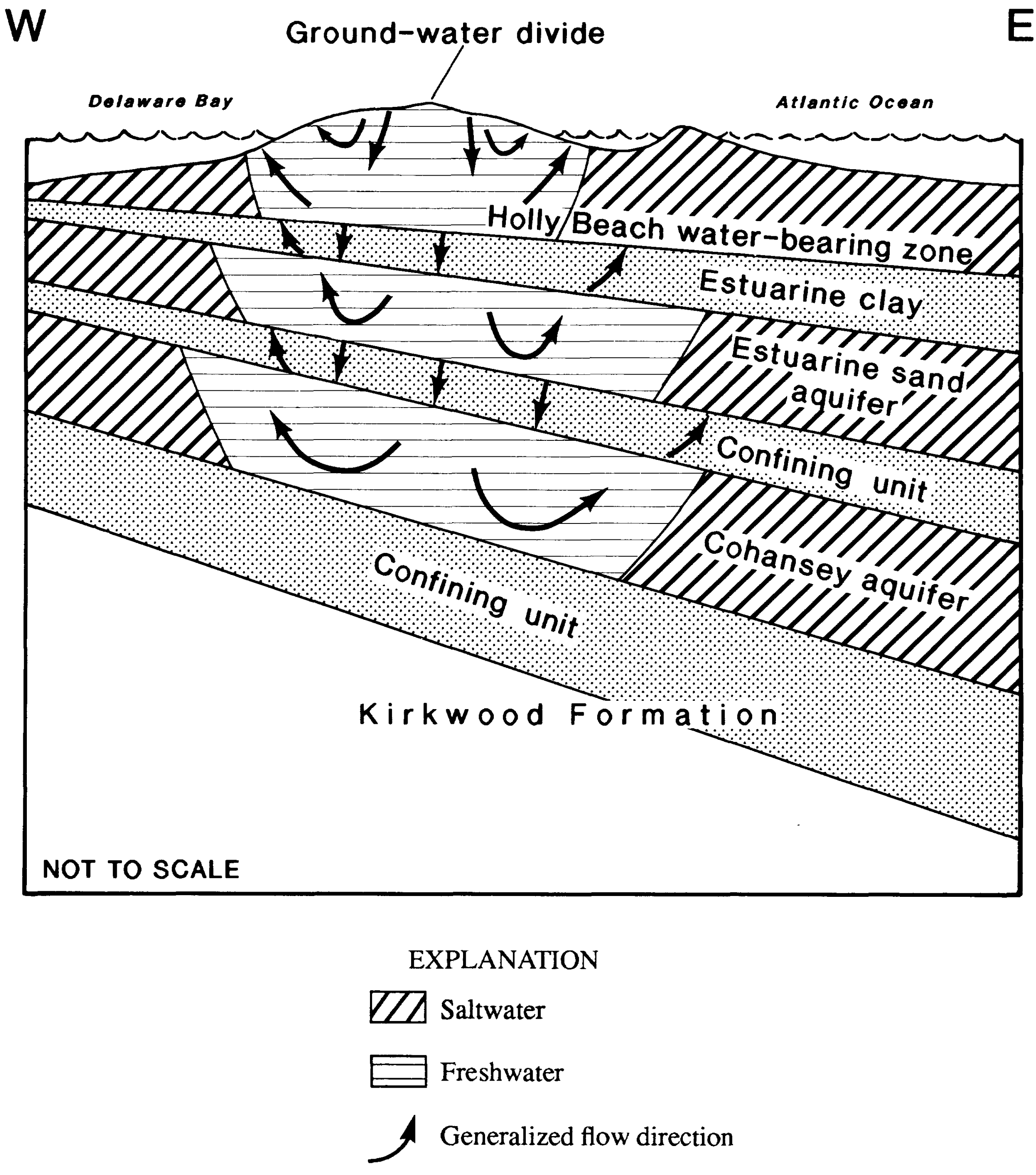


Figure 5.--Diagrammatic section of the shallow aquifer system after development.

Development of ground-water supplies has reversed these vertical-flow directions. Present-day (1989) lateral flow in the confined aquifers is toward pumping centers. Freshwater heads, which had been above sea level to inhibit landward movement of the saltwater-freshwater interface, have been lowered below sea level during development, enabling saltwater encroachment.

The recharge area is the entire land-surface area where precipitation infiltrates and percolates to the water table. This excludes onshore area that is covered by surface waters that carry runoff to the bay or ocean. Water that enters the ground-water system near surface-water bodies flows through the shallowest part of the system and discharges to streams as base flow. All the precipitation that enters the ground-water system flows in the Holly Beach water-bearing zone for some part of its residence time. Only a fraction of this water in this aquifer flows down to the estuarine sand aquifer, and only a fraction of that amount reaches the Cohansey aquifer.

The recharge area of the confined aquifers is centered slightly west of the ground-water divide (the highest point in the water table that separates ground water that discharges to the Delaware Bay from ground water that discharges to the Atlantic Ocean). Water that enters the system farther inland flows into the deeper part of the Holly Beach water-bearing zone and can enter the estuarine sand aquifer. Ultimately, water that enters the system around the divide can reach the Cohansey aquifer.

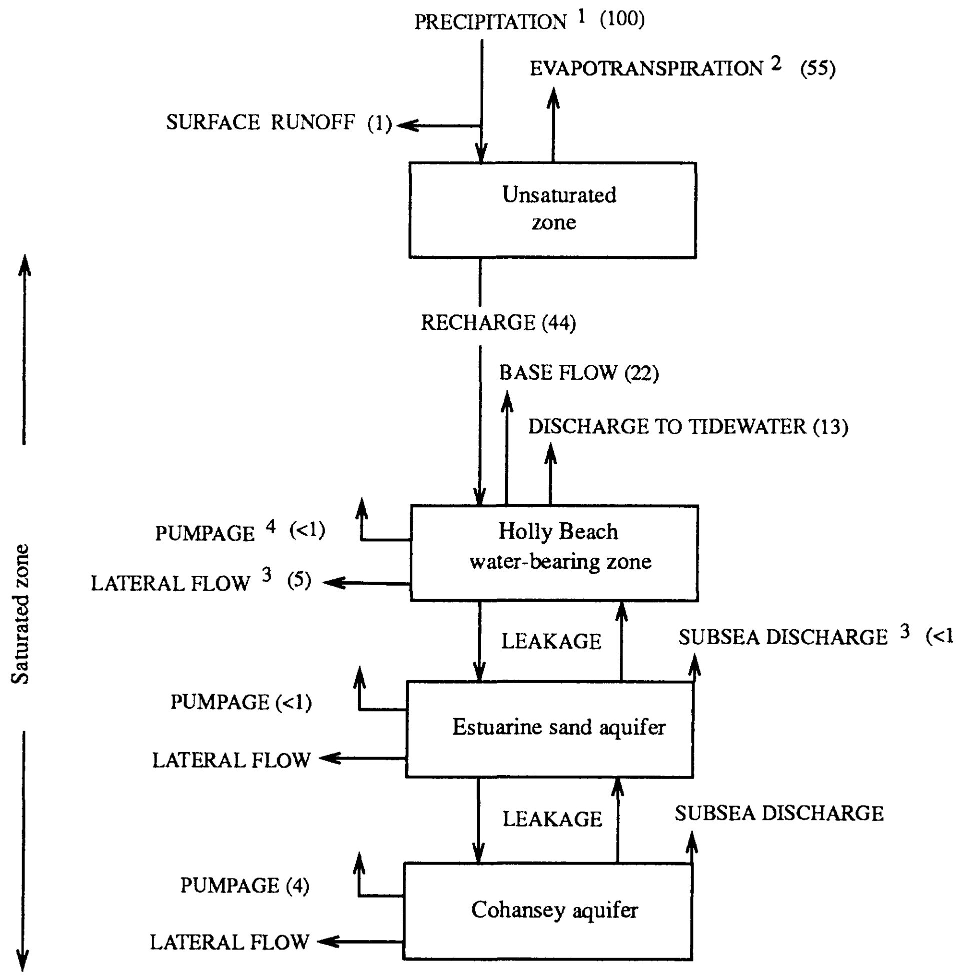
Even under predevelopment conditions, seasonal and long-term climatic variations cause the recharge area to expand, contract, and move with shifts in the ground-water divide. With development, changing flow patterns caused by variable pumping rates and locations add further variations in the shape and position of the recharge area. On the Cape May peninsula, the recharge area overlying the confined aquifers has enlarged, whereas the recharge area of the unconfined aquifer has contracted, because of the increased downward leakage and the diversion of upward-flowing ground-water to the withdrawal wells.

The amount of freshwater recharge on the peninsula to the shallow aquifer system was estimated from a generalized hydrologic budget (fig. 6) for the flow system in 1989. In the hydrologic budget, the water source for the unsaturated zone (betweeen land surface and the water table) is precipitation; outflows consist of surface runoff, evapotranspiration, and recharge to the saturated zone. The net change in ground- and surface-water storage is assumed to be negligible because, over a sufficiently long time, these components of the water budget are very small compared to the effects of changes in inflows to and outflows from the aquifer system.

A rough estimate of recharge was made through use of a water-balance equation for annual conditions,

$$R = P - ET - RO ,$$

where evapotranspiration (ET) and surface runoff (RO) amounts were subtracted from average precipitation (P) to obtain recharge to the saturated zone (R).



EXPLANATION

→ INPUTS AND OUTPUTS OF WATER--Numbers in parentheses are percentages of precipitation.

< less than

[1] R.D. Schopp (U.S. Geological Survey, written commun., 1987)
[2] Gill (1962a, p. 33)
[3] Not disaggregated by aquifer
[4] Excluding domestic wells

Figure 6.--Estimated hydrologic budget for the peninsula in 1989.

For the purpose of comparing flow components, conversion of units from inches per year to cubic feet per second was done on the basis of the approximate land-surface areas of recharge and discharge on the peninsula (57 and 49 mi^2, respectively). From south to north in the County, average precipitation ranges from 41 to 45 in/yr. Evapotranspiration is assumed to be about 55 percent of precipitation on the basis of long-term streamflow records for the Maurice River basin in Cumberland County, where evapotranspiration appears to be the only significant loss of water (Gill, 1962a, p. 33). Surface runoff is small compared to discharge to surface-water bodies in the entire area. Substituting estimates of these three components into and solving the water-balance equation yields an estimated recharge to the shallow aquifer system that is about half the amount that initially enters the unsaturated zone.

The calculated amount of recharge (approximately 18 in/yr) is then input to the hydrologic budget for the saturated zone--

$$R = BF + LF + DT + DS + P ,$$

where BF is base flow to surface-water bodies, LF is net lateral ground-water flow, DT is discharge to tidewater, DS is subsea discharge of freshwater to the saltwater zone, and P is consumptive pumpage.

Flow-correlation analyses for streams on the peninsula with the Tuckahoe River (G.B. Carleton, U.S. Geological Survey, written commun., 1990) indicate that mean annual flow on the peninsula is approximately 1.0 ft^3/s per square mile of drainage (discharge) area. Estimates made by using the hydrograph-separation techniques of Pettyjohn and Henning (1979) indicate that base flow accounts for approximately 80 percent of the total flow in the Tuckahoe River over the period of record, 1970-89. By using an estimated drainage area on the peninsula of 49 mi^2, total mean annual base flow can be computed.

Net lateral ground-water flow, which includes flow from the mainland to the peninsula, is estimated from water-level gradients to be about 5 percent of the estimated recharge. Ground-water discharge to saltwater zones (DS) is small. Virtually all of the pumpage from the confined aquifers is consumptive, reaching the ocean through sewer lines. Most of the pumpage from the unconfined aquifer, however, is considered as non-consumptive. Discharge to tidewater is estimated using the budget equation.

This analysis highlights the importance of precipitation as the main source of freshwater recharge to the shallow aquifer system on the peninsula. Small lateral ground-water flow from the mainland to the peninsula indicates that the aquifers are hydrologically isolated from the rest of the County. If more of the recharge is ultimately removed for water supply, less water is available to help maintain high ground-water levels that slow inland movement of salty ground water, and less water is available to maintain streamflows that inhibit increases in onshore surface-water salinity.

Information on the present-day (1989) flow system was derived from (1) water-table and potentiometric-surface maps constructed from measured water levels reported by Eckel and Walker (1986), (2) simulated-head maps prepared by Martin (1990), and (3) maps constructed from two seasonal water-level surveys conducted in 1988 (table 4). Contour maps of low ground-water levels

Table 4.--Water-level data used in constructing seasonal water-table and potentiometric-surface maps for 1988

[Latitude and longitude, in degrees, minutes, seconds; USGS, U.S. Geological Survey; NJDEP, New Jersey Department of Environmental Protection; SCS, Soil Conservation Service; WD, Water Department; MUA, Municipal Utilities Authority; WC, Water Company; AUTH, Authority; TWP, Township; BD ED, Board of Education; APTS, Apartments; Altitude of land surface, in feet above sea level; Screened interval, top and bottom of well screen in feet below land surface; *, in bottom of well; Water-level altitude, in feet above or below sea level with date of measurement; HLBC, Holly Beach water-bearing zone; ESRNS, Estuarine sand aquifer; CPMY[1], Cape May Formation; CNSY, Cohansey aquifer; CKKD[2], Kirkwood-Cohansey aquifer system; OB, observation well; WI, withdrawal well; RE, injection well; - -, data not available or applicable]

USGS Well Number	Location: Latitude	Location: Longitude	Owner	Local number	Year drilled	Altitude	Screened interval	Water-level altitude, Summer: Level	Summer: Date	Water-level altitude, Fall: Level	Fall: Date	Aquifer	Type of well
9- 11	385612	745457	CAPE MAY CITY WD	CMCWD 1 OBS	1940	7	281-321	-30	8/	-14	12/01	CNSY	OB
9- 17	385651	745310	US COAST GUARD	USCG 1	1943	11	292-322	-30	8/25	-10	12/01	CNSY	WI
9- 20	385616	745800	US GEOLOGICAL SURVEY	TRAFFIC CIRCLE OBS	1960	9	15- 20	1	8/25	4	12/01	HLBC	OB
9- 22	391100	744521	NOVASACK BROS	1	1965	25	56-112	10	9/09	9	12/08	ESRNS	WI
9- 27	385643	745533	CAPE MAY CITY WD	CMCWD 3	1950	7	277-306	-39	8/24	-20	12/07	CNSY	WI
9- 28	385641	745749	NW MAGNESITE CO	NW MAG 2	1953	10	235-265	-16	8/25	-6	12/01	CNSY	WI
9- 29	385640	745805	NW MAGNESITE CO	NW MAG 1	1942	10	296-321	-9	8/23	-9	12/01	CNSY	WI
9- 42	385723	745240	BORDEN CO(SNOW)	SNOW 3	1969	5	259-289	-31	8/21	-12	12/04	CNSY	WI
9- 43	385724	745521	CAPE MAY CITY WD	CMCWD 5	1966	15	246-276	-36	8/24	-16	12/07	CNSY	WI
9- 45	385701	745528	CAPE MAY CITY WD	CMCWD 4	1965	10	270-300	-40	8/24	-20	12/07	CNSY	WI
9- 48	385748	745533	US GEOLOGICAL SURVEY	CANAL 5 OBS	1957	17	242-252	-35	8/25	-17	12/01	CNSY	OB
9- 49	385804	745742	US GEOLOGICAL SURVEY	HIGBEE BEACH 3 OBS	1957	6	241-250	-22	8/25	-13	12/01	CNSY	OB
9- 52	385851	745715	LOWER TWP MUA	LTMUA 1	1956	18	241-262	-27	8/24	-16	12/07	CNSY	WI
9- 54	385905	745625	LOWER TWP MUA	LTMUA 2	1962	14	212-247	-30	8/25	-16	12/07	CNSY	WI
9- 57	385919	745518	LOWER TWP MUA	LTMUA 3	1974	20	262-302	-28	8/25	-13	12/07	CNSY	WI
9- 58	390015	745440	CAPE MAY COUNTY	1	1942	20	248-275	-27	8/23	-14	12/08	CNSY	WI
9- 59	390015	745440	CAPE MAY COUNTY	2	1942	20	252-278	-27	8/23	-14	12/08	CNSY	WI
9- 60	390056	745426	US GEOLOGICAL SURVEY	AIRPORT 7 OBS	1957	13	242-257	-26	8/23	-12	12/08	CNSY	OB
9- 65	390130	745350	WILDWOOD WD	RIO GRANDE 34	1966	12	172-242	-30	8/26	-11	12/06	CNSY	WI
9- 70	390137	745352	WILDWOOD WD	RIO GRANDE 36	1967	10	48- 63	8	8/24	8	12/06	CPMY	WI
9- 80	390213	745056	US GEOLOGICAL SURVEY	CAPE MAY 42 OBS	1957	14	242-252	-10	8/	-4	12/08	CNSY	OB
9- 81	390211	745055	US GEOLOGICAL SURVEY	CAPE MAY 23 OBS	1956	15	23- 26	4	8/	5	12/08	HLBC	OB
9- 89	390425	745446	US GEOLOGICAL SURVEY	OYSTER LAB 4 OBS	1957	7	195-210	-7	8/26	-2	12/01	CNSY	OB
9- 99	390611	744838	US GEOLOGICAL SURVEY	CAPE MAY CO PK 8 OBS	1957	11	214-230	2	8/	4	12/01	CNSY	OB
9-143	391557	744411	GIEBERSON, FRED	1	1973	25	110-140	19	8/30	19	11/06	CNSY	WI
9-150	385607	745556	US GEOLOGICAL SURVEY	WEST CAPE MAY 1 OBS	1957	7	283-293	-28	8/25	-13	12/01	CNSY	OB
9-154	385932	744851	WILDWOOD WD	WWD 2	1928	10	293-354	-16	8/26	3	12/08	CNSY	WI
9-155	385935	744954	WILDWOOD CLAM CO	3-1971	1971	5	311-331	-24	8/26	-3	12/08	CNSY	WI
9-159	385830	745021	WILDWOOD WD	WWD 35	1967	8	249-360	- -		-2	12/06	CNSY	RE
9-162	391044	744617	NOVASACK BROS	2	1966	30	90-138	7	9/09	7	12/08	ESRNS	WI
9-168	391430	744848	WOODBINE WC	6	1967	45	135-157	25	8/	24	12/09	CNSY	WI
9-171	385901	745405	LOWER TWP BD ED	1	1973	10	149-161	-9	8/26	-6	12/01	ESRNS	WI
9-175	391539	744343	KOHLER, JOHN	1	1979	23	90-140	15	8/30	15	12/06	CNSY	WI
9-180	390159	745337	WILDWOOD WD	RIO GRANDE 42	1979	15	250*	-28	8/24	-12	12/06	CNSY	WI
9-182	385841	745000	STOKES LAUNDRY	2	1980	7	320-350	-31	8/25	-5	12/06	CNSY	WI
9-183	385724	745243	BORDEN CO(SNOW)	4	1979	5	260-290	- -		-12	12/04	CNSY	WI
9-186	391621	744354	US GEOLOGICAL SURVEY	USGS AC 14 OBS	1985	14	20- 22	2	8/30	11	11/29	CKKD	OB
9-187	390218	745609	CAPE MAY COUNTY	CAPE MAY F-35	1965	10	186-190	-11	8/26	-6	12/08	CNSY	OB
9-188	390215	745440	CAPE MAY COUNTY	CAPE MAY F-36	1965	10	229-233	-14	8/24	-5	12/08	CNSY	OB
9-189	390215	745440	CAPE MAY COUNTY	CAPE MAY F-37	1965	5	83- 87	-11	8/24	-5	12/08	ESRNS	OB
9-190	390215	745440	WILDWOOD CITY	CAPE MAY F-40	1971	5	22- 30	1	8/24	2	12/08	HLBC	OB
9-191	390219	745611	US GEOLOGICAL SURVEY	FISHING CREEK HB-1	1987	10	14- 17	1	8/26	1	12/08	HLBC	OB
9-206	390218	745609	CAPE MAY COUNTY	CAPE MAY F-7	1965	10	108-112	-6	8/26	-3	12/08	ESRNS	OB
9-207	391121	745114	US GEOLOGICAL SURVEY	JAKES LANDING-1	1987	10	80- 90	4	9/09	3	12/08	CNSY	OB
9-208	390212	745557	US GEOLOGICAL SURVEY	BSR-6	1987	7	98-108	-6	8/26	-3	12/08	ESRNS	OB
9-210	385946	745725	CAPE MAY COUNTY	CAPE MAY C-1	1965	11	216-221	-15	8/24	-8	12/08	CKKD	OB
9-212	385946	745725	CAPE MAY COUNTY	CAPE MAY C-3	1965	11	45- 50	6	8/24	6	12/08	HLBC	OB
9-214	390050	745659	CAPE MAY COUNTY	CAPE MAY F-44	1965	20	205-210	-14	8/26	-9	12/08	CKKD	OB
9-215	390050	745659	CAPE MAY COUNTY	CAPE MAY F-45	1965	20	120-125	-8	8/26	-4	12/08	ESRNS	OB
9-224	390626	744739	CAPE MAY CO MUA	SLUDGE COMPOST FAC 1	1983	9	105-115	2	8/23	2	12/09	ESRNS	WI
9-238	391159	745338	BOHM, DAVID	BOHM SOD FARM	1984	8	60-100	2	8/22	- -		CKKD	WI
9-255	391642	745046	CAPRIONI, RICHARD	SEWAGE SERVICE	1983	55	5- 20	50	8/01	- -		CPMY	OB
9-256	391719	744514	TUCKAHOE FIRE CO	TUCKAHOE FIRE CO	1981	25	138-158	13	8/23	14	11/29	CNSY	WI
9-258	390456	744948	S JERSEY FUEL	S JERSEY FUEL RS-4	1986	25	8- 18	13	8/	13	12/08	HLBC	OB
9-259	391118	744324	LUTH HOME OCEANVIEW	LUTHERAN HOME	1985	25	6- 31	9	8/24	7	12/06	CPMY	OB

Table 4.--Water-level data used in constructing seasonal water-table and potentiometric-surface maps for 1988 --Continued

USGS Well Number	Location Lati-tude	Location Longi-Tude	Owner	Local number	Year drilled	Alti-tude	Screened interval	Water-level altitude Summer Level	Summer Date	Fall Level	Fall Date	Aqui-fer	Type of well
9-261	390032	745612	CAPE MAY CO LIBRARY	LIBRARY 1024	1982	10	145-160	-17	8/24	-13	12/01	CNSY	WI
9-262	391553	743850	NJDEP	FOSBENNERS 1/NJ-1S	1983	35	19- 34	- -		10	12/14	HLBC	OB
9-264	391515	744125	UPPER TWP	UPPER TWP LANDFILL 1	1985	5	5- 25	3	9/09	2	12/07	CPMY	OB
9-265	391510	744119	UPPER TWP	UPPER TWP LANDFILL OBS	1979	21	10- 20	5	9/09	6	12/07	CPMY	OB
9-266	391554	743851	SAPP, WILLIAM	GRACE OIL CO ETK-10	1986	28	20- 35	5	8/21	6	12/14	CPMY	OB
9-267	391554	743851	SAPP, WILLIAM	GRACE OIL CO ETK-2D	1986	28	45- 60	5	8/21	6	12/14	CPMY	OB
9-269	391336	744913	BORO OF WOODBINE	STATE SCHOOL P12	1984	32	10- 20	20	9/09	19	12/08	CPMY	OB
9-270	391554	745131	DENNIS TWP	BELLEPLAIN SLF 4	1986	55	8- 28	49	8/	- -		CPMY	OB
9-271	391330	744809	CAPE MAY CITY MUA	WOODBINE LANDFILL	1986	33	12- 32	21	9/09	20	12/08	CPMY	OB
9-273	390226	745102	GARDEN LK MOB HOMES	GARDEN LK PK 1985	1985	15	220-260	-5	9/09	-1	12/13	CNSY	WI
9-274	391043	744333	NJ HIGHWAY AUTHORITY	SEAVILLE SERV AREA 1	1954	15	62- 84	4	8/	10	12/06	CPMY	WI
9-275	391025	744828	J SHORE HAVEN INC	AIRSTREAM CAMPGROUND	1983	18	50- 60	6	8/24	- -		CPMY	WI
9-276	391045	744332	NJ HIGHWAY AUTHORITY	SEAVILLE SERV AREA 2	1954	15	62- 84	- -		10	12/06	CPMY	WI
9-278	385851	745638	CHANNEL APARTMENTS	CHANNEL APTS	1983	20	31- 41	12	8/22	13	12/06	HLBC	WI
9-281	390710	745134	SOIL CONSERV SERVICE	BD21CH	1967	8	176-181	1	8/	3	12/08	CNSY	OB
9-282	390710	745134	SOIL CONSERV SERVICE	BD21ES	1967	8	90- 95	2	8/	3	12/08	ESRNS	OB
9-284	390749	744943	SOIL CONSERV SERVICE	BD20CH1	1967	17	126-132	2	8/	6	12/09	CNSY	OB
9-285	390749	744943	SOIL CONSERV SERVICE	BD20CH2	1967	17	201-206	2	8/	4	12/08	CNSY	OB
9-286	390608	745005	SOIL CONSERV SERVICE	BD23ES	1967	19	92- 98	6	8/	6	12/08	ESRNS	OB
9-292	390337	744623	US GEOLOGICAL SURVEY	WETLANDS 1 OBS	1988	5	251-261	0	8/26	2	12/01	CNSY	OB
9-293	390337	744623	US GEOLOGICAL SURVEY	WETLANDS 2 OBS	1988	5	155-165	0	8/26	-1	12/01	ESRNS	OB
9-294	390337	744623	US GEOLOGICAL SURVEY	WETLANDS 3 OBS	1988	5	105-115	0	8/26	-1	12/01	ESRNS	OB
9-295	390337	744623	US GEOLOGICAL SURVEY	WETLANDS 4 OBS	1988	5	80- 90	0	8/26	-1	12/01	HLBC	OB
9-310	390018	744748	WILDWOOD WD	RIO GRANDE 39 NEW	1986	5	279-357	- -		-1	12/09	CNSY	RE
9-317	391421	744840	WOODBINE MUA	WOODBINE MUA 7	1981	42	135-158	- -		22	12/09	CKKD	WI

1 Assigned as the Holly Beach water-bearing zone in the model
2 Assigned as the Cohansey aquifer in the model

(summer 1988) and intermediate ground-water levels (fall 1988) in the three aquifers show the variations of water-levels through the year (figs. 7 and 8). The apparent decline in water levels in some wells between the summer and the fall is within the range of measurement error. The amount of available data differs from aquifer to aquifer. Of the three aquifers, the interpretations of water-level contours in the estuarine sand aquifer are the least certain, because they are supported by the fewest data. Throughout the report, the term "interpreted" will refer to a contoured surface resulting from interpretation of certain types of point data.

These maps are based primarily on water levels measured in observation wells. Water levels in withdrawal wells are, by definition, not in equilibrium because of the effects of pumping. Local cones of depression of heads around withdrawal wells can lead to misinterpretation of the regional ground-water-flow regime. To avoid such misinterpretation, water levels in withdrawals wells were used only as an auxiliary guide when contouring. Similarly, the concentration-related density difference between freshwater and saltwater causes freshwater heads above the saltwater-freshwater interface to be slightly higher than if freshwater alone were present. The effect of ocean tides on heads also must be considered, especially in the unconfined aquifer. A one-dimensional analysis (Fetter, 1980, p. 146-147) based on assumptions of a maximum tidal range of 6 ft, a tidal period of 12 hours, and average aquifer thickness indicates that the amplitude of tidal fluctuation in head for the unconfined aquifer is not significant (less than 1 ft).

Seasonal variation in the cones of depression and head gradients can be seen clearly in the potentiometric-surface maps of the confined aquifers. Moreover, head differences with the unconfined aquifer are indicative of hydrologic separation between the two flow systems on the peninsula. Flow in the unconfined system on the peninsula is mainly toward the coast, but flow in the confined system is primarily toward the pumping centers. Water-level contours in the little-pumped, unconfined aquifer resemble the topography surface. The effect of the Cape May Canal (fig. 1) on these heads is evident; its construction locally dewatered the unconfined aquifer. Comparison of figures 7 and 8 with the head maps in Gill (1962a, figs. 46 and 47) indicates that water levels in the Holly Beach water-bearing zone have changed little since the 1950's.

The similarity in heads in the estuarine sand and the Cohansey aquifers further indicates that the confining unit separating them is leaky. Drawdowns in the estuarine sand aquifer are greater than can be accounted for by the small amount of withdrawals from wells screened in it. The heads clearly are influenced by withdrawals from the Cohansey aquifer. The absence of the cone of depression in the Cohansey aquifer in figure 8 at Wildwood is the result of ground-water injection operations in the vicinity.

Withdrawals and Artificial Recharge

Since the early 1900's, about half the water used in Cape May County was supplied by shallow ground-water withdrawals (Schuster and Hill, in press). The balance came primarily from deeper aquifers. Surface sources supplied only a small amount of water, and therefore, these diversions are not considered in this report. During summer, tourism-related water demands on the shallow aquifers increase dramatically. Compared to demands during the

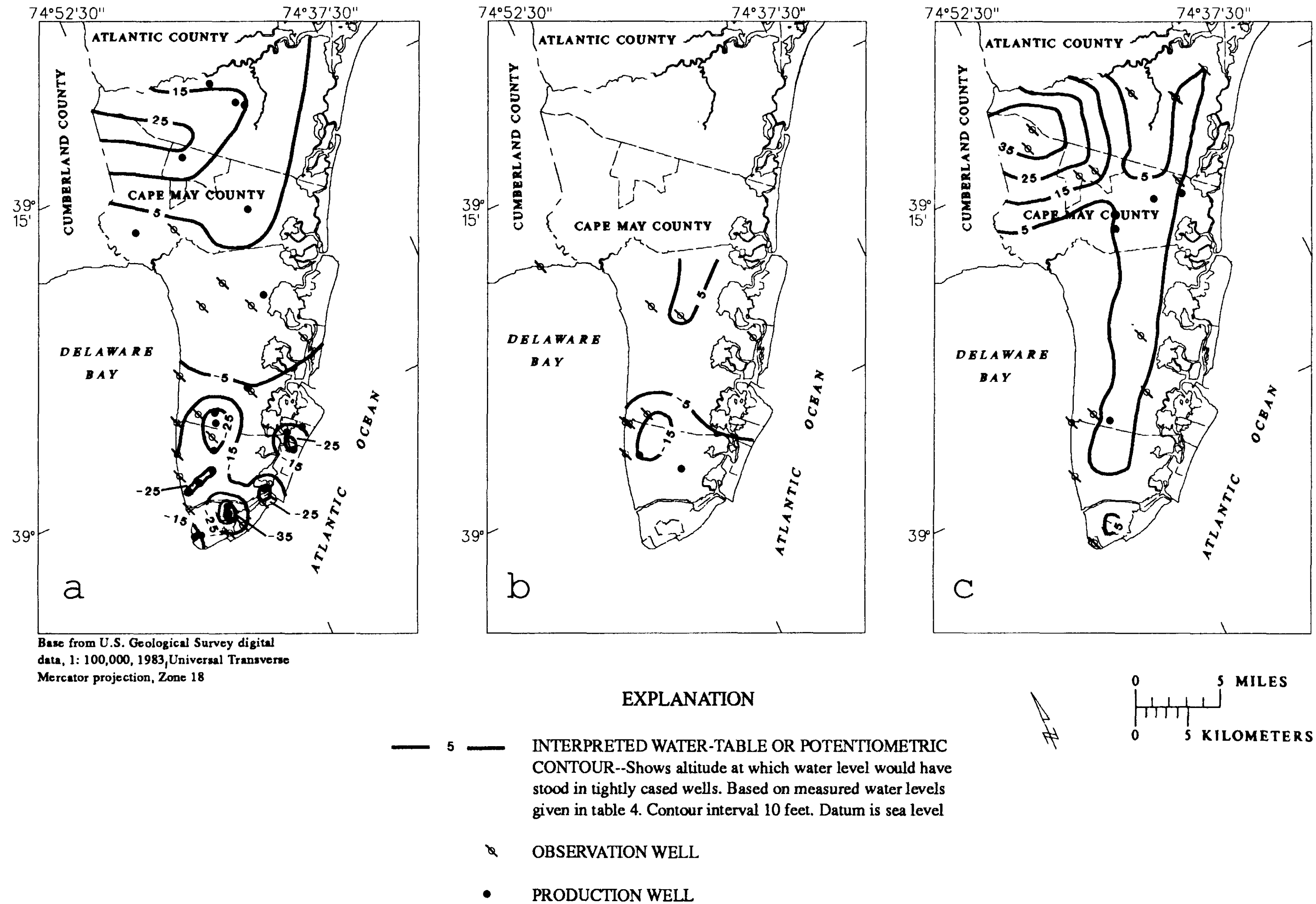


Figure 7.--Interpreted water-table and potentiometric surfaces for summer 1988 in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

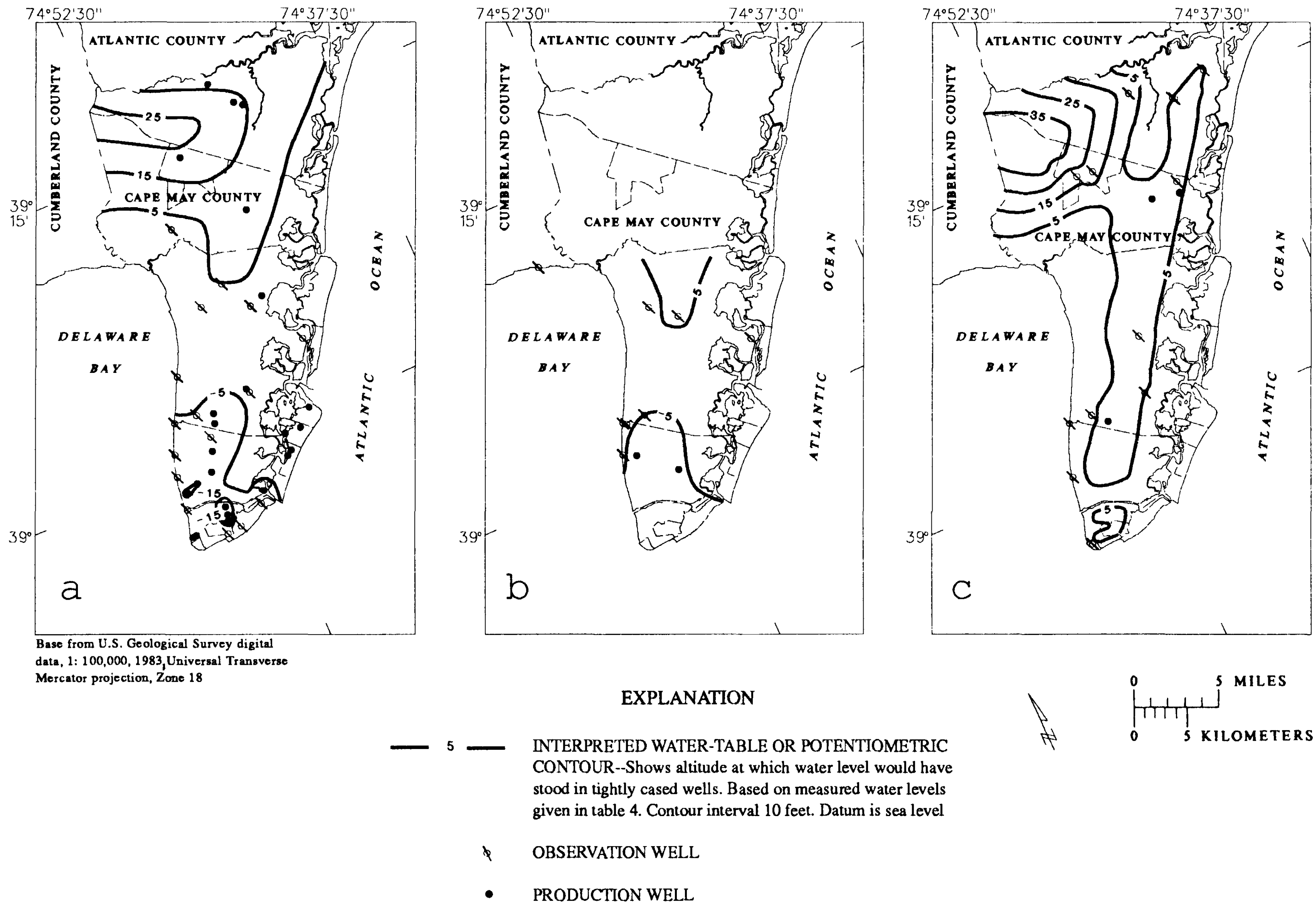


Figure 8.--Interpreted water-table and potentiometric surfaces for fall 1988 in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

rest of the year, current summer demands typically cause a fourfold increase in withdrawals from the shallow aquifers. In terms of percent increase, however, winter consumption is outpacing summer consumption, chiefly because of increases in the County's permanent population.

The Cohansey aquifer supplies more than 40 percent of the overall pumpage. Pumpage from the Cohansey aquifer has almost quadrupled since the early 1900's. By comparison, the estuarine sand aquifer is used much less and mainly for domestic supply, notably in the Villas area. Similarly, the Holly Beach water-bearing zone is comparatively unused, supplying small amounts of domestic and agricultural water.

During 1956-1986, public-supply needs led to an annual-average increase of 0.01 Mgal/d in the rate of withdrawals. In 1986, average pumpage was 7 Mgal/d, about 85 percent of which was used for public supply. Pumpage for industry and irrigation has continued to be less than 15 percent of the total. Irrigation pumpage in the early part of the development period could be underestimated, however, because agricultural acreage in the County has been declining as land is developed for residential and recreational use. Furthermore, most domestic pumpage is unreported, but this generally non-consumptive pumpage and its associated effect on the total ground-water system is believed to be small (Roger Tsao, New Jersey Department of Environmental Protection and Energy, written commun., 1990).

Location of the main withdrawal and observation wells tapping the shallow aquifer system are shown in figure 9 and listed in table 5; available pumpage and injection data are listed in table 6. Two-thirds of the public-supply withdrawals from the shallow aquifer system has been removed at the Wildwood Water Department's Rio Grande well field, located in Middle Township a mile northwest of Rio Grande. Ground-water has been pumped from all three shallow aquifers there. Seven wells tap the Cohansey aquifer and two wells tap the estuarine sand aquifer. Pumping from the Holly Beach water-bearing zone, however, ceased in the mid-1980's as a result of a local gasoline spill (Schuster and Hill, in press). A large part of the balance of the public-supply withdrawals has come from wells screened in the Cohansey aquifer that belong to the Cape May City Water Department and the Township of Lower Municipal Utilities Authority.

Increased ground-water withdrawals have had significant effects on the area's hydrology. When the freshwater level drops below sea level, saltwater intrusion can occur. Decreasing water levels in the aquifers have enabled significant landward movement of saline ground water toward withdrawal centers. Because of this problem, several freshwater-management schemes have been tested. For example, Cape May Point has tried to reduce or stop withdrawals at some locations and purchase water from other communities. Cape May City has relocated wells farther inland or withdrawn water from different aquifers.

Wildwood has used artificial recharge, a method that not only mitigates saltwater encroachment but increases water supply. Since 1967, the Wildwood Water Department has used some of its withdrawals to recharge the confined aquifers during the non-summer months. Water is withdrawn from the Cohansey and estuarine sand aquifers at the Rio Grande field and is injected into four wells in the heavily tourist-populated area (tables 5 and 6). During the

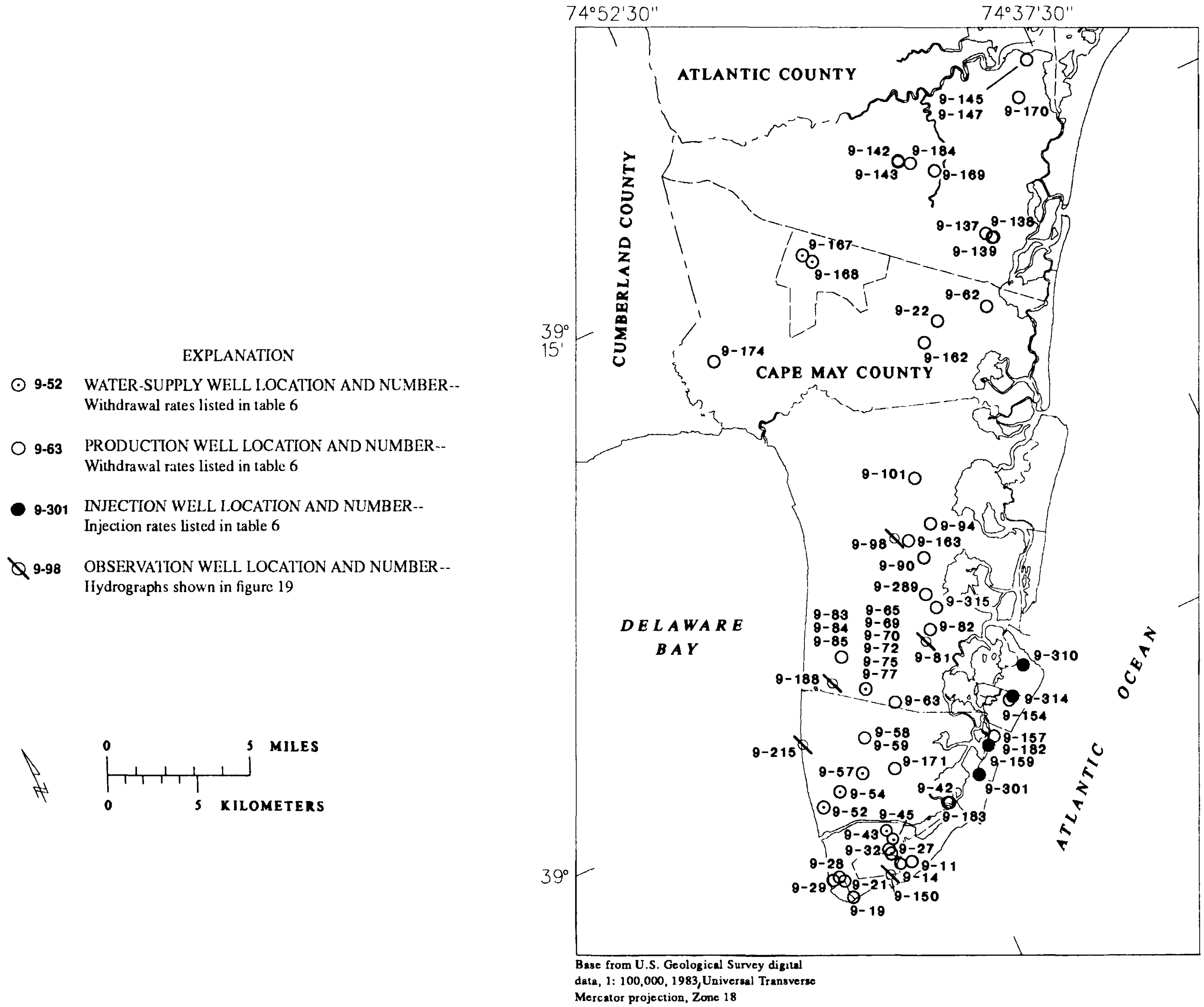


Figure 9.--Locations of selected wells tapping the shallow aquifer system in Cape May County.

Table 5.--Records for withdrawal and injection wells in the shallow aquifer system of Cape May County

[**, pumpage from more than one well; USGS, U.S. Geological Survey; WD, Water Department; MUA, Municipal Utilities Authority; CO, Company; WC, Water Company; BD ED, Board of Education; ELEC, Electric Company; Altitude of land surface, in feet above sea level; Screened interval, top and bottom of well screen in feet below land surface; *, bottom of well; Date range for 1918-80, see Zapecza and others, 1987; HLBC, Holly Beach water-bearing zone; ESRNS, Estuarine sand aquifer; CPMY[1], Cape May Formation; CNSY, Cohansey aquifer; CKKD[2], Kirkwood-Cohansey aquifer system]

USGS well number	Location: Latitude	Location: Longitude	Owner	Local number	Year drilled	Altitude of land surface	Screened interval	Data available	Aquifer
9- 11	385612	745457	CAPE MAY CITY WD	CMCWD 1 OBS	1940	7	281-321	1956-62	CNSY
9- 14	385615	745509	CAPE MAY CITY WD	LAFAYETTE 2	1945	12	282-322	1956-64	CNSY
**9- 19	385557	745738	CAPE MAY PT WD	LIGHTHOUSE 1	1916	6	260-592	1918-57	CNSY
9- 21	385631	745741	CAPE MAY PT WD	SUNSET 2	1958	13	250-280	1958-72	CNSY
**9- 22	391100	744521	NOVASACK BROS	1	1965	25	56-112	1965-88	ESRNS
**9- 27	385643	745533	CAPE MAY CITY WD	CMCWD 3	1950	7	277-306	1956-88	CNSY
9- 28	385641	745749	NW MAGNESITE CO	NW MAG 2	1953	10	235-265	1956-80	CNSY
9- 29	385640	745805	NW MAGNESITE CO	NW MAG 1	1942	10	296-321	1956-80	CNSY
**9- 32	385650	745535	CAPE MAY CITY WD	BROADWAY 1	1927	12	270-300	1927-55	CNSY
**9- 42	385723	745240	BORDEN CO(SNOW)	SNOW 3	1969	5	259-289	1969-87	CNSY
9- 43	385724	745521	CAPE MAY CITY WD	CMCWD 5	1966	15	246-276	1967-88	CNSY
9- 45	385701	745528	CAPE MAY CITY WD	CMCWD 4	1965	10	270-300	1966-88	CNSY
**9- 52	385851	745715	LOWER TWP MUA	LTMUA 1	1956	18	241-262	1958-88	CNSY
9- 54	385905	745625	LOWER TWP MUA	LTMUA 2	1962	14	212-247	1987-88	CNSY
9- 57	385919	745518	LOWER TWP MUA	LTMUA 3	1974	20	262-302	1974-80,87-88	CNSY
9- 58	390015	745440	CAPE MAY COUNTY	1	1942	20	248-275	1956-87	CNSY
9- 59	390015	745440	CAPE MAY COUNTY	2	1942	20	252-278	1956-80	CNSY
9- 62	391048	744321	CORDES, WILLIAM	LOWER TWP		10	50*	1956-88	CPMY
9- 63	390052	745300	HAND, HOLMES	2 1958		20	50*	1958-80,84	CPMY
**9- 65	390130	745350	WILDWOOD WD	RIO GRANDE 34	1966	12	172-242	1981-88	CNSY
**9- 69	390136	745342	WILDWOOD WD	RIO GRANDE 33	1966	9	236-260	1966-80	CNSY
**9- 70	390137	745352	WILDWOOD WD	RIO GRANDE 36	1967	10	48- 63	1967-84	CPMY
**9- 72	390138	745350	WILDWOOD WD	RIO GRANDE 31	1950	10	108-135	1956-88	ESRNS
9- 75	390140	745348	WILDWOOD WD	RIO GRANDE 37	1967	10	40- 60	1967-80	CPMY
**9- 77	390142	745346	WILDWOOD WD	RIO GRANDE 14	1913	8	82-103	1918-78	ESRNS
9- 82	390228	745034	CAPE MAY CANNER	1-1969	1969	10	229-260	1969-88	CKKD
9- 83	390248	745413	HOWELL, HOWARD	HOWELL 1		5	110*	1956-83	ESRNS
9- 84	390248	745413	HOWELL, HOWARD	HOWELL 2		5	28*	1956-80	CPMY
9- 85	390248	745413	HOWELL, HOWARD	HOWELL 3		5	28*	1956-80	CPMY
9- 90	390433	744938	KEUFFEL & ESSER CO	MIDDLE TWP	1954	15	100-120	1956-80	ESRNS
9-101	390654	744841	BOHM, LAWRENCE	1	1969	20	40- 92	1969-86	ESRNS
9-137	391238	744159	NAGATSUKA, JOHN	NAG 3	1966	20	84*	1966-80	CPMY
9-138	391239	744202	NAGATSUKA, JOHN	NAG 1	1966	20	67*	1966-80,84-86	CPMY
9-139	391250	744212	NAGATSUKA, JOHN	NAG 2	1966	20	79*	1966-86	CPMY
9-142	391555	744412	GIEBERSON, FRED	2	1973	30	25- 45	1973-80	CPMY
9-143	391557	744411	GIEBERSON, FRED	1	1973	25	110-140	1973-88	CNSY
9-145	391707	743756	ATL CITY ELEC	ACEC 1	1961	9	130-150	1961-88	CKKD
9-147	391707	743756	ATL CITY ELEC	ACEC 2R-LAYNE 3	1962	9	125-145	1962-64	CKKD
9-154	385932	744851	WILDWOOD WD	WWD 2	1928	10	293-354	1956-88	CNSY
9-157	385841	745000	STOKES LAUNDRY	1	1966	7	312-338	1966-80	CNSY
9-159	385830	745021	WILDWOOD WD	WWD 35	1967	8	249-360	1967-78	CNSY
9-162	391044	744617	NOVASACK BROS	2	1966	30	90-138	1984-88	ESRNS
**9-163	390513	744955	NJ/AMERICAN WATER CO	NEPTUNUS 6	1955	15	27- 43	1956-67	HLBC
**9-164	390513	744955	NJ/AMERICAN WATER CO	NEPTUNUS 2A	1939	20	26- 44	1939-55	HLBC
**9-167	391415	744852	WOODBINE WC	WOODBINE 2	1961	35	139-159	1922-55,61-88	CNSY
9-168	391430	744848	WOODBINE WC	6	1967	45	135-157	1987-88	CNSY
9-169	391513	744302	BETTS, WALTER	36-394	1968	10	116-160	1968-87	CNSY
**9-170	391611	743849	UPPER TWP BD ED	1	1952	30	65- 80	1981-86	CPMY
9-171	385901	745405	LOWER TWP BD ED	1	1973	10	149-161	1981-88	ESRNS
9-174	391240	745403	BUGANSKI, ANTHY	IRR-1979	1979	12	45- 75	1984-88	CKKD
9-176	385830	745021	WILDWOOD WD	WWD 35A	1978	8	252-338	1979-88	CNSY
9-182	385841	745000	STOKES LAUNDRY	2	1980	7	320-350	1981-88	CNSY
9-183	385724	745243	BORDEN CO(SNOW)	4	1979	5	260-290	1984-87	CNSY
9-184	391544	744347	UPPER TWP BD ED	2	1984	15	110-140	1985-86,88	CKKD
**9-289	390330	745010	GARDEN LK MOB HOMES	GARDEN LK PK 1981	1981	15	237-257	1986-88	CNSY
9-301	385732	745124	WILDWOOD WD	WWD 44-RECHARGE 4	1983	5	190-245	1986-88	ESRNS
9-310	390018	744748	WILDWOOD WD	RIO GRANDE 39 NEW	1986	5	279-357	1986-88	CNSY
9-314	385930	744852	WILDWOOD CITY	RECHARGE 3	1982	10	212-325	1982-88	CNSY
**9-315	390317	745010	WILDWOOD CNTRY CLUB	GOLF CLUB 2-1975-OW3	1975	10	228-248	1984-88	CNSY

[1] Assigned as the Holly Beach water-bearing zone in the model
[2] Assigned as the Cohansey aquifer in the model

Table 6.--Ground-water withdrawals from and injection of freshwater into wells in the shallow aquifer system of Cape May County: (a) withdrawal wells, 1981-88 and (b) injection wells, 1967-88

[data on withdrawals prior to 1980 are in Zapecza and others, 1987, tables 2 and 3; injection wells are used for both ground-water withdrawals and injection of freshwater; --, data not available or not applicable]

a.

GROUND-WATER WITHDRAWALS [million gallons per year]

	U.S. Geological Survey well number											
Year	9-22	9-27	9-42	9-43	9-45	9-52	9-54	9-57	9-58	9-59	9-62	9-65
1981	50.6	51.4	37.5	250.9	233.8	189.6	--	--	5.4	23.7	0.	1233.3
1982	54.5	51.4	25.8	205.0	282.6	192.8	--	--	5.4	23.7	0.	1291.4
1983	63.8	28.1	29.6	174.9	296.0	201.7	--	--	5.5	22.2	.2	1225.1
1984	52.2	6.8	25.0	115.7	273.8	198.5	--	--	14.1	--	.1	1285.8
1985	48.0	16.6	42.4	152.0	238.0	217.3	--	--	8.4	--	.1	1258.8
1986	66.0	15.4	28.3	275.6	135.2	250.8	--	--	.8	2.9	.3	1270.5
1987	59.5	22.8	27.7	287.3	131.9	88.6	68.8	75.0	6.6	5.4	--	1326.2
1988	56.3	8.2	--	298.8	114.7	100.2	59.5	136.6	--	--	.1	1270.

	U.S. Geological Survey well number											
Year	9-70	9-72	9-82	9-83	9-101	9-138	9-139	9-143	9-145	9-154	9-162	9-167
1981	78.2	161.8	4.9	1.9	0.	--	0.4	0.3	3.7	22.0	--	113.2
1982	83.0	175.9	19.9	1.9	.1	--	.4	.3	4.1	21.9	--	115.9
1983	87.5	161.9	16.4	1.6	.1	--	1.2	.4	4.3	24.8	--	122.6
1984	51.8	201.3	18.1	--	16.7	.2	.7	.4	5.8	27.5	41.8	101.4
1985	--	173.0	15.7	--	13.0	1.0	1.3	.4	2.6	31.3	45.4	108.3
1986	--	120.7	14.8	--	16.2	.6	1.1	.4	4.6	20.7	45.4	107.2
1987	--	94.4	15.6	--	--	--	--	.1	.6	24.3	52.9	108.9
1988		140.2	14.9	--	--	--	--	.4	1.3	5.1	53.1	109.5

	U.S. Geological Survey well number									
Year	9-168	9-169	9-170	9-171	9-174	9-182	9-183	9-184	9-289	9-315
1981	--	31.0	12.0	1.6	--	1.0	--	--	--	--
1982	--	31.0	4.0	1.7	--	8.3	--	--	--	--
1983	--	31.0	3.1	1.4	--	30.2	--	--	--	--
1984	--	63.2	1.4	1.5	11.6	33.3	26.3	--	--	.1
1985	--	34.0	.8	1.4	7.2	35.2	16.9	2.8	--	17.2
1986	--	34.0	1.2	1.6	20.	33.0	25.5	2.4	7.4	19.3
1987	--	30.0	--	--	25.7	32.9	27.9	--	13.0	24.7
1988	.2	--	--	1.6	29.5	34.1	--	1.2	14.8	18.2

b.

	U.S. Geological Survey well number									
	GROUND-WATER WITHDRAWALS [million gallons per year]					INJECTION OF FRESHWATER [million gallons per year]				
Year	9-159	9-176	9-301	9-310	9-314	9-159	9-176	9-301	9-310	9-314
1967	--	--	--	--	--	27.2	--	--	--	--
1968	69.3	--	--	--	--	99.5	--	--	--	--
1969	91.2	--	--	--	--	92.3	--	--	--	--
1970	61.6	--	--	--	--	119.9	--	--	--	--
1971	102.4	--	--	--	--	75.8	--	--	--	--
1972	69.2	--	--	--	--	71.4	--	--	--	--
1973	78.4	--	--	--	--	80.9	--	--	--	--
1974	89.4	--	--	--	--	77.2	--	--	--	--
1975	72.0	--	--	--	--	75	--	--	--	--
1976	51.0	--	--	--	--	78.1	--	--	--	--
1977	87.1	--	--	--	--	36.5	--	--	--	--
1978	42.2	--	--	--	--	56.7	--	--	--	--
1979	--	68.4	--	--	--	--	66.5	--	--	--
1980	--	52.8	--	--	--	--	55.8	--	--	--
1981	--	48.9	--	--	--	--	65.2	--	--	--
1982	--	59.8	--	--	29.1	--	54.5	--	--	83.1
1983	--	53.9	--	--	52.1	--	42.8	--	--	69.4
1984	--	50.2	--	--	51.8	--	65.1	--	--	61.9
1985	--	32.0	--	--	46.3	--	45.7	--	--	42.4
1986	--	35.9	24.2	0.	59.9	--	51.7	56.8	24.4	78.8
1987	--	45.7	46.7	47.0	44.5	--	40.9	48.6	59.4	68.6
1988	--	61.4	45.0	45.0	44.8	--	49	51.2	52.8	79.5

summer peak-demand period, the same four wells are used to withdraw approximately 84 percent of the amount of water injected. P.J. Lacombe (U.S. Geological Survey, written commun., 1990) estimates that a cylinder of ground-water (including aquifer material) having a diameter of as much as 1,200 ft is created by each injection well. This injection is a likely cause of the diminution of the size of the local cone of depression in the area that was reported by Gill (1962a). Injection wells also have been used on a small scale by the Atlantic City Electric Company near Ocean City since 1965.

Saltwater Encroachment

In undisturbed coastal-aquifer systems, fresh ground water flows toward the sea, meets denser salty ground water, mixes with and rises above the salty ground water, and leaks upward in a shallower aquifer or into the sea. Within each aquifer, a wedge-shaped body (in section, as shown in fig. 5) of saltwater tends to develop beneath the less dense freshwater. Because of the density difference between the two fluids, the toe (the intersection of the saltwater-freshwater interface with the bottom of the aquifer) of the saltwater wedge generally lies farther landward than does the tip (the intersection of the interface with the top of the aquifer). The shape and location of the interface are determined by the freshwater head and gradient. The interface between freshwater and saltwater (transition zone) is diffuse and the concentration gradient is nonlinear. Dynamic mixing of the two fluids occurs and is caused by tidal cycling, seasonal variations in local recharge, and pumping (Cooper and others, 1964). The width of the transition zone is greatest near shore, where tidal action increases, and pumping can be nearby. Mechanical mixing during advective ground-water flow is a more effective dispersion mechanism than molecular diffusion. The mixing induces a cyclic flow of saltwater (on the saltwater side of the interface) from offshore to the zone of mixing and back out again.

Under undisturbed conditions, the interface is stationary. Any increase in circulation in the freshwater region will cause the interface to move toward the sea and a decrease will cause the interface to move toward the land. Such movement can be induced by changes in recharge or discharge. Locale also is an important factor in determining interface movement (Cape May County is surrounded by saltwater on three sides). Aquifer-system response depends on local flow conditions and hydraulic characteristics (including inhomogeneity and anisotropy) and can be expected to be regionally asymmetric. Movement of the interface typically takes much longer than do changes to the flow system that induce the movement. Rate of movement depends on the position of the interface in the ground-water flow system and changes with the hydraulic gradient.

The two major constituents of seawater (Hem, 1985) are chloride (average concentration, 19,000 mg/L) and sodium (average concentration, 10,500 mg/L). Other major constituents are sulfate (2,700 mg/L), magnesium (1,350 mg/L), and calcium, potassium, and bicarbonate, all of which are present at small concentrations (less than 410 mg/L). The U.S. Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level (SMCL) for chloride concentration in potable water, 250 mg/L, is based primarily on acceptable taste and other aesthetic characteristics (USEPA, 1988).

In southern Cape May County, measured chloride concentrations have increased in supply wells for more than 50 years. Adequate data documenting the problem are, however, quite limited. Determining the exact location of the saltwater-freshwater interface in each aquifer would require a large data-collection effort, both onshore and offshore. Saltwater encroachment (as shown by high and (or) rising chloride concentrations) into the Holly Beach water-bearing zone has affected only coastline domestic-supply wells. Chloride concentrations increase abruptly in ground-water near the ocean and bay. Short-term sea-level flooding resulting from storms and tides also can increase chloride concentrations in this aquifer. South of the Cape May Canal, the distributions of chloride concentrations in this aquifer suggest that the tip of the peninsula is hydrologically isolated, like an island.

Saltwater encroachment occurs along the western coast of the peninsula in both the Holly Beach water-bearing zone and the estuarine sand aquifer. At Villas, increases in chloride concentrations in domestic wells have been observed since the mid-1960's, forcing abandonment of many of these wells. Results of a extensive investigation of domestic and observation wells in the area in 1984 (David Rutherford, Cape May County Planning Board, written commun., 1987) indicated that the 250 mg/L isochlor (line of equal chloride concentration) in the estuarine sand aquifer was at least 4000 feet inland of the Delaware Bay. The distance of the salty ground water to the Rio Grande well field was still over 8000 feet. Currently, chloride concentrations at the well field are low (less than 50 mg/L) in all three aquifers.

In the Cohansey aquifer, saltwater encroachment has occurred around the tip of the peninsula, notably affecting the wells belonging to the Cape May City Water Department (P.J. Lacombe, U.S. Geological Survey, written commun., 1990). The wells are separated by an average distance of 2200 feet (fig. 9). Wells at Columbia (well number 9-11) and Lafayette Avenues (9-14) have been abandoned as a result of high chloride concentrations in ground-water. These wells contained water exceeding 250 mg/L chloride in 1950 and 1963, respectively. The next-most inland well, 9-27, exceeded 250 mg/L chloride by 1984, and was retired as a major public-supply well. Located farther inland, well 9-45 has also contained water with rising chloride concentrations, but these values are below the SMCL for potable water. The most inland well, 9-43, contains water with chloride concentrations below 25 mg/L.

The Lower Township wells also contain water with low chloride concentrations. In Wildwood, increases in chloride concentrations have been uneven. Ten public- and industrial-supply wells screened in the Cohansey aquifer have been abandoned because of chloride contamination. Data for other areas along the ocean side are few. Geophysical data indicate that water is saline in the Cohansey aquifer beneath the barrier islands (P.J. Lacombe, U.S. Geological Survey, oral commun., 1990).

SIMULATION OF SALTWATER ENCROACHMENT

A mathematical model is a simplified representation of a physical system that behaves in a manner similar to the real system. Before modeling schemes are presented for the analysis of saltwater encroachment in coastal aquifer systems, a brief discussion of the differences between analytical and numerical models is presented. In some physically simple or abstract situations, it is possible to describe an aquifer system analytically and to draw conclusions about the water moving through it, provided certain simplifying assumptions. In real-world situations, however, complexities combine to violate the simplifying assumptions of analytical models.

The alternative is to use a numerical model. Numerical models lack the generality of analytical models but have the advantage of increased resemblance to the specific system being simulated. Numerical models are based on discretization of the ground-water-flow system. Discretization is the division of a continuous system into a finite number of mutually exclusive cells (called a grid, designating cells by row, column, and layer), with the assignment of a set of hydrogeologic properties to each cell. Each cell has a node at its center where variables such as head or saltwater-freshwater interface elevation are computed from mathematical equations. The numerical model, SHARP[1], by Essaid (1990a) was used to simulate saltwater encroachment in this study.

The transition zone where fresh and salty ground water meet can be modeled as a dispersed-interface or a sharp-interface (Reilly and Goodman, 1985). In reality, the interface is diffuse and saline concentrations increase steadily through the zone of mixing into the saltwater zone. The dispersed-interface approach is the more realistic of the two approaches in that it represents the transition zone between freshwater and saltwater as a concentration gradient across which mixing occurs. In contrast, the sharp-interface approach does not account for mixing (assumes no movement of solutes by dispersion), and the transition zone is assumed to be abrupt. An increase in mixing associated with interface movement, which can lead to a further widening of the transition zone, is not accounted for. Furthermore, using the sharp-interface approach, density is assumed to be a constant value in the freshwater zone and a slightly higher constant value in the saltwater zone. At the interface boundary (a sharp front representing an approximate 10,000-mg/L isochlor), however, the effects of the density difference between the two zones can be taken into account.

A decrease in sharp-interface model accuracy is evident near the sharp interface and in regions with steep head gradients, such as near cones of depression. The sharp-interface approach requires that the width of the transition zone between fresh- and saltwater be small relative to the thickness of the aquifer. According to Gill (1962a, fig. 50), the 30- and 500-mg/L isochlors in the Holly Beach water-bearing zone are separated by approximately 4,000 ft on the peninsula. In the estuarine sand aquifer, the distance separating the 50- and 2,000-mg/L isochlors is approximately 7,000 ft (Gill, 1962a, fig. 45). Finally, the distance separating the 50- and 1,000-mg/L isochlors in the Cohansey aquifer is approximately 5,000 ft (Gill, 1962a, fig. 34). All of these distances are large compared to the thicknesses of the aquifers. Because the saltwater gradually mixes with freshwater over a distance, simulation of the transition zone as a sharp interface is not fully satisfactory.

Despite these limitations, the sharp-interface approach is able to reproduce the general position, shape, and behavior of the saltwater-freshwater interface. Simulation of trends in saltwater encroachment are affected less by the simplifying assumptions. The sharp-interface approach also greatly simplifies and accelerates the numerical computations required by making it unnecessary to solve any chloride-transport equations. Hill (1988) observes that, for a cross-sectional model of the Cape May Peninsula, the SHARP model tends to yield more conservative estimates of interface position (nearer to shore) than does SUTRA[2] (Voss, 1984), a dispersed-interface model.

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[1] "SHARP" stands for sharp interface

[2] <u>S</u>aturated <u>U</u>nsaturated <u>TRA</u>nsport

Another consideration in simulating saltwater encroachment is that of model dimensionality. Three-dimensional models, although more realistic than those of lesser dimension, have several drawbacks. In general, three-dimensional models make large demands on computer resources and will fail to reach a solution more often than do one- or two-dimensional models. For example, most models based on the dispersed-interface approach are limited to one or two dimensions because of the large computational demands. Despite providing information on saltwater-freshwater mixing and on flow near pumping wells, dispersed-interface models are unable to represent an aquifer system's three-dimensional geometry and dynamics.

The SHARP model used in this study is a compromise in terms of dimensionality. It is a quasi-three-dimensional model, so called because it consists of a two-dimensional areal model for each aquifer with vertical interconnection between aquifers through one-dimensional leakage terms. The quasi-three-dimensional approximation permits simplification of the coupled partial-differential flow equations by integrating them over the thickness of the aquifer. This simplification results in flow that is completely horizontal within aquifers and completely vertical through confining units. The flow equations are linearized and formulated numerically by means of a finite-difference scheme based on a block-centered grid and a fully implicit time discretization. The model permits variable grid spacing.

The matrix of equations (combining all grid cells) is solved iteratively using the strongly implicit procedure (SIP). Saltwater and freshwater heads are solved for simultaneously, and the results are used to determine the elevation of the interface. Unlike many sharp-interface models in which saltwater is assumed to be static because of the Ghyben-Herzberg approximation (Freeze and Cherry, 1979, p. 375-376), SHARP is a two-fluid model that includes storage and flow dynamics for both the saltwater and freshwater domains.

The model FORTRAN 77 code has been modified to produce a ground-water budget (D.A. Pope, U.S. Geological Survey, oral commun., 1990) for the Cape May peninsula area and to output head-hydrographs for comparison with measured water-level hydrographs. A separate program for plotting interface tip and toe positions also was developed (Mary Martin, U.S. Geological Survey, written commun., 1990).

Model Design and Input Data

Model discretization was carried out in two stages. First, a square-mesh grid consisting of 59 rows, 52 columns, and 3 aquifer layers covering an area of 1,761 mi^2 was used to determine whether model lateral-boundary conditions would affect the flow system on the peninsula. The grid covered a region extending from the Tuckahoe River, which is the northern border of Cape May County, to the Delaware coast in the south, and from Cumberland County in the west to a point about 14 mi east of the County coast (an area larger than that shown in fig. 1.)

Simulations with the first grid indicated that the ground-water flow system on the peninsula was unaffected by the choice of lateral-boundary conditions. The area of the model grid was therefore reduced and grid-cell size was decreased to improve simulation speed and accuracy. A nonuniform-mesh grid covering an area of approximately 782 mi^2 (fig. 10) and consisting of 42 rows and 40 columns was constructed. The second grid, also centered on the peninsula, has an east-west dimension of about 22 mi and a north-south dimension of about 35 mi (the same dimensions as those shown in fig. 1). The smallest cells, which are 2,000 ft square, are in the southern part of the County where the most accurate head and saltwater-freshwater interface information are desired. Of the 5,040 cells in the second grid, 561 are inactive.

Ground-water flow in the water-table aquifer under the barrier islands and the Cape May Canal was not simulated because of adverse interface-movement effects on model stability and solution-convergence speed. If these local flow systems were to be included, a much finer discretization of these areas than the one employed would be required to obtain an acceptable solution. Also, because few data are available, outcrop areas for the estuarine sand aquifer in Delaware Bay hypothesized by Schuster and Hill (in press) were not considered.

An example of boundary conditions required by the model ground-water flow equations are shown areally in fig. 10 and shown for a generalized section along a row of the model through the peninsula in fig. 11. Constant freshwater heads representing the average stage in surface-water bodies and areas shown as wetlands on U.S. Geological Survey 1:24,000-scale topographic-quadrangle maps were assigned to lateral and top boundaries onshore. These boundary conditions are assumed to follow the Tuckahoe River east-west and the border with Cumberland County north-south. A bottom-leakance value for sediments beneath surface-water bodies and wetlands was assigned to represent the interaction of these bodies with the water-table aquifer below. Offshore, the constant-head boundary represents equivalent freshwater head of saltwater, owing to the density difference between freshwater and saltwater. Inspection of the magnitude of flows to constant head boundaries indicates that these boundaries provide no significant artificial sources or sinks of water. In the remaining onshore (outcrop) areas, the water-table aquifer receives a specified ground-water recharge from above which is constant through time. The model's bottom boundary was assigned as a no-flow boundary to represent the tight confining unit separating the Cohansey aquifer from the underlying Kirkwood aquifers. These boundary conditions were used in both the predevelopment steady-state and 1989 transient simulations.

Initial conditions required by the model equations consist of freshwater heads (including onshore lateral boundaries, equivalent-freshwater-head boundaries in the Atlantic Ocean and Delaware Bay, and top boundaries) and altitudes of the saltwater-freshwater interface. Freshwater heads and interface elevations were chosen so that the simulated saltwater heads were zero (sea level). Isolated pockets of saltwater can appear in the freshwater zone when the model makes a first solution iteration; they will remain during subsequent iterations as there will be no outlet for that water. Such pockets can develop in areas where hydrogeologic units are very thin. The pockets were avoided in the model by adjusting (lowering) the initial interface altitudes in the affected model cells.

A steady-state solution was assumed to have been reached when aquifer system inflow and outflow reached equality, and the change in system storage

EXPLANATION

LATERAL BOUNDARY--

- Constant freshwater head
- Constant saltwater head

TOP BOUNDARY--

- ▪ Specified recharge
- ☐ Constant head, freshwater or saltwater, as appropriate

NO-FLOW BOUNDARY--Bottom boundary (not shown) is also a no-flow boundary

A A' LINE OF HYDROGEOLOGIC SECTION--Sections shown in figure 23

Figure 10.-- Model grid and boundary conditions.

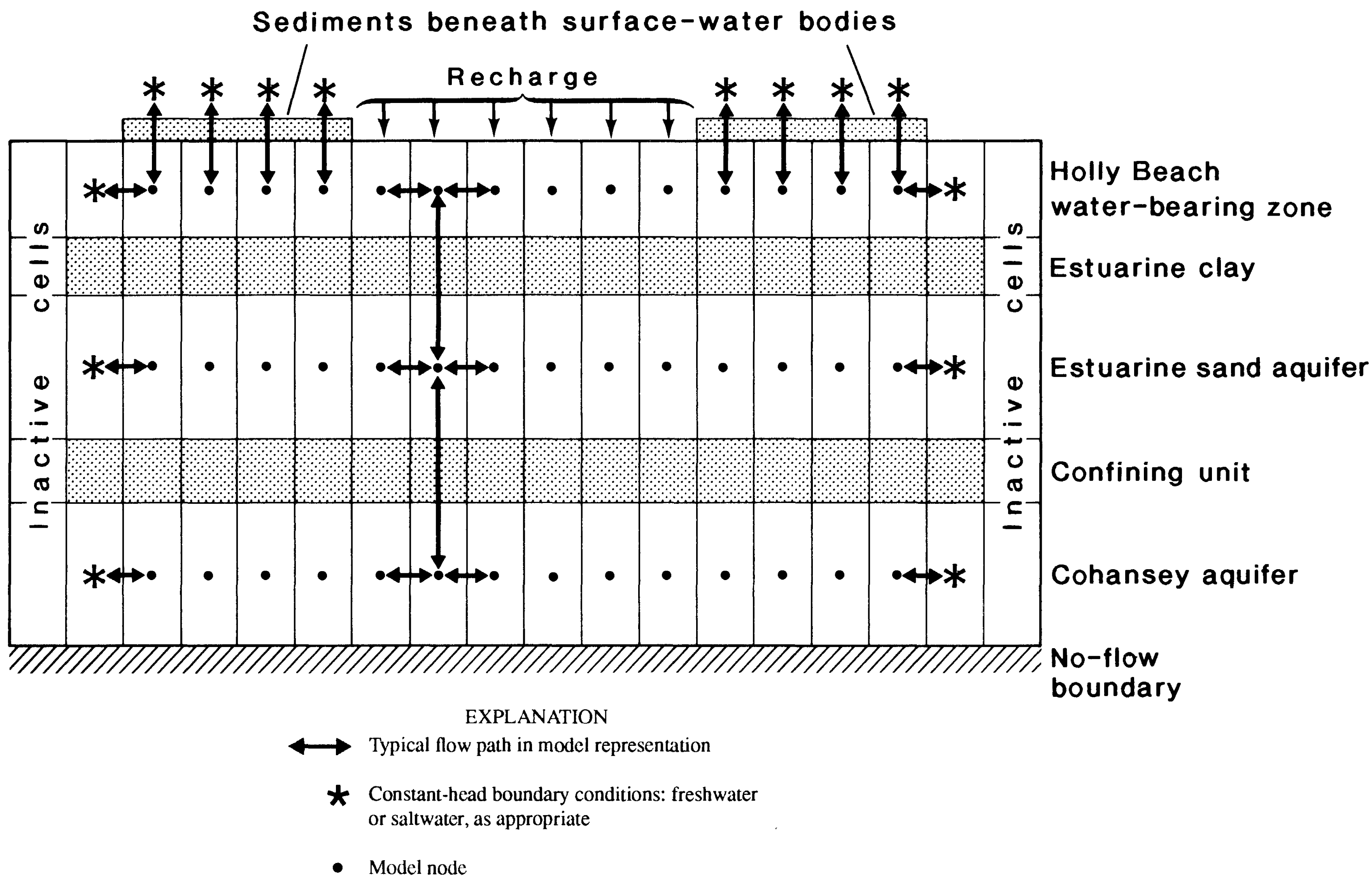


Figure 11.--Generalized vertical section along a row of the model on the peninsula.

was near zero. Because the aquifer system is shallow and annual fluctuations in head were small, the steady-state assumption is reasonable. Slow movement of the saltwater-freshwater interface required a long simulation time to achieve a steady-state solution. Although some further saltwater encroachment occurred in the Cohansey aquifer after meeting the criteria for a predevelopment steady-state solution, the results were taken as initial conditions for the 1896-1989 transient simulation with pumpage.

The initial time-step size was chosen to be 10 days for the predevelopment, steady-state simulation. This time-step size was gradually increased to 12 years (after 100 time steps) and then was fixed through the remainder of the simulation. Eight pumping periods (fig. 12), beginning with January 1896 and ending with January 1989, were chosen for the transient simulation. The criteria for selecting these periods were the need for (1) accurate discretization of the observed withdrawal curve and (2) the period to end in a year for which sufficient field data were available to calibrate the model. Withdrawals are annual rates that are averaged over the pumping periods chosen. The eight pumping periods range in length from 4 to 25 years and consist of 10 time steps per period. A model time-step size multiplier of 1.5 was applied in each period to accommodate the dynamic response of the stressed aquifer system. (When heads change significantly over a pumping period, most of the change is simulated in the beginning time steps of the period.) For injection wells, the net amount injected minus the amount withdrawn (generally a value greater than zero) is input to the model. Pumpage from domestic wells was not included in the model.

The simulated freshwater-saltwater ratio of dynamic viscosities is 0.9. The ratio of densities is 1:1.025. Where an aquifer or confining unit thins out, a 1-ft thickness was simulated because the model does not allow for the pinching out of units, and hydraulic properties were adjusted to make the 1-ft layer identical to an adjacent layer and therefore absent in the model. The model option for confining-unit leakage was set to "restricted mixing", meaning that saltwater in an aquifer was not allowed to leak into freshwater in an overlying or underlying aquifer, and that leakage of freshwater was distributed between the freshwater and saltwater zones based on the amount of freshwater in the cell receiving the leakage. The restricted-mixing option places the interface farther offshore in a less conservative position than does the "complete-mixing" option. The restricted-mixing option, therefore, counters the affect of conservative interface positioning resulting from the model's inability to simulate mixing in the transition zone. The complete-mixing method could have been used, but it could have resulted in erratic interface movement during transient simulation when leakage is significant because of pumping.

The following simulation parameters were adjusted by trial and error to achieve the best model solution and most rapid convergence to solution: weighting factor used in projecting interface position based on projections from previous and current iterations of the SIP solver (WFAC), 0.5; parameter used to control unwanted oscillations in interface tip and toe position by fixing the interface after a certain number of iterations (NUP), 25; maximum number of solution iterations allowed per time step (ITMAX), 125; number of iteration parameters for SIP solver (NITP), 6; factor used in calculating iteration parameters (WITER), 1,000; solution-relaxation factor (RFAC), 0.4; and solution-convergence closure criterion (ERR), 0.09 ft.

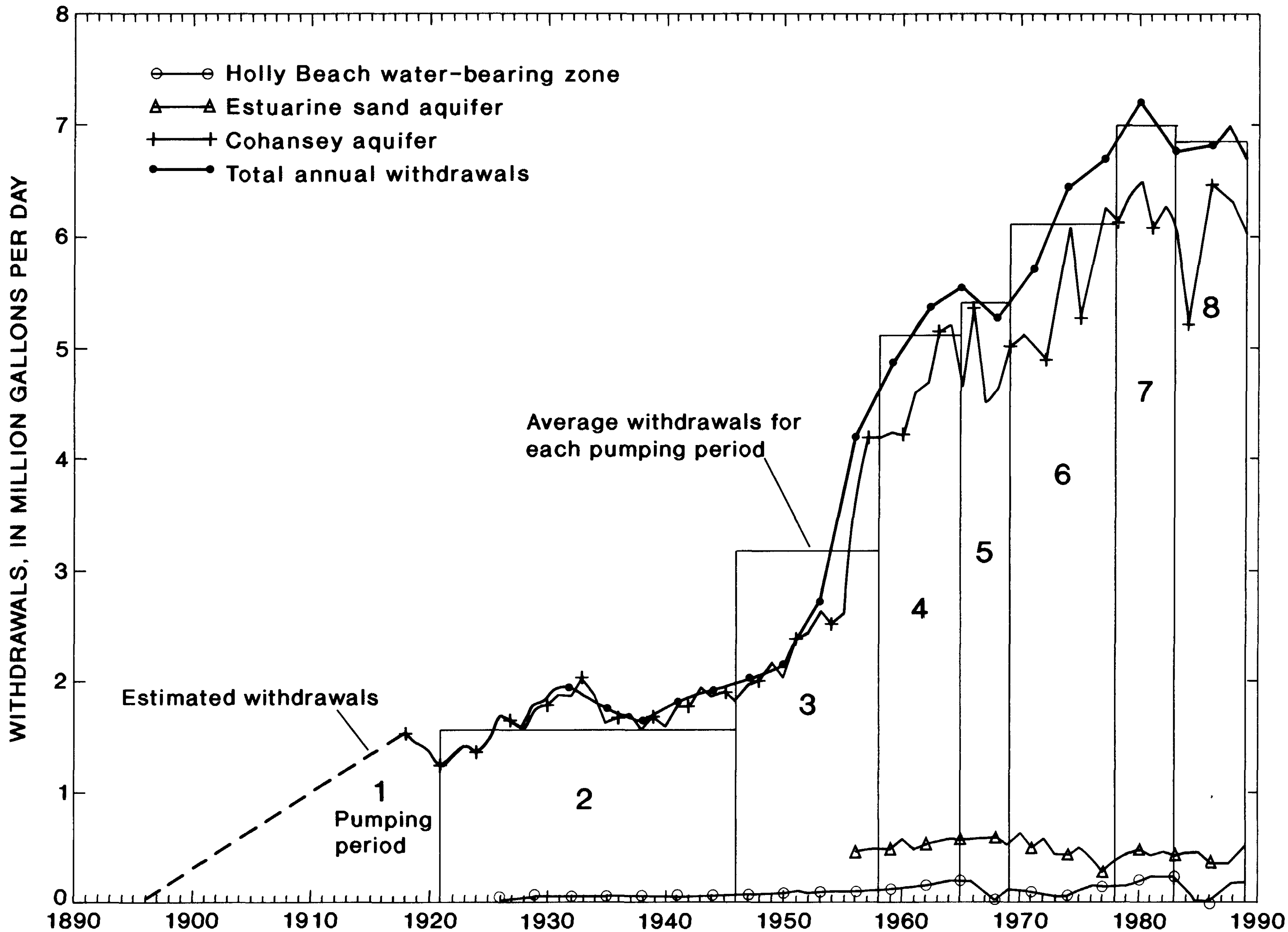


Figure 12.--Estimated and average ground-water withdrawals during simulated pumping periods.

Model Calibration

Differences between simulated and measured hydraulic heads and saltwater-freshwater interface positions can result from several possible causes. These include field-data quality (including methods used in collecting data and data interpretation), spatial and temporal averaging in the model, model discretization and sensitivity, and violation of model assumptions.

Field data were limited partly because (1) access to wells was poor; (2) water levels in withdrawal wells were measured before they had fully recovered from pumping; (3) wells with elevated chloride concentrations were sealed, thus prohibiting collection of additional data on saltwater encroachment at that location; or (4) field tests on aquifer properties are lacking. Modelers are required to interpret or make inferences about field data if measurements are unavailable. Spatial averaging results when the heterogeneous properties of a region are represented by a single average value at some point within it--in this case, a model node. Similarly, temporal averaging occurs when time-series data, such as withdrawals, are represented by an average value over a pumping period. Furthermore, the degree of spatial averaging is tied to the discretization of the model. The larger the size of a cell, the greater the degree of spatial averaging. The model also can be sensitive to certain parameters, responding with large changes in results. These effects are, unfortunately, unavoidable as are constraints on available computing facilities. Lastly, assumptions inherent in the models almost always must be violated in practice. A basic requirement in applying a model is to ensure that such violations are minor and that their effects on results are not significant.

In this study, the model was calibrated mainly by trial-and-error adjustment of aquifer hydraulic conductivities and confining-unit leakances. Both the steady-state and transient simulations were calibrated simultaneously to insure data consistency. For simplicity, aquifer hydraulic conductivity was assumed to be homogeneous and isotropic. Hydraulic conductivity affects the head gradients in the aquifer system and drawdowns around the wells. Leakance controls the amount of water moving vertically through the aquifer system. Recharge to the water table, aquifer specific yield or specific-storage coefficients, and porosities also were adjusted slightly. Calibrated values for storages (table 7) were 0.25 in the Holly Beach water-bearing zone and 0.00001 for the estuarine sand aquifer and Cohansey aquifer. A porosity of 0.3 was assigned to all aquifers.

Few data are available with which to calibrate the model to predevelopment conditions. Contours of hydraulic head and flow patterns for the simulation can be compared to those interpreted by Gill (1962a) and Zapecza (1989) and simulated by Martin (1990). The studies reported by Zapecza and Martin involved much larger areas than the current study and, therefore, provide only an approximate guide to predevelopment head contours and flow patterns. The scale of Gill's (1962a) work, however, is compatible with the scale of the current study. Data for calibration of predevelopment saltwater-freshwater interface positions are insufficient.

The principal criterion for evaluating the transient pumped simulation was the comparison of interpreted average 1988 heads with simulated annual average heads for that time. Average water-table and potentiometric surfaces based on

Table 7.--Simulated hydraulic properties of aquifers and confining units

[ft^2/d, feet squared per day; ft/d, feet per day; in./yr, inches per year; 1/d, per day; - - -, no data or not applicable]

Aquifer	Transmissivity (ft^2/d)	Horizontal Hydraulic conductivity (ft/d)	Storage	Porosity
Holly Beach	7,769-63,731	518	0.25	0.3
Estuarine sand	604-4,923	30	.00001	.3
Cohansey	151-1,184	5	.00001	.3

Confining unit	Leakance (1/d)	Vertical hydraulic conductivity (ft/d)
Sediments beneath surface-water bodies	0.98	- - -
Estuarine clay	.00002-.00009	0.00086
Clay overlying the Cohansey aquifer	.0006-.005	.057

measured water levels were derived by averaging surfaces from the interpreted summer and fall maps shown in figures 7 and 8 and are biased toward low-water conditions. The last model pumping period ends on January 1, 1989; thus, the dates of the simulated and interpreted average surfaces differ slightly.

Generally, a difference between simulated and interpreted heads of ≤ 5 ft was considered good, but such a close match was not expected in the immediate vicinity of wells where steep head gradients occur. Maps of head-difference residuals representing the differences between simulated and interpreted surfaces also were used in the transient calibration. These maps could not be used in the predevelopment calibration because interpreted head data were too few. Because of significant differences between simulated and interpreted heads, the ± 5-ft tolerance was applied to the area outside the major local cone of depression at the Rio Grande well field. Given the scale of the study, however, results and conclusions drawn for locations away from centers of major cones of depression are likely to be unaffected.

Hydrographs of water levels measured in 27 observation wells were used to constrain the transient calibration further. These hydrographs are for periods of record longer than 10 years. The 27 sites are well-distributed spatially and by aquifer and are located mainly on the Cape May peninsula. The estuarine sand aquifer is represented by the fewest wells (4), and the Holly Beach water-bearing zone is represented by the most (12). Simulated hydrographs were generated at the node for the cell in the model that contains the observation well. Locations of model nodes and wells do not necessarily coincide; however, nearly all of the wells lie within the smallest grid cells, so the maximum possible offset between the wells and nodes is 1,400 ft.

Because few measured chloride concentrations in ground-water are as high as 10,000 mg/L (approximate value representing the simulated sharp front), interface matching was considered a secondary calibration criterion in comparison to head matching. The only measured chloride concentration above 10,000 mg/L was in the unconfined aquifer, near Stone Harbor (fig. 1). Chloride data were classified on the basis of concentration and age (collected before 1980 or during 1980-89).

The final criterion for calibration was that the simulated nonunique set of hydraulic properties agree reasonably well with the ranges of reported values for these characteristics and the simulated ground-water flow system agrees with the conceptual ground-water flow system discussed earlier.

Although dependent on estimation methods and test conditions, the ranges of reported properties shown earlier in table 3 are used as the limits for calibration efforts. The spatial distribution of calibrated transmissivities is shown in figure 13. As can be seen in table 7, the calibrated transmissivity values for the three aquifers are within the range of reported values, although the values for the Holly Beach water-bearing zone are high. This could be related to the allotment of insufficient surficial discharge area in the top boundary of the model, in part as a result of the large grid cell size on the mainland. Because the model may underrepresent these areas, and because the saltwater-freshwater interface in the Holly Beach water-bearing zone is close to shore, the available area for surficial discharge is very small. An increase in surficial discharge area, accompanied by a more accurate distribution of areal recharge and an increase in leakance for the

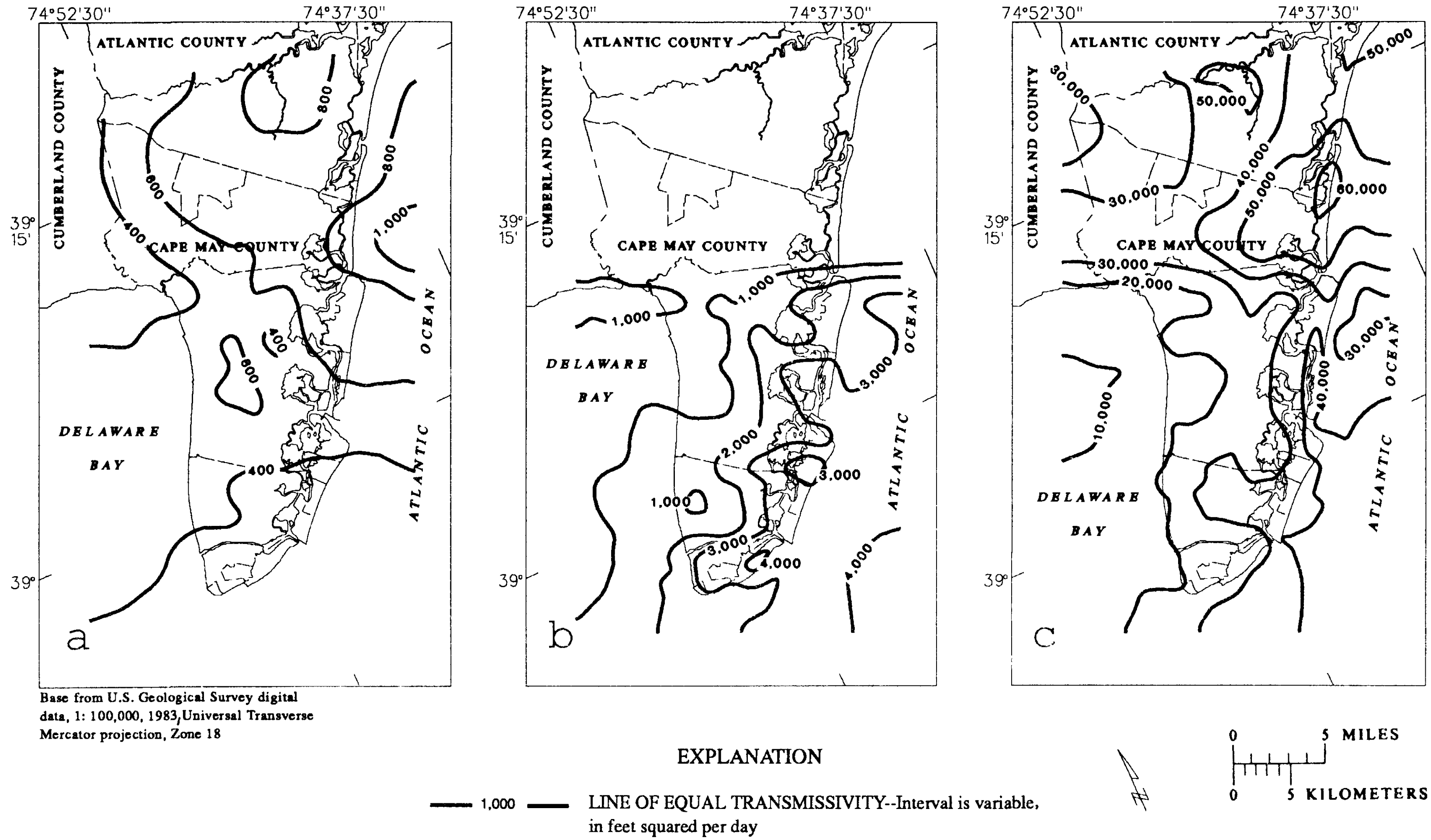


Figure 13.--Simulated transmissivity in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

estuarine clay confining unit, probably would allow for lower calibrated transmissivity for the unconfined aquifer. The use of a lowered transmissivity in the present model causes areas of high head in the Holly Beach water-bearing zone.

Calibrated confining-unit leakance values (maps not shown) are consistent with reported values, except for the bottoms of surface-water bodies, where they are too high. The leakance of bottom materials, for example, probably is lower than the value used in the model owing to the presence of clay layers more than 10 ft thick in some places (Good, 1965). Finally, error in the calibration of saltwater-freshwater interface position and discretization accuracy caused a small percentage of the withdrawal to be erroneously removed from the saltwater zone. Similarly, most of the injected water was added to the saltwater zone, but this is plausible because the injection wells are located near the interface.

A sensitivity analysis of hydraulic parameters, done as part of the calibration procedure, aids in evaluating the data and the effect of assumptions on the simulation results. For this model, transmissivity and recharge of the Holly Beach water-bearing zone and leakance of the estuarine clay confining unit were the most sensitive parameters. It is not surprising that shallow-flow components would dominate in a recharge-driven ground-water system. Offshore lateral-boundary conditions were tested by changing the constant head boundary to a no-flow boundary to evaluate the choice of boundary. No difference in simulation results was found. Sensitivity to discretization and pumpage were not tested.

Predevelopment Steady-State Conditions

Although Gill (1962a, fig. 32) mapped an interpreted, predevelopment potentiometric surface for the Cohansey aquifer, no data are available on predevelopment heads in the estuarine sand aquifer or in the Holly Beach water-bearing zone. The 1958 winter and summer potentiometric surfaces for the estuarine sand aquifer shown in Gill (1962a, figs. 43 and 44), however, are generally similar to 1957-58 surfaces for the Cohansey aquifer north of the Cape May Canal (Gill, 1962a, figs. 30 and 31). The simulated predevelopment potentiometric surface in the estuarine sand aquifer, therefore, was roughly compared with the interpreted predevelopment potentiometric surface for the Cohansey aquifer. Because the Holly Beach water-bearing zone has generally been undeveloped, the average of the summer 1957 and winter 1958 interpreted water-level surfaces in Gill (1962a, figs. 47 and 46) can be assumed to be representative of predevelopment conditions.

Comparisons of simulated and interpreted hydraulic heads for the three aquifers (fig. 14) is generally better on the peninsula than on the mainland, partly because of the coarseness of the model grid on the mainland and the higher density of available data on the peninsula. On the mainland, for example, Gill's predevelopment potentiometric surface for the Cohansey aquifer is based on a single data point. Although the simulated and interpreted surfaces for the three aquifers differ, the comparison at observation well locations (not shown) agrees closely in both cases. In general, model fit is better for the Holly Beach water-bearing zone than it is for the Cohansey or estuarine sand aquifers.

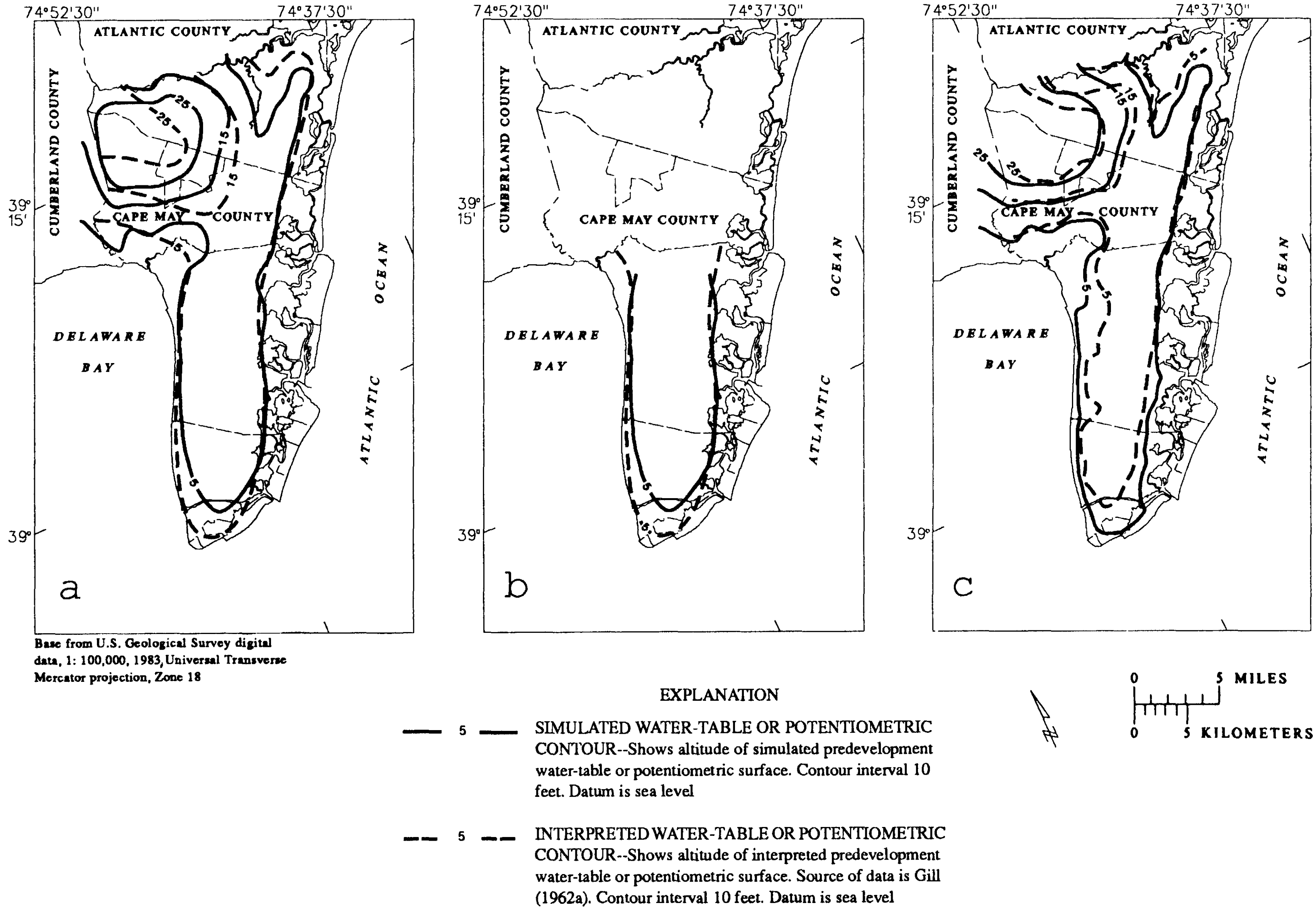


Figure 14.--Simulated and interpreted predevelopment water-table and potentiometric surfaces in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

Simulated leakage maps showing vertical recharge and discharge to the aquifers through the system's confining units are shown in figure 15. Simulated predevelopment recharge and discharge areas correspond to those postulated in the conceptual model. On the peninsula, downward leakage occurs along the centerline, and upward leakage takes place around the perimeter and through the bottoms of low-lying wetland areas. Only a small amount of recharge leaks down to the Cohansey aquifer (magnitude of leakage not shown on figure).

Data for calibration of predevelopment saltwater-freshwater interface positions are insufficient. Simulated interface tip and toe positions in the Cohansey aquifer (fig. 16) seem reasonable in comparison with the 250 mg/L isochlor location inferred by Gill (1962a, fig. 32). The ocean side isochlor follows the shoreline of the southern peninsula and moves inside the barrier islands north of Wildwood. The position of the isochlor was based on historical reports of water quality and on the estimated length of time for saltwater encroachment to take place in areas originally yielding freshwater.

1989 Transient Conditions

Development of ground-water supplies has changed directions and rates of flow within the shallow aquifer system. Current maps constructed on the basis of interpreted water level contours from measured data and contours resulting from simulations are shown in figure 17. Head-difference residuals between the two cases, used to quantitatively assess model fit, are shown in figure 18. Emphasis should be placed on residuals at model nodes nearest to observation wells rather than on contours.

Figures 17 and 18 indicate a good match for the Holly Beach water-bearing zone because simulated and interpreted heads are within ± 5 ft of each other in most places. For the estuarine sand aquifer, the simulated and interpreted heads are within 5 ft, except near the center of the cone of depression at the Rio Grande well field. Simulated heads are lower than interpreted heads there, probably because of inaccuracies in model-grid or pumping-period discretization, spatial averaging within model cells, inhomogenieties and anisotropy in aquifer properties, the presence of large vertical-flow components near cone of depression centers (which the model does not simulate), or errors in interpreting contours for seasonal head maps. The areal extent of simulated cones of depression in figure 17, however, does agree with the areal extent interpreted from measured data.

Most differences in simulated and interpreted head for the Cohansey aquifer are within 5 ft. The match is not close near the Rio Grande well field, around the tip of the peninsula, and in the northwestern part of the County. Inaccurate interpretation of the complicated potentiometric surface in southern part of the peninsula probably accounts for the second discrepancy, whereas the large grid-cell size in the north is the likely cause of the third discrepancy.

Simulated water-level hydrographs at nearest model nodes are superimposed on measured water-level hydrographs from observation wells in figure 19. It should be emphasized that the simulated hydrographs reflect annual conditions, and do not represent seasonal fluctuations. The five hydrographs shown in the figure were selected from a total of 27 on the basis of distribution

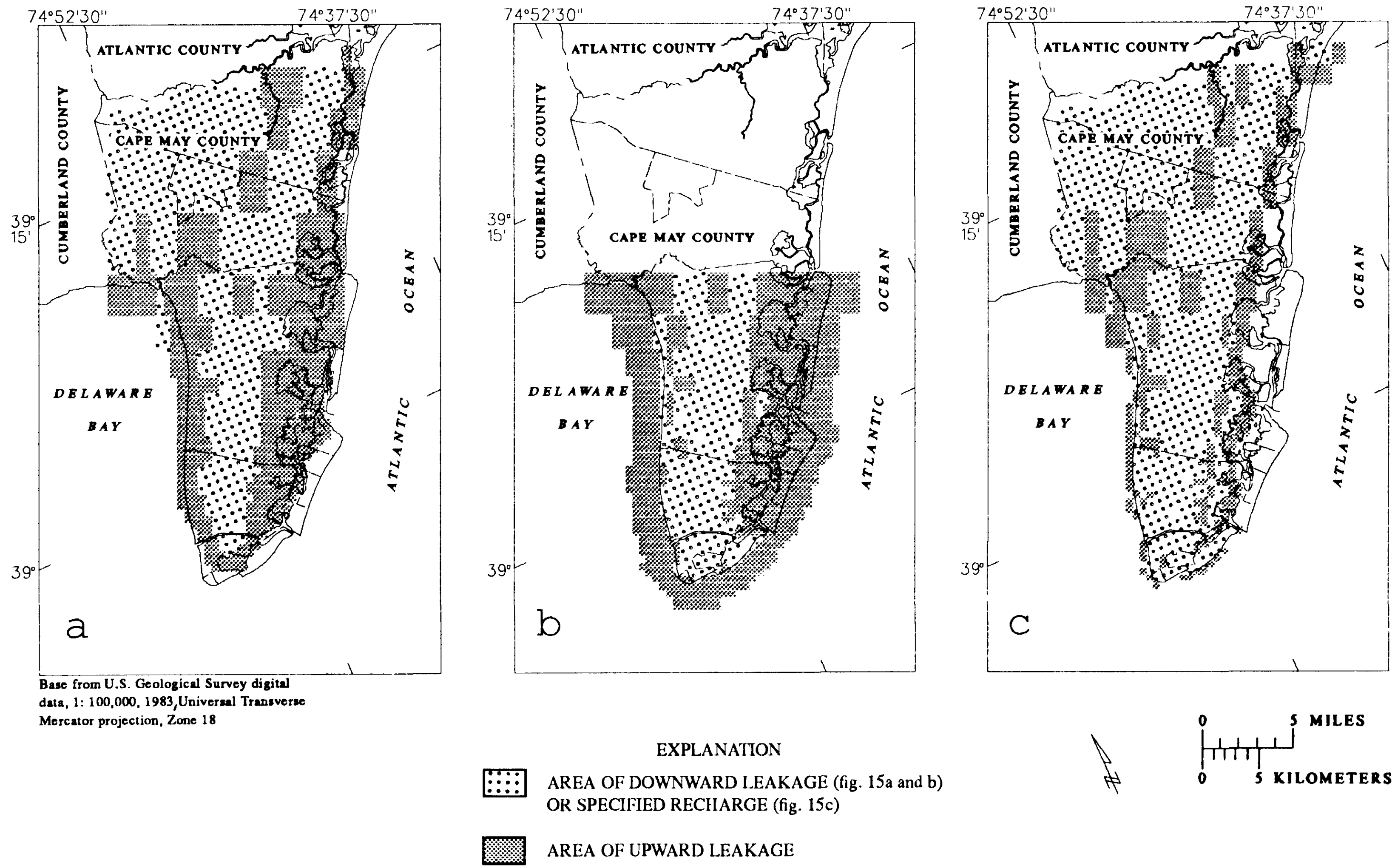


Figure 15.--Simulated predevelopment confining-unit leakage through the (a) clay confining unit overlying the Cohansey aquifer, (b) estuarine clay confining unit, and (c) bottoms of surface-water bodies.

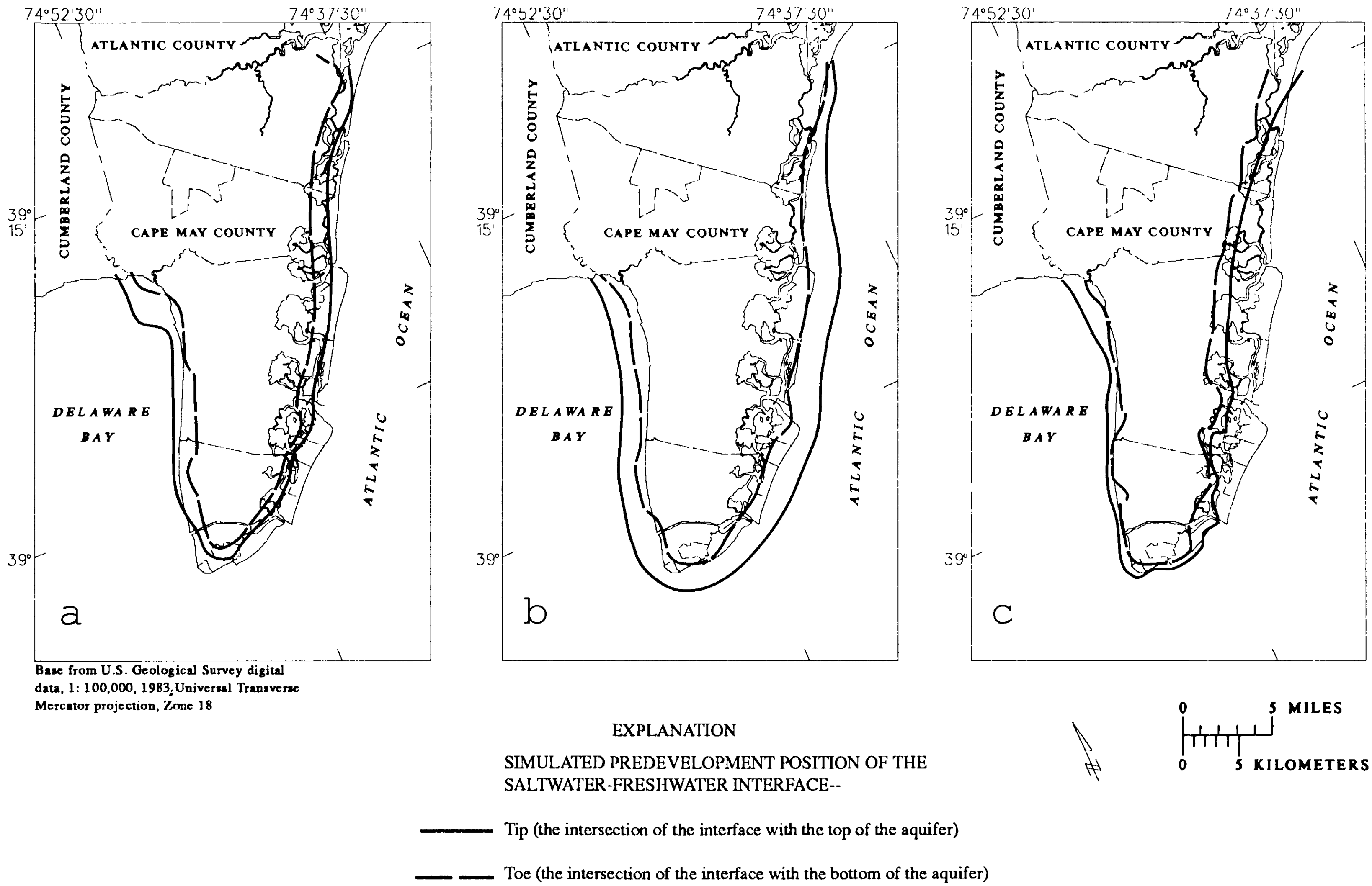
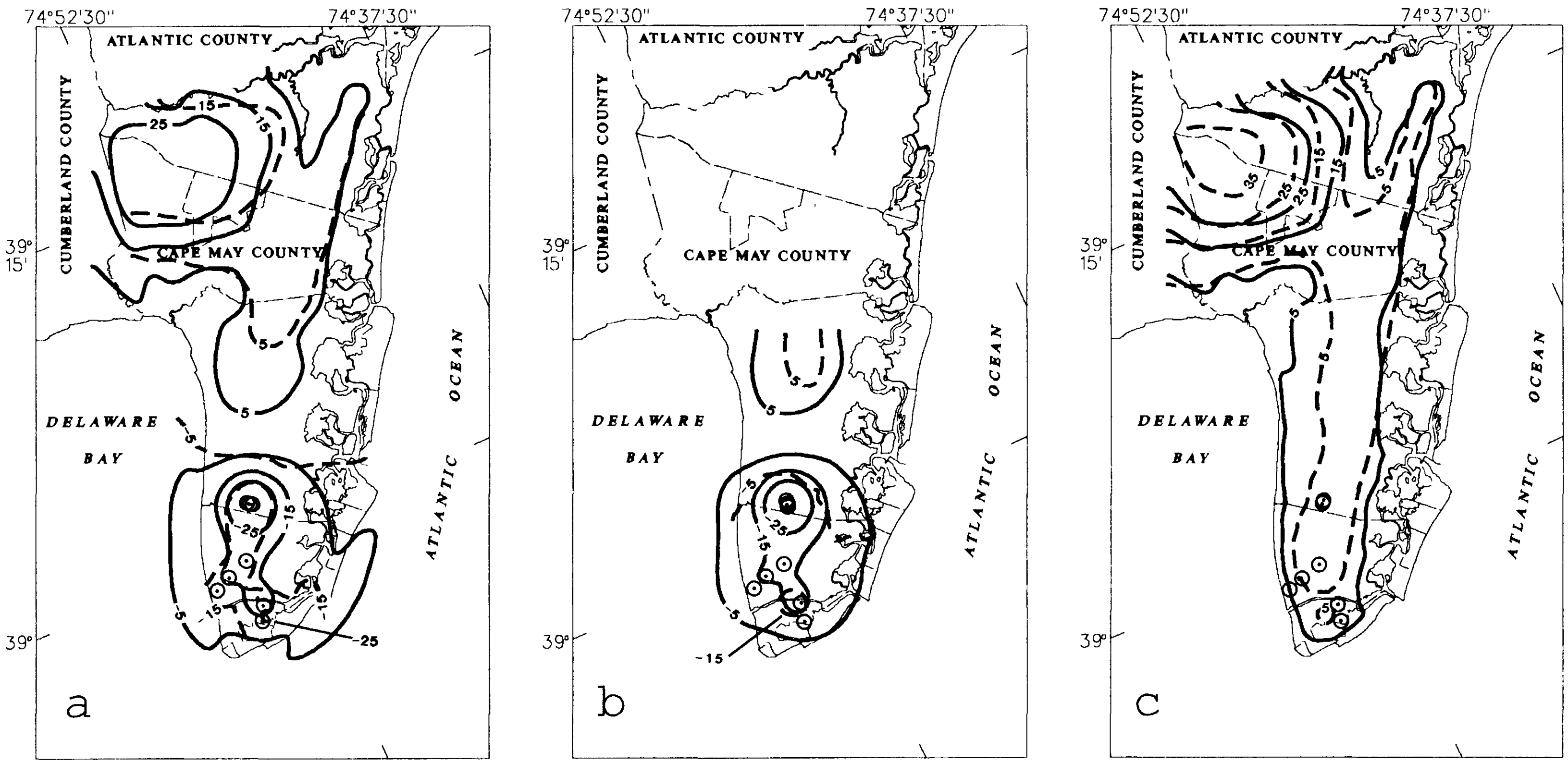
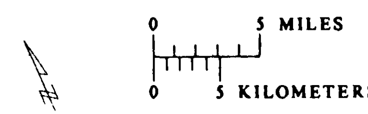


Figure 16.--Simulated predevelopemnt saltwater-freshwater interface in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.



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



EXPLANATION

5 — SIMULATED WATER-TABLE OR POTENTIOMETRIC CONTOUR--Shows altitude of simulated 1989 water-table or potentiometric surface. Contour interval 10 feet. Datum is sea level

5 - - INTERPRETED WATER-TABLE OR POTENTIOMETRIC CONTOUR--Shows altitude of seasonally averaged water levels for 1988 based on measured water levels given in table 4. Contour interval 10 feet. Datum is sea level

⊙ WATER-SUPPLY WELL

Figure 17.--Simulated and interpreted water-table and potentiometric surfaces for 1989 in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

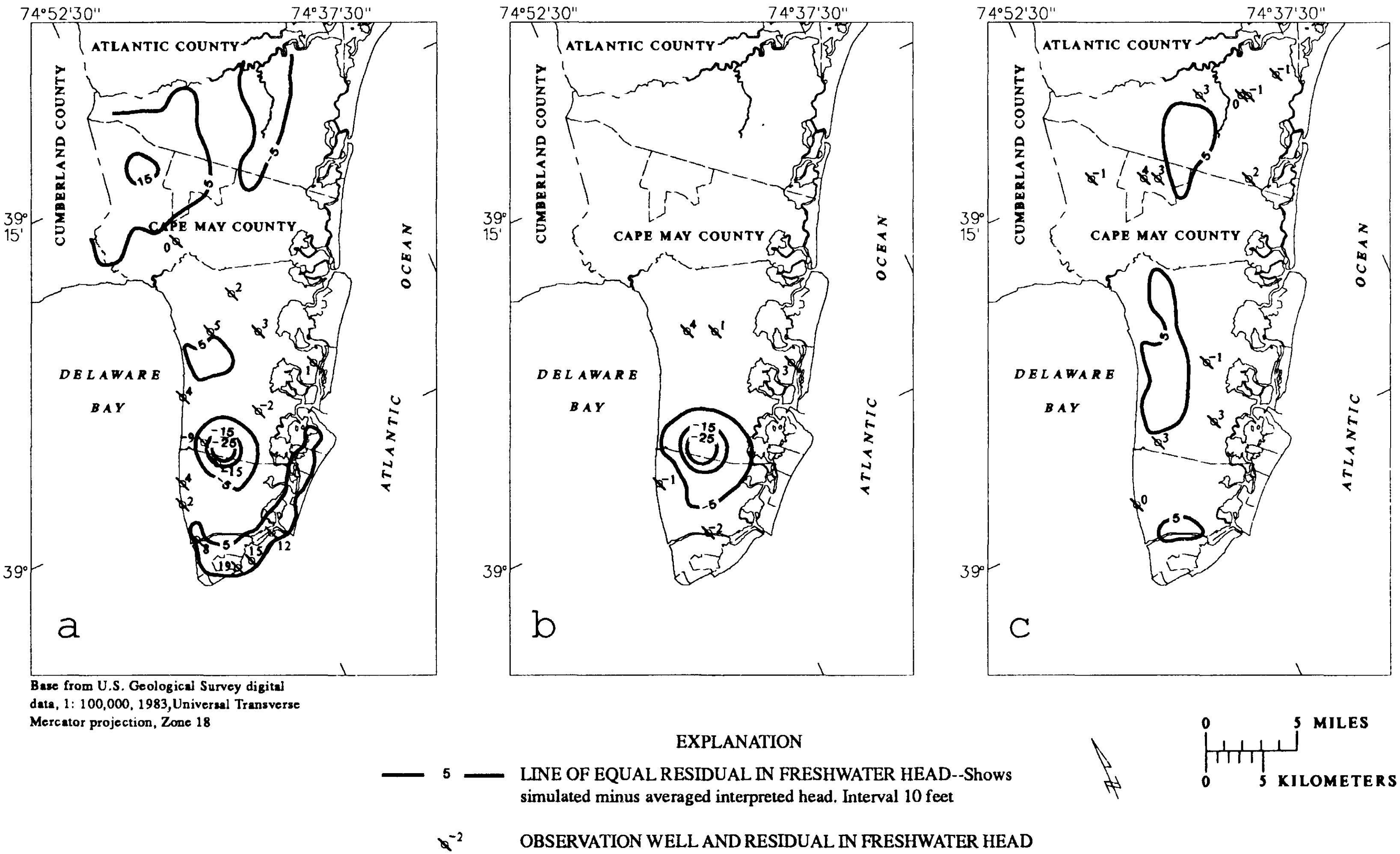


Figure 18.--Freshwater-head residuals for 1989 in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

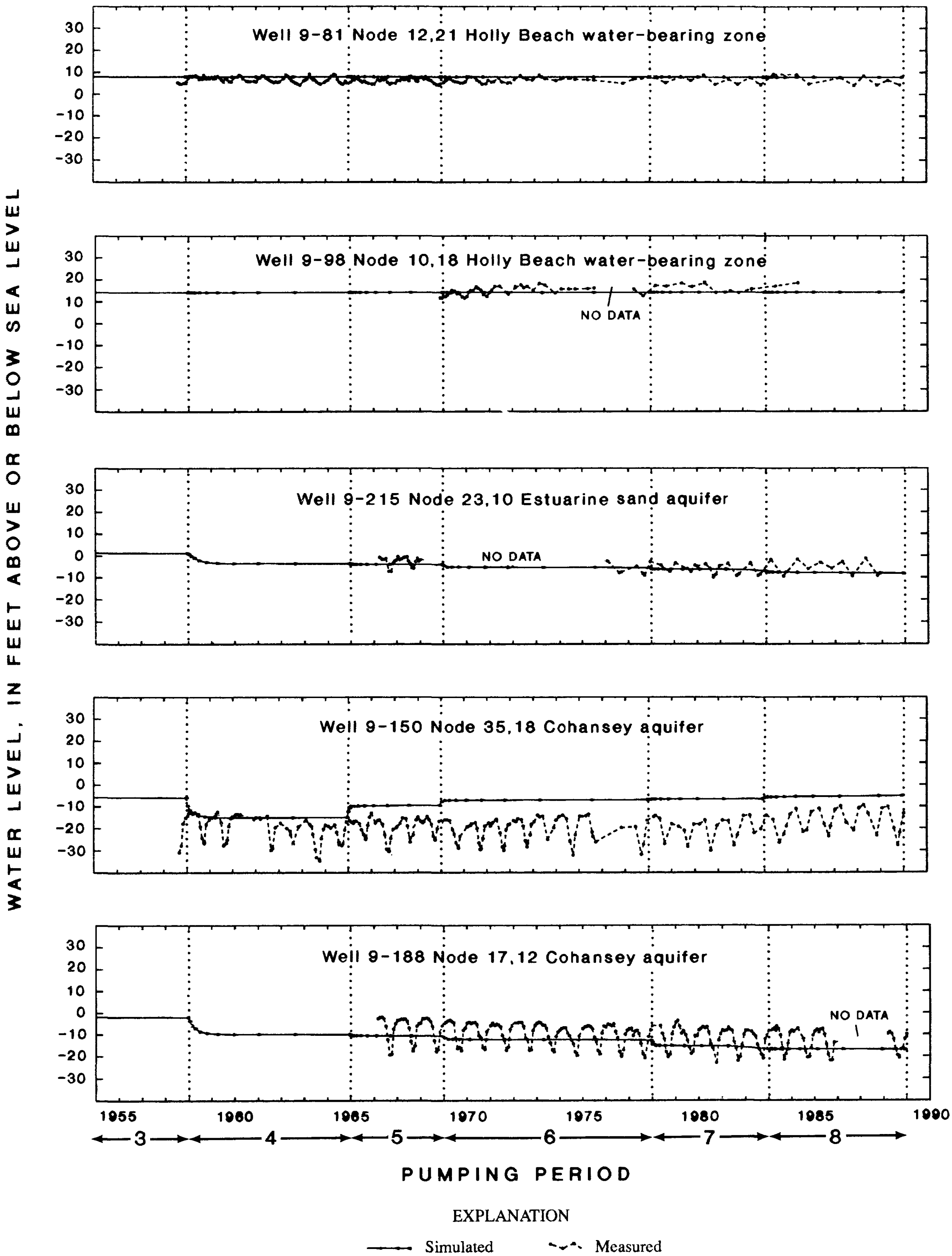


Figure 19.--Simulated and measured water-level hydrographs. (Well locations shown in figure 9.)

among the aquifers and proximity to the major withdrawal centers. For all the hydrographs, the fit was within ± 6, 5, and 4 feet in the Cohansey aquifer, estuarine sand aquifer, and the Holly Beach water-bearing zone, respectively.

Spatial distribution of simulated leakage through the confining units for 1989 conditions is shown in figure 20. Areas of leakage correspond to those postulated earlier in the conceptual model. Comparison of figures 20c and 15c shows negligible change in location of surficial discharge in predevelopment and postdevelopment. Downward leakage, however, increases at the major withdrawal centers in the southern part of the peninsula through the estuarine clay confining unit (figs 20b and 15b) and the clay confining unit overlying the Cohansey aquifer (figs 20a and 15a). This leakage accounts for much of the source water to supply wells. Upward leakage through these two confining units is diminished correspondingly on the peninsula as shown by a reduction in the amount of associated shading in figure 20.

Simulated ground-water budgets for the peninsula for predevelopment and 1989 conditions are further proof of the fact that ground-water development has modified flows through the shallow aquifer system. The budget area is for the entire peninsula and does not represent only the source area of water for the major withdrawal centers. The budget provides an indication of the overall accuracy of the model. For the SHARP model, total inflow to the system minus total outflow from the system ideally equals the total change in storage, but will not because of calibration inaccuracies. Any budget error is the discrepancy in this equality, relative to the amount of inflow. For the Cape May model, the discrepancy was approximately 1 percent for predevelopment steady-state and 1989 transient conditions.

Inflows of water in the ground-water budget (fig. 21) are recharge, regional ground-water flow from mainland Cape May to the peninsula, injection (subtracted from pumpage and is not shown), leakage, and release of water from aquifer storage (averaged over the pumping period). Outflows include discharge to surface-water bodies (base flow, to tidewater, and to saltwater bodies), pumpage, lateral ground-water flow to the ocean and bay, and leakage. Base flow and discharge to tidewater include that to streams, marshes, swamps, estuaries, and other wetland areas. Subsea discharge within the peninsular area with outflow through model conversion of freshwater to saltwater (computed from differences in leakage components between the aquifers) is small and is not included.

On the basis of the calibrated ground-water budget in 1989, regional flow from the mainland to the peninsula accounts for about 3 percent of the total peninsular recharge of 78 ft^3/s. Total peninsular recharge includes infiltration to the water table (76 ft^3/s) and regional ground-water flow from the mainland to the peninsula (2 ft^3/s). This percentage is approximately the same as estimated from net lateral flow in the conceptual peninsula ground-water budget in 1989 (fig. 6). The discharges in the calibrated budget are calculated for a slightly larger area (resulting from discretization) than the area used in the conceptual budget. The additional area is accounted for in shoreline discharge to the ocean and bay. The allotment of insufficient surficial discharge area in the top boundary of the model has forced more ground-water to exit the peninsular budget area laterally than by vertical discharge, in contrast to the conceptual budget.

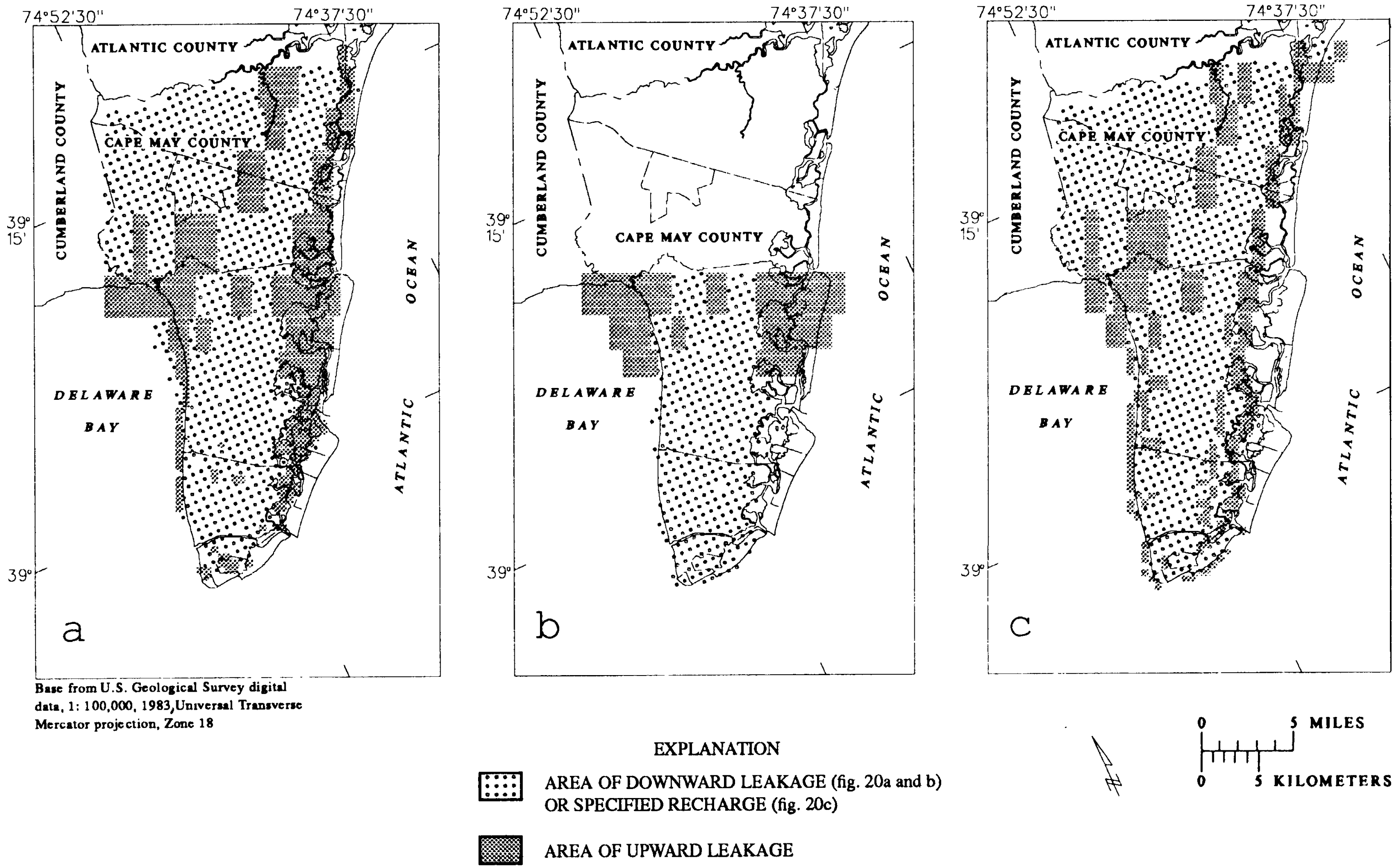


Figure 20.--Simulated 1989 confining-unit leakage through the (a) clay confining unit overlying the Cohansey aquifer, (b) estuarine clay confining unit, and (c) bottom of surface-water bodies.

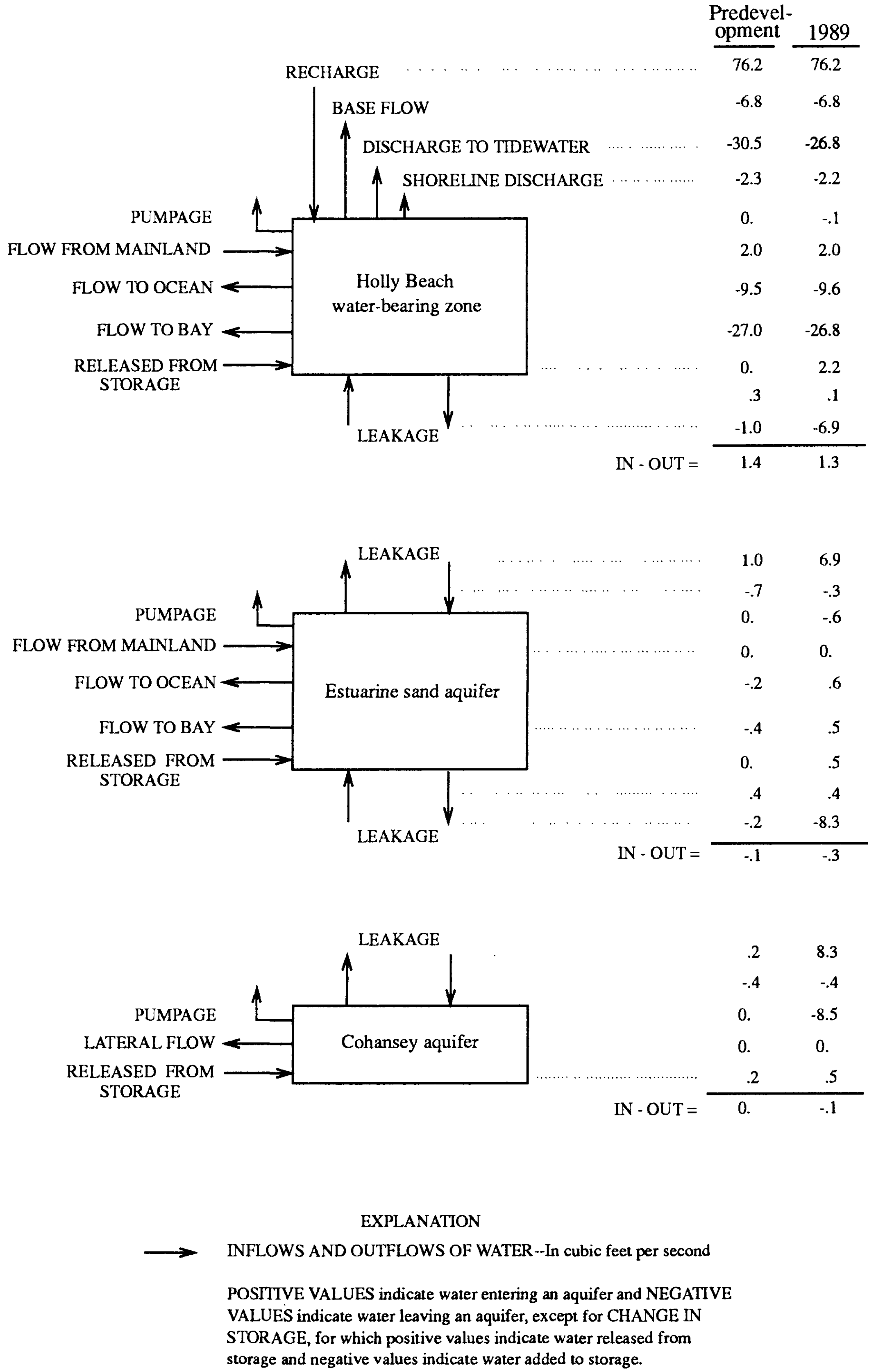


Figure 21.--Simulated ground-water budgets for the peninsula for predevelopment conditions and 1989.

Ground-water-supply development has decreased surficial discharge to tidewater, increased downward leakage, and released water from aquifer storage, as can be seen by comparing budget flows for simulated predevelopment conditions with those for 1989. For example, vertical leakage from the water table aquifer to the confined aquifers increases approximately 5.9 ft^3/s, from 1.0 ft^3/s under predevelopment conditions to 6.9 ft^3/s under 1989 conditions (partly the result of decreased surficial discharge and partly due to conversion of some predevelopment discharge areas to recharge areas in 1989)--an increase of almost 8 percent of the total peninsular recharge. Total average pumpage from the confined aquifers, 9.1 ft^3/s, is more than 9 times greater than downward leakage to these aquifers during predevelopment conditions. For the confined aquifers, the difference between this pumpage and the increase in downward leakage is made up by lateral ground-water inflow and water released from aquifer storage. If withdrawal rates stay constant, release of water from storage will cease and diversion of flow (for example, from ground-water-discharge areas) will occur. Components of the simulated salt ground-water budget (not shown) are small and changed much less than components of the freshwater domain.

Saltwater Encroachment in 1989

The amount of development that a coastal aquifer system can support depends on (1) the amount of ground-water that can be intercepted by means of optimal location of wells, (2) the amount of induced recharge from surface-water sources that is considered to be acceptable, and (3) the amount of saltwater encroachment that can be tolerated. Saltwater can enter an aquifer system either horizontally by landward movement of the saltwater-freshwater interface or vertically by leakage into the freshwater zone. Because the interface responds slowly to development compared to ground-water levels, a more immediate pathway for saltwater contamination is through leakage. Thus, the full extent of saltwater encroachment may not be realized for a long time after ground-water development plans are implemented.

In Cape May, saltwater that has encroached in the estuarine sand aquifer may leak into the Cohansey aquifer. Calculations of leakage travel times (not shown) through the confining unit separating these two aquifers from simulated leakage rates suggests this. At the major withdrawal centers, leakage travel times are reduced to a few years by 1989. The decrease in travel times from predevelopment in the estuarine clay confining unit at these locations is less dramatic.

For the 1989 transient calibration, measured chloride-concentration data from well water were compared with simulated positions of the saltwater-freshwater interface. Because measured chloride concentrations at most of the wells are less than 10,000 mg/L (approximate value representing the simulated sharp front), accurate matching with the simulated interface is not possible. The interpreted 250-mg/L chloride isochlor, for which more data are available, is inferred to move in the same direction but at a faster rate than the 10,000-mg/L isochlor. Positions of these isochlors also depend on the depths of the screen intervals of the wells (where vertical diffusion in the aquifer can occur).

Because of the lack of data and inability to simulate dispersion effects cited earlier, interface movement and rates of movement, rather than actual configuration, are emphasized. The simulated saltwater-freshwater interfaces for the shallow aquifers are shown with measured chloride concentrations from well water in figure 22. "Problem areas"--those in which chloride concentrations show a high and (or) rising trend over time--are highlighted in the figure. The measured concentrations are irregularly distributed and were obtained by a variety of sampling methods. For example, water samples for the Holly Beach water-bearing zone were collected from drilled and driven wells.

The simulated saltwater-freshwater interface in the Holly Beach water-bearing zone follows the western and southern coasts of the peninsula and lies inside of the barrier islands on the eastern coast. The simulated interface is nearly vertical, in part because the calibrated value for leakance of sediments beneath surface-water bodies is high. If this leakance were decreased, the slope of the interface in the unconfined aquifer would become more gentle. Of the simulated interfaces in the three aquifers, that in the estuarine sand is calibrated strongest and lies furthest away from the peninsula. Simulated interface position in the Cohansey aquifer is calibrated weakest and lies the closest.

These results differ from the interpretation of Schuster and Hill (in press), who interpreted the saltwater-freshwater interface in the Cohansey aquifer to be slightly seaward of that in the estuarine sand aquifer around the peninsula's tip. The poor agreement between the interpreted and simulated interfaces in the Cohansey aquifer on the peninsula's southwestern coast could not be improved. Several factors could account for the onshore position of the simulated interface. For example, new information (P.J. Lacombe, U.S. Geological Survey, oral commun., 1990) indicates that the thickness of the Cohansey aquifer may be greater at the southern part of the peninsula than was simulated. Further, initial conditions for the predevelopment simulation do not account for long-term sea-level changes. (This effect on a shallow, local aquifer-system was assumed to be small.)

Pleistocene sea-level fluctuations, which took place during glacial and interglacial time, add complexity to an investigation of the saltwater-encroachment problem. The last major lowstand in sea level was about 18,000 years ago, during the Wisconsin glacial age. The sea has been rising since then. Results of simulations by Meisler and others (1985) of the post-Wisconsin period suggest that the composite saltwater-freshwater interface in the northern Atlantic Coastal Plain is not in equilibrium with present-day sea level, but rather with sea levels that are 50 to 100 ft below present. These investigators estimate that the interface is moving landward at a rate of about 0.1 ft per year. This rate of interface movement is much slower than rates based on increases in dilute chloride concentrations (for example, the 250 mg/L potable water limit) from well water in Cape May or simulated rates in this study, supporting the conclusion that the present interface position is between that of equilibrium with the sea level of the Wisconsin lowstand and that of equilibrium with the present sea level. A simulation that incorporated hydrogeologic and sea-level changes (requiring a new model grid) might improve the calibration of interface positions in all the aquifers; distances and rates of interface movement are nevertheless valid.

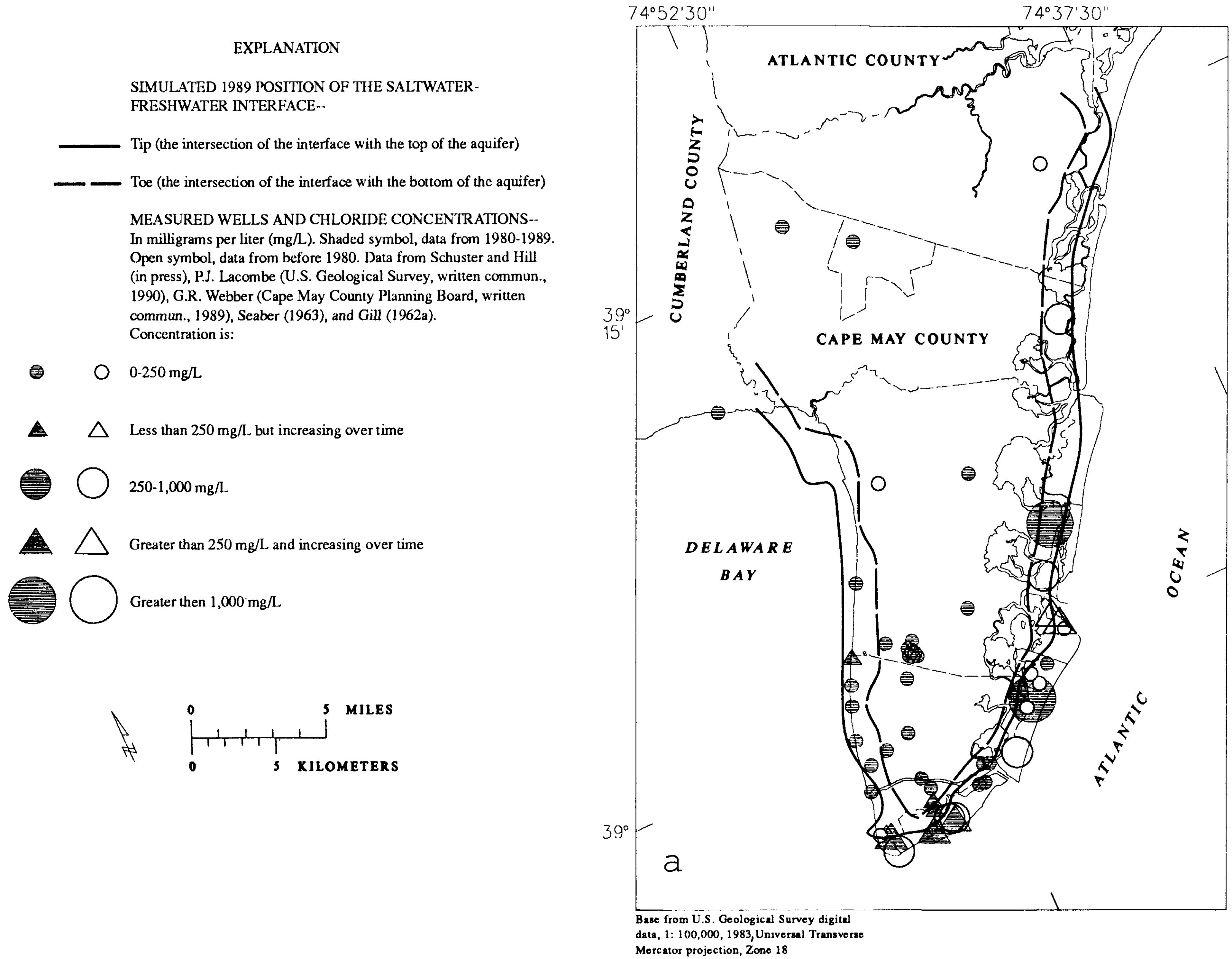


Figure 22.--Simulated 1989 saltwater-freshwater interface and measured chloride concentrations in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone.

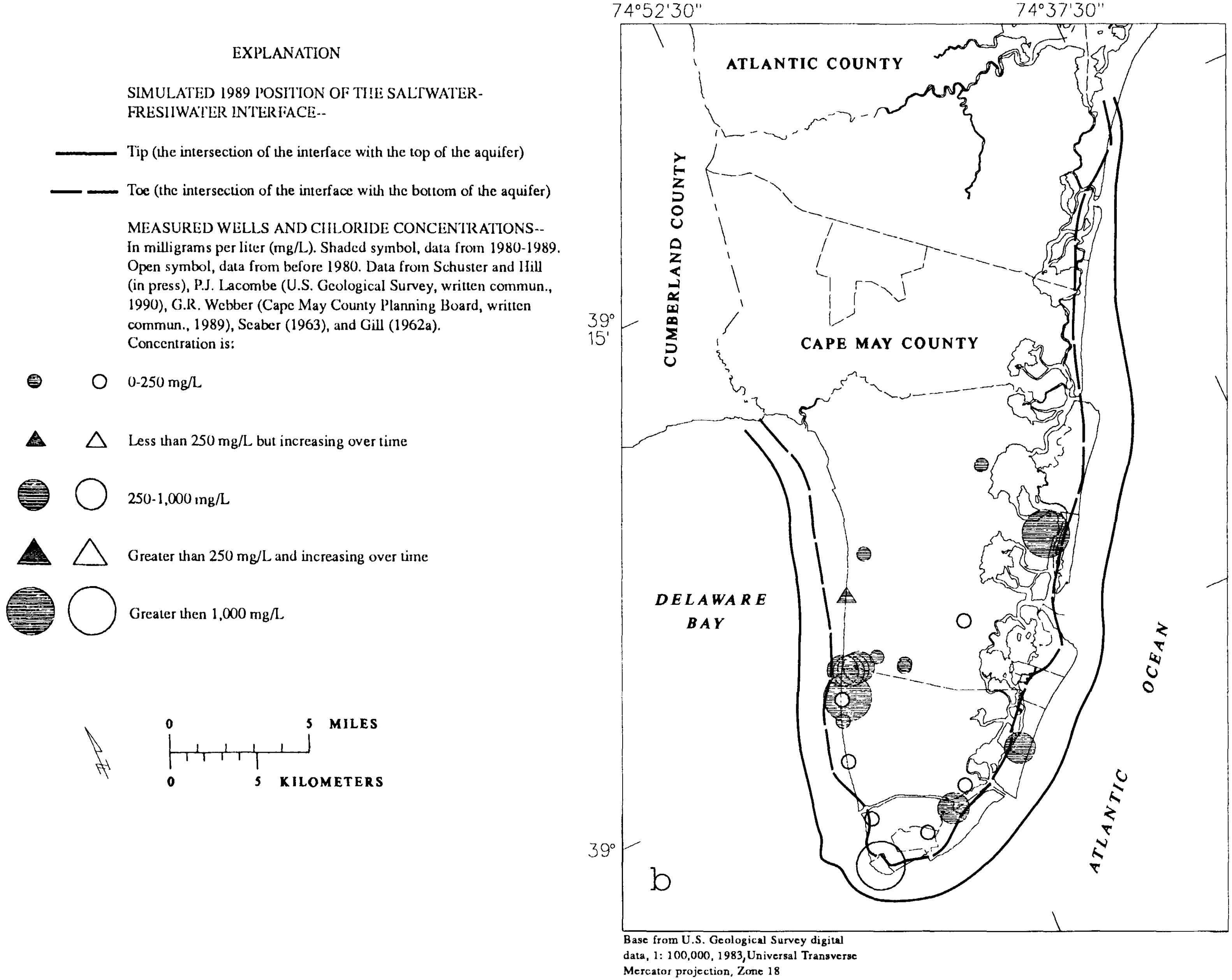


Figure 22.--Simulated 1989 saltwater-freshwater interface and measured chloride concentrations in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone--Continued.

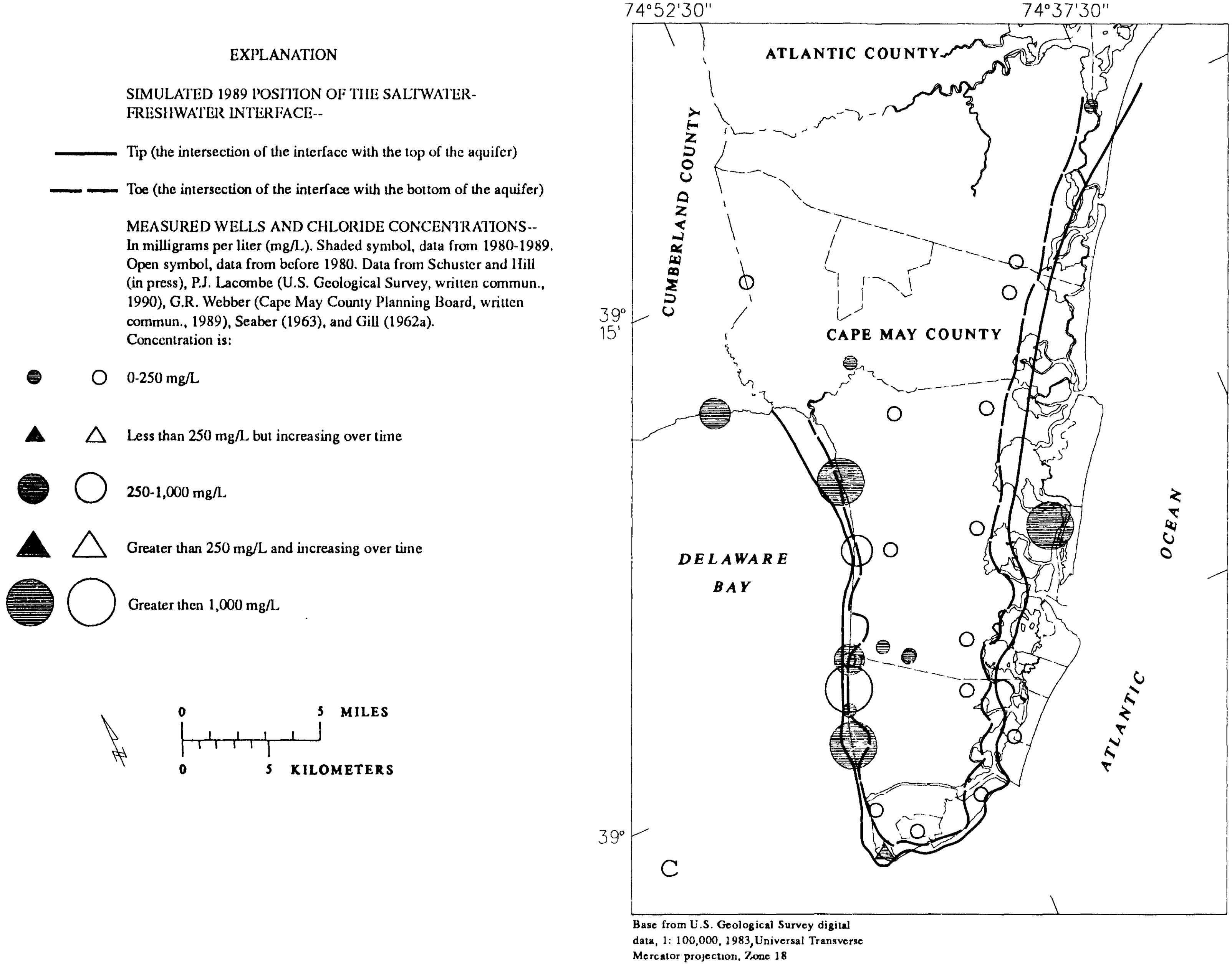


Figure 22.--Simulated 1989 saltwater-freshwater interface and measured chloride concentrations in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone--Continued.

In section (fig. 23), the saltwater-freshwater interfaces in the Holly Beach water-bearing zone and the estuarine sand aquifer are offset laterally from one another. The sections pass through the pumping centers at Rio Grande and Cape May City. The interface in the Cohansey aquifer is approximately in the same location with that in the estuarine sand aquifer, further indicating the confining unit separating the two aquifers is leaky. In contrast to Gill's (1962a) interpretation, the simulated interface in the Cohansey aquifer is slightly steeper than that in the estuarine sand aquifer.

Simulated positions of the saltwater-freshwater interface toe (the intersection of the interface with the bottom of the aquifer) in the confined aquifers for predevelopment and 1989 conditions are shown in figure 24. Estimates of average rate of movement of the simulated interface (table 8) can be made by dividing greatest interface-toe movement toward the major withdrawal centers by the length of the development period. This calculation assumes that solutes travel at the velocity of ground-water flow--that is, most of the movement is by advection and dispersion is small. Movement is also assumed to be aligned with the direction of ground-water flow. Calculations of average rates of movement over time also are different from instantaneous rates which change with location and time.

Saltwater-freshwater interface movement is greatest in the estuarine sand aquifer and least in the Holly Beach water-bearing zone. The minimal amount of movement in the Holly Beach water-bearing zone is related to the small change in water levels (which are still above sea level) in the aquifer over the development period. Interface movement in the Cohansey aquifer for Lower Township are not shown because of model calibration inaccuracies in interface position in this area discussed earlier. (Interface movement in this aquifer toward these wells was less than in the estuarine sand aquifer.) Simulated interface movement in the Cohansey aquifer near Cape May City is much smaller than interpreted movement of the 250-mg/L chloride isochlor (the potable water interface) during the development period. Simulated interface movement of 690 ft is compared with interpreted movement of 6,500 ft (P.J. Lacombe, U.S. Geological Survey, written commun., 1990). Near Rio Grande, simulated interface movement in the estuarine sand aquifer of 630 ft is compared with interpreted movement of 5,000 ft. The large interpreted interface movement of the potable water interface reflects large dispersion effects in the part of the transition zone where chloride concentrations are low. Inaccuracies in interpretation of isochlors from measured point concentrations or model calibration also could account for differences between simulated interface and interpreted interface movement.

Results of Predictive Simulations

Predictive simulations can be used to test aquifer-system response to alternative ground-water-management plans. This is done by comparing changes in ground-water heads, flows, and saltwater encroachment simulated by the model for different scenarios. Although these hypothetical simulations adequately predict changes in head and flow, they permit only an inference of changes in saltwater encroachment; uncertainty exists in predictions of saltwater-freshwater interface movement rate and predictions of when the interface will reach a given well. This uncertainty is caused partly by the inability of the ground-water model to simulate closely local scale conditions and from the variations in water density and solute-dispersion effects.

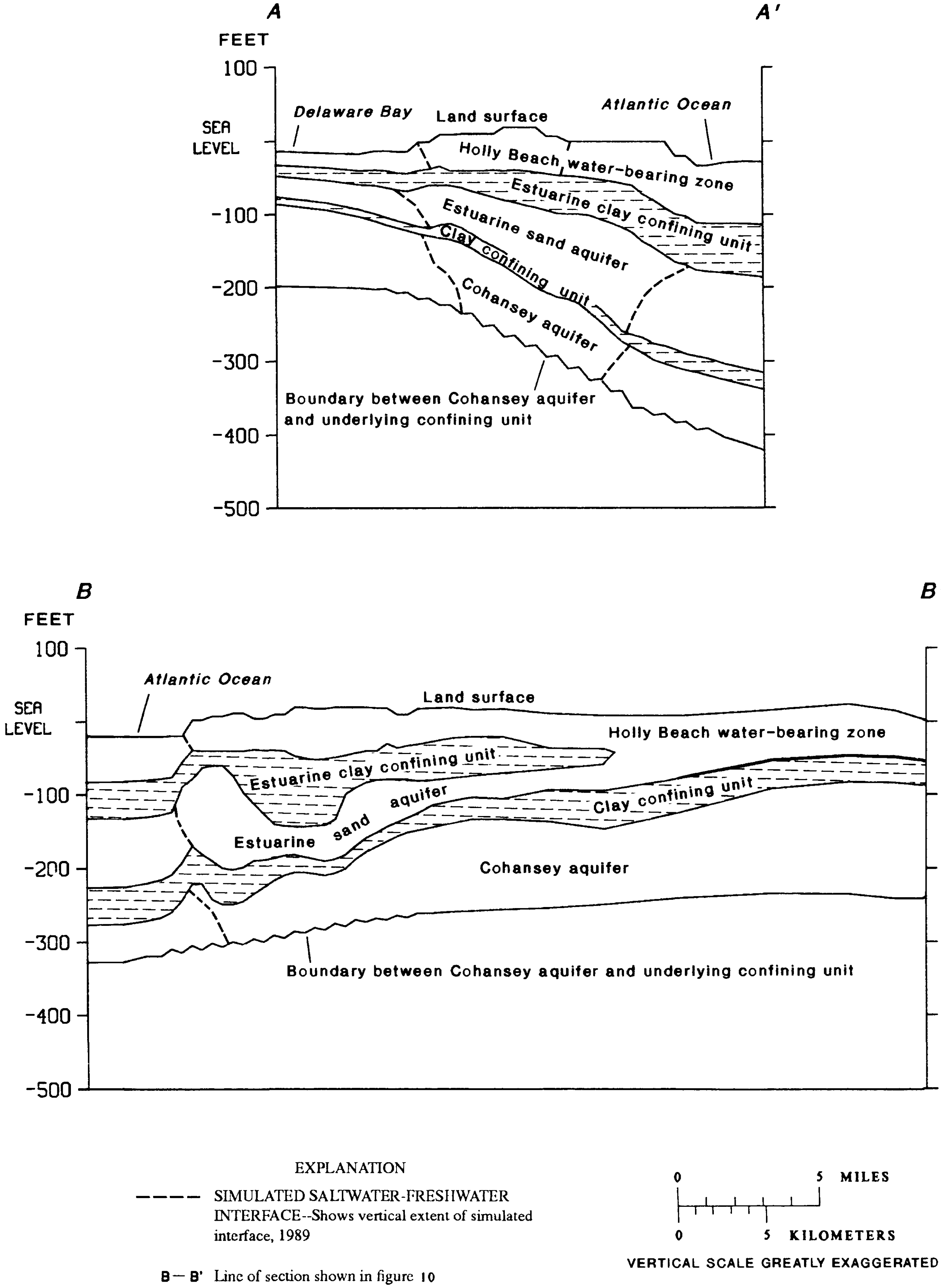


Figure 23.--Simulated hydrogeologic sections A-A' and B-B' through Rio Grande and Cape May City for 1989.

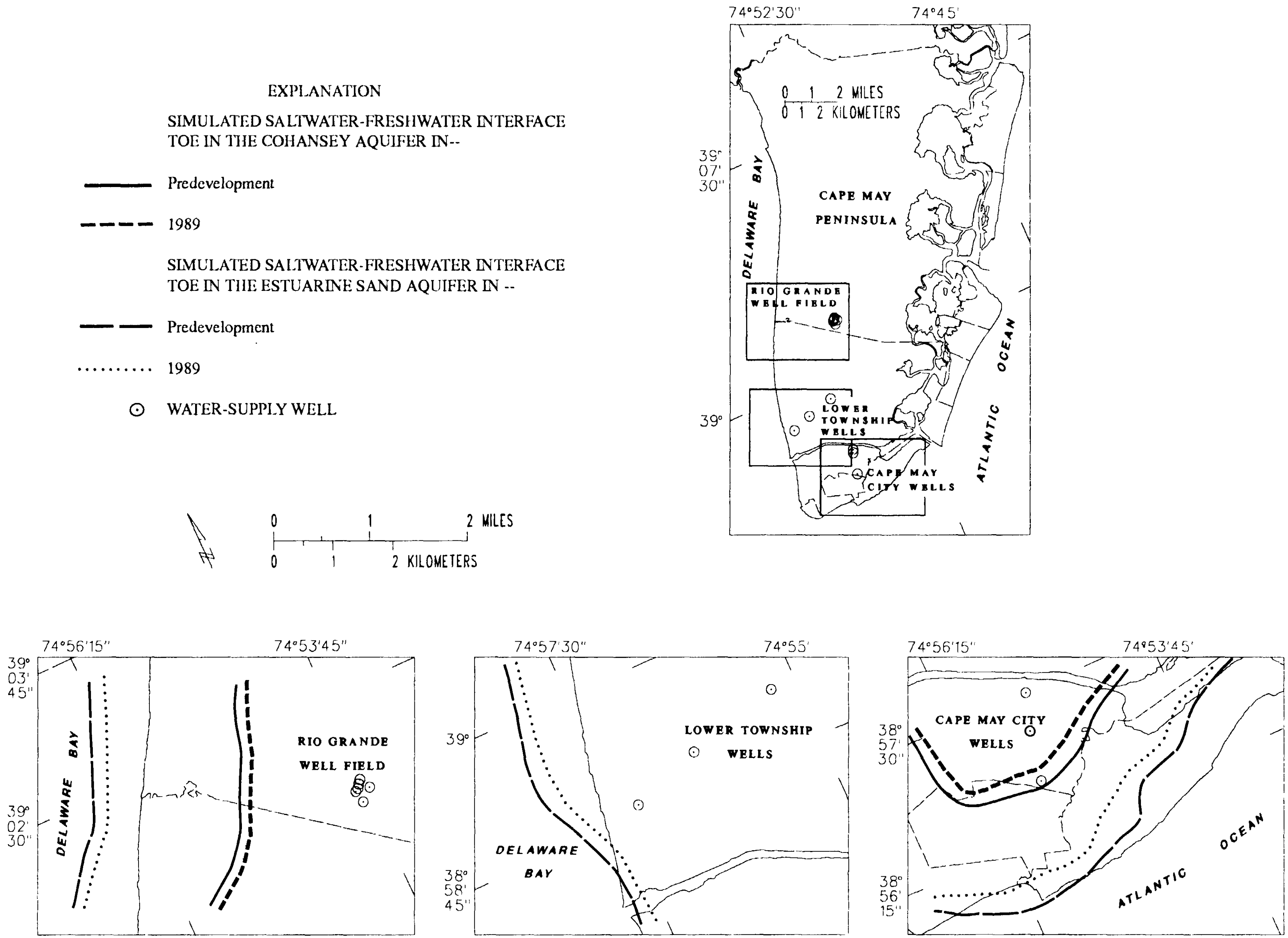


Figure 24.--Simulated positions of the saltwater-freshwater interface toe for predevelopment conditions and 1989 in the Cohansey and estuarine sand aquifers.

Table 8.--Examples of movement of the saltwater-freshwater interface toe from predevelopment conditions through 1989

[Movement to ± 50 ft of value shown]

	Greatest advance toward:	Movement from predevelopment conditions to 1989
Estuarine sand aquifer	Rio Grande	630
	Lower Township	820
	Cape May City	1,500
Cohansey aquifer	Rio Grande	660
	Cape May City	690

The model approximates the interface as an abrupt (sharp) transition from freshwater to saltwater. In reality, the interface is a gradual transition that, on the basis of lines of equal chloride concentration interpreted from results of analyses of well water in Cape May County, probably is several thousand feet wide. Model predictions must be evaluated with the understanding that saline ground water is advancing faster in front of the simulated interface, where chloride concentrations are low, than at the simulated interface, where chloride concentrations are high. Consequently, the model yields much smaller estimates of interface movement than estimates made from dilute chloride concentrations measured at the front of the transition zone.

Another factor affecting the accuracy of predictive results is the accuracy of the data used for calibrating the model. For example, measured water levels used for comparison with simulated hydraulic heads can be inaccurate by 5 ft or more. In addition, the values of aquifer properties derived through the calibration process are not unique. With a different set of properties (and simulation parameters), a different model solution would have been reached. The implications of an different calibration are unknown.

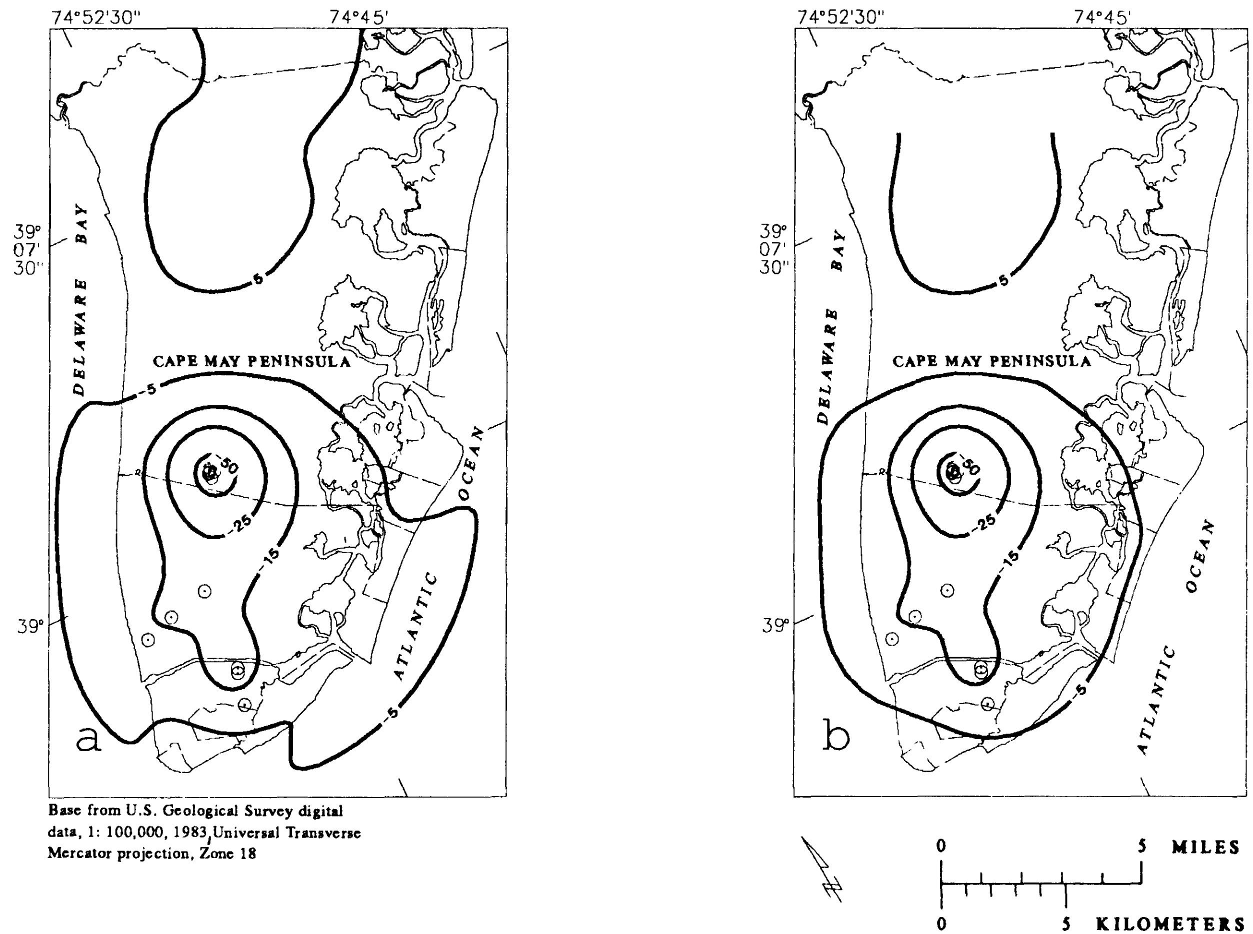
For each of the management scenarios described below, the calibrated 1989 transient model was used to predict shallow aquifer system behavior through 2049. Scenarios 1, 2, and 4 consist of two pumping periods of 30 years each, whereas scenarios 3 and 5 consist of six pumping periods of 10 years each. (Because the latter two scenarios involve increasing withdrawals, gradual increases over 10-year periods were chosen.) All pumping periods include a constant time step size of 1 year to allow for accurate tracking of the saltwater-freshwater interface. Recharge to the aquifer system is assumed to be constant through the planning period.

The hydrogeologic setting of the Cape May peninsula acts to restrict the number of reasonable scenarios that need to be explored for shallow ground-water-system development, because the practical location for wells is where water levels are highest and the saltwater-freshwater interface is furthest away. Wells cannot realistically be located in the extreme southern or northern parts of the peninsula. Wells located near the peninsula's tip would have saltwater nearby on three sides; at the northern end of the peninsula, there is risk of inducing saltwater recharge from Dennis Creek and the extensive swamps. Hence, the scenarios are restricted to prediction of aquifer system response to (1) withdrawals at various sites along the axis of the peninsula, and (2) withdrawals from different combinations of the three aquifers composing the shallow aquifer system.

Scenario 1: No Change in Current Demand or Withdrawal Location

In the first scenario, the existing (1989) well locations are used and withdrawal rates are set equal to the those used in the last pumping period (1983-88) of the transient simulation. Scenario 1 is, therefore, a "no change" simulation in which withdrawal rates are simply continued into the future, and constitutes a baseline for comparison with the other scenarios.

Simulated hydraulic heads for 2049 for scenario 1 are shown in figure 25. Heads in the Holly Beach water-bearing zone (not shown) are unchanged, whereas heads have declined slightly in the estuarine sand and Cohansey aquifers from 1989 (fig. 17). Landward movement of the simulated saltwater-freshwater



EXPLANATION

—— 5 —— SIMULATED POTENTIOMETIC CONTOUR--Shows altitude of simulated potentiometric surface in 2049. Contour interval 10 and 25 feet. Datum is sea level

⊙ WATER-SUPPLY WELL

Figure 25.--Simulated potentiometric surface, Scenario 1, 2049, in the (a) Cohansey aquifer and (b) estuarine sand aquifer.

interface toe toward the three major well fields during 1989-2049 is shown in figure 26. Little movement of the interface is predicted in the Holly Beach water-bearing zone in this or in any of the other scenarios. Because of the small response in heads and interface movement and the small change in water levels measured during 1960-89, the effects of the scenarios on this aquifer are not discussed further. Similarly, because heads and interface positions in the mainland part of the County generally are also unaffected, they are not discussed further.

For comparative purposes, simulated saltwater-freshwater interface-toe movement toward the well fields during 1989-2049 (table 9) are computed. For scenario 1, movement in the Cohansey aquifer toward Rio Grande is inferred to be approximately 450 ft by 2049. Movement of the interface near Cape May City is estimated to be about 400 ft during the same period. Movement in the estuarine sand aquifer at these two locations are estimated to exceed those in the Cohansey aquifer. Movement toward the Lower Township wells in the estuarine sand aquifer is estimated to be 1,210 ft.

Table 9.--Examples of movement of the saltwater-freshwater interface toe during 1989-2049

[Movement to ± 50 ft of value shown]

	Greatest advance toward:	Scenario 1 (no change in demand)	Scenario 2 (reduced demand)	Scenario 3 (increased demand)	Scenario 4 (aggregated demand)	Scenario 5 (increased and redistributed demand)
Estuarine sand aquifer	Rio Grande	710	400	1,240	2,190	590
	Lower Township	1,210	630	2,800	210	140
	Cape May City	1,030	660	1,270	550	530
Cohansey aquifer	Rio Grande	450	290	630	1,320	200
	Cape May City	400	260	580	180	130

Another way to compare the scenarios is to consider the inflows to, and the corresponding outflows from, the shallow aquifer system, as specified in the ground-water budget. For this scenario, the budget for the peninsula in 2049 (fig. 27) is similar to the budget in 1989. Upward discharge to tidewater and the amount of water released from storage decrease slightly.

Scenario 2: Reduced Demand at 1989 Withdrawal Locations

In this scenario, withdrawals are reduced arbitrarily 25 percent below average 1983-88 amounts to investigate the effect on hydraulic heads and flows, and saltwater-freshwater interface movement. Simulation of this scenario results in a reduction in the extent of the cones of depression at Rio Grande and Cape May City in the estuarine sand and the Cohansey aquifers compared to scenario I (fig. 28). In addition, advancement of the simulated interface toes toward the major well fields since 1989 is less than in scenario 1 (fig. 29 and table 9). The ground-water budget for the peninsula

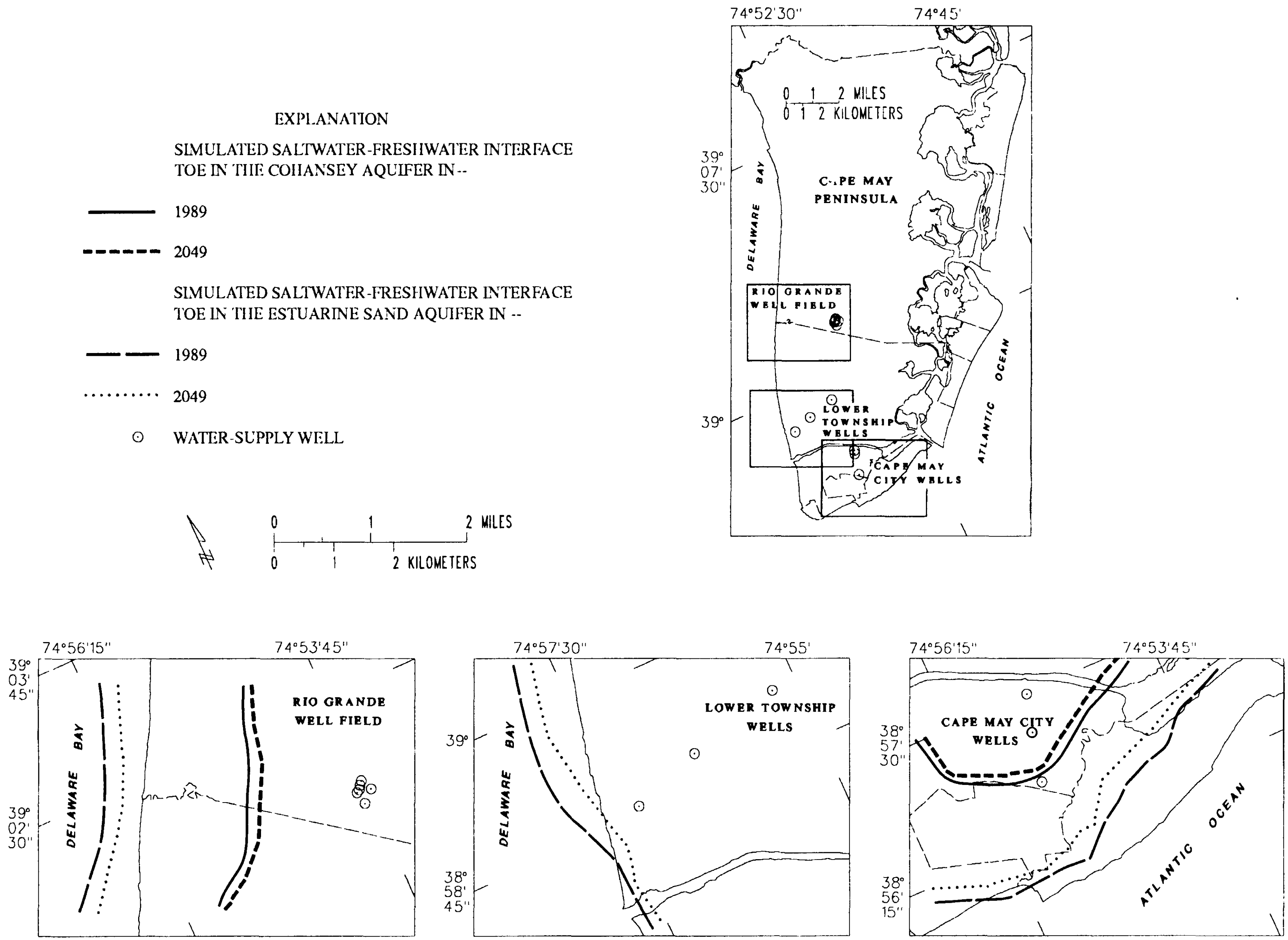
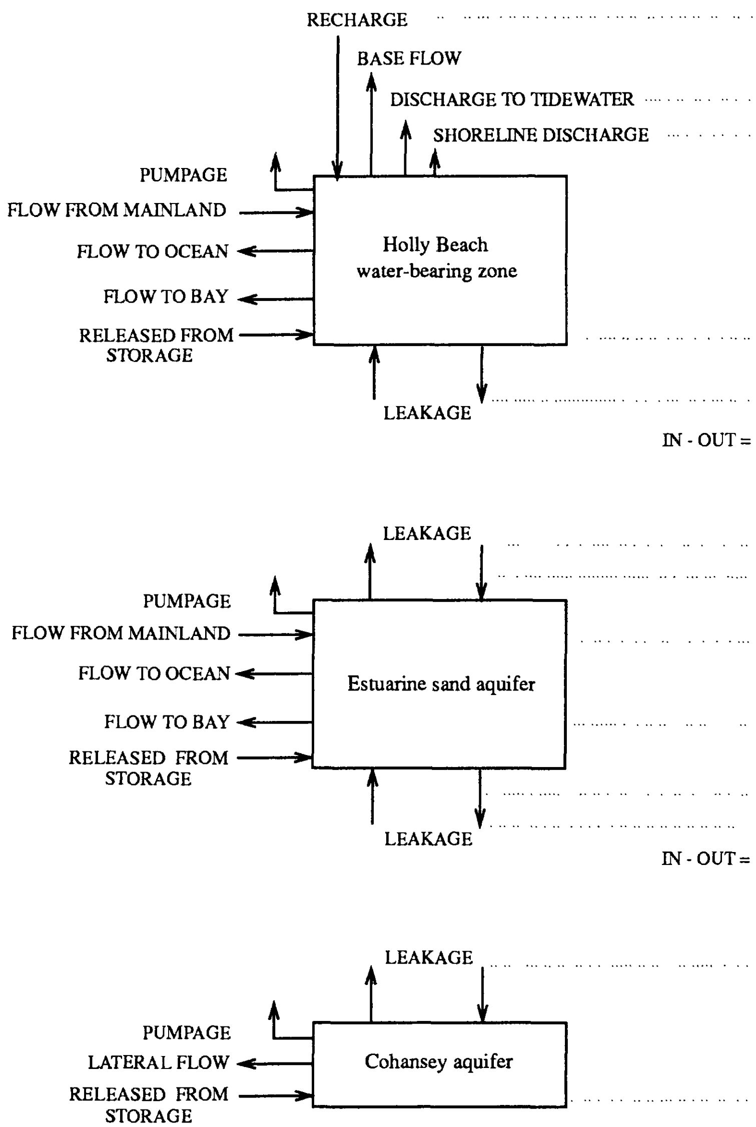


Figure 26.--Simulated positions of the saltwater-freshwater interface toe, 1989 and Scenario 1, 2049, in the Cohansey and estuarine sand aquifers.



		Pumping scenario				
	1989	1	2	3	4	5
	76.2	76.2	76.2	76.2	76.2	76.2
	-6.8	-6.8	-6.8	-6.8	-6.8	-5.5
	-26.8	-25.4	-26.6	-22.5	-24.9	-21.2
	-2.2	-2.2	-2.2	-2.2	-2.2	-2.2
	-.1	-.1	-.1	-.2	0.	0.
	2.0	2.0	2.0	2.0	2.0	2.1
	-9.6	-9.5	-9.4	-9.6	-9.4	-9.5
	-26.8	-26.7	-26.8	-26.4	-26.8	-26.9
	2.2	.8	.2	2.4	.9	4.1
	.1	.1	.2	.1	.1	0.
	-6.9	-7.1	-5.6	-11.6	-7.8	-15.6
IN - OUT =	1.3	1.3	1.1	1.4	1.3	1.5

	1989	1	2	3	4	5
	6.9	7.1	5.6	11.6	7.8	15.6
	-.3	-.2	-.3	-.2	-.2	0.
	-.6	-.6	-.5	-1.0	-8.9	0.
	.0	.0	.0	.0	.0	.4
	.6	.6	.4	1.0	.3	.8
	.5	.5	.3	1.2	.4	.2
	.5	.7	.2	1.6	.4	.6
	.4	.4	.4	.5	2.2	.2
	-8.3	-8.5	-6.3	-15.0	-2.1	-18.0
IN - OUT =	-.3	0.	-.2	-.3	-.1	-.2

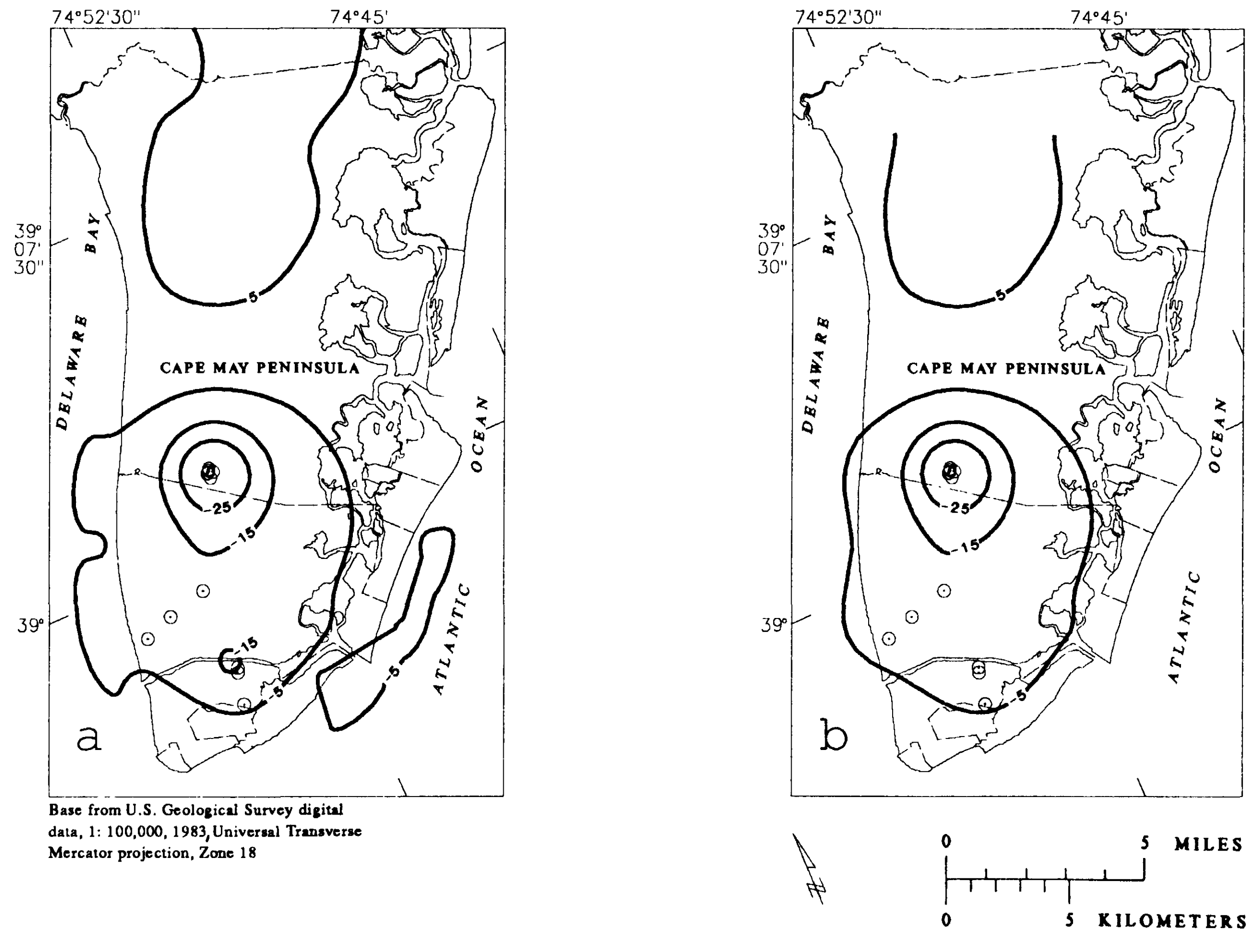
	1989	1	2	3	4	5
	8.3	8.5	6.3	15.0	2.1	18.0
	-.4	-.4	-.4	-.5	-2.2	-.2
	-8.5	-8.5	-6.4	-15.0	-.4	-18.6
	0.	0.	0.	.1	0.	.3
	.5	.5	.2	.4	.4	.6
IN - OUT =	-.1	.1	-.3	0.	-.1	.1

EXPLANATION

→ INFLOWS AND OUTFLOWS OF WATER--In cubic feet per second

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.

Figure 27.--Simulated ground-water budgets for the peninsula for 1989 and 2049.



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

EXPLANATION

—— 5 —— SIMULATED POTENTIOMETIC CONTOUR--Shows altitude of simulated potentiometric surface in 2049. Contour interval 10 feet. Datum is sea level

⊙ WATER-SUPPLY WELL

Figure 28.--Simulated potentiometric surface, Scenario 2, 2049, in the (a) Cohansey aquifer and (b) estuarine sand aquifer.

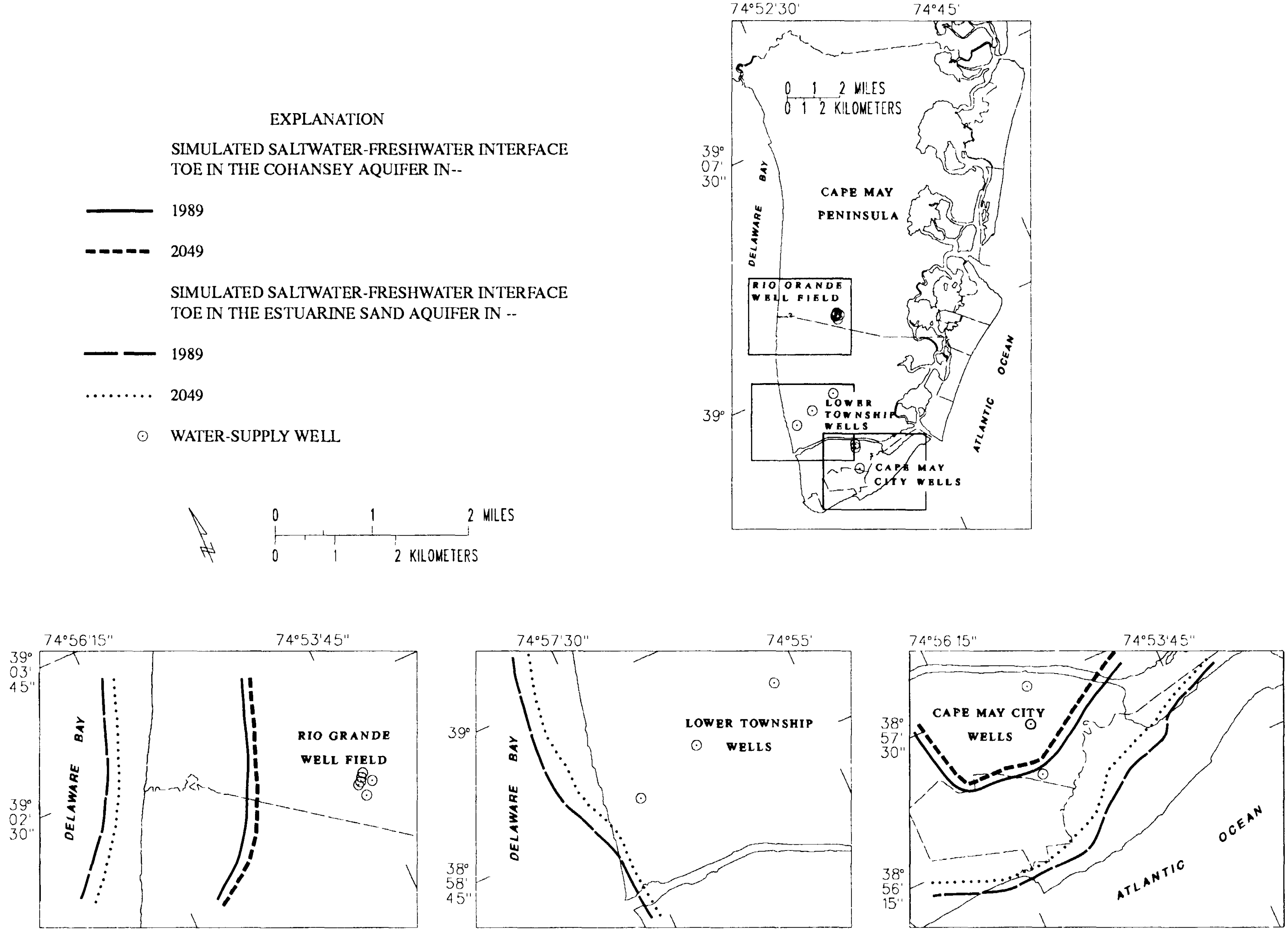


Figure 29.--Simulated positions of the saltwater-freshwater inteface toe, 1989 and Scenario 2, 2049, in the Cohansey and estuarine sand aquifers.

in 2049 (fig. 27) indicates an increase in discharge to tidewater and a decrease in downward leakage through the confining units (to supply the wells screened in the Cohansey aquifer) compared to the baseline scenario.

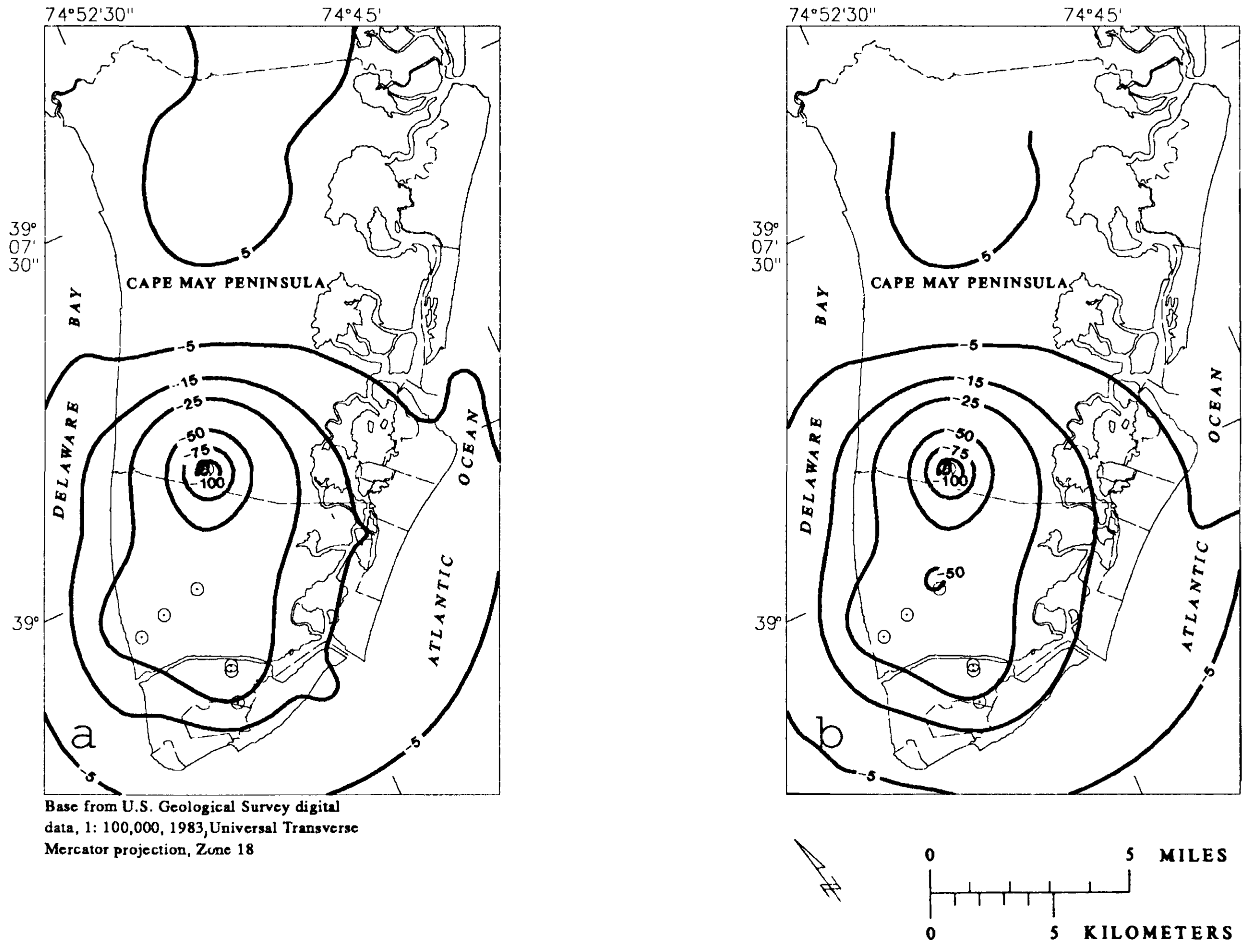
Scenario 3: Increased Demand

This scenario of increased withdbawals is based on projected increases in dwelling-unit construction and sewer capacity for the City of Cape May, City of Wildwood, and Township of Lower over the planning period (Elwood Jarmer, Cape May County Planning Board, written commun., 1989). Only public-supply withdrawals of the last model pumping period (1983-88) are increased, by a percentage equal to the larger of the projected percentage increases in dwelling-unit construction or sewer capacity through 2019. Increases in withdrawals for the period from 2019 through 2049 were derived in a similar fashion through use of maximum-growth estimates of these two criteria. Withdrawals for other purposes continue at 1983-88 rates. Percentage increases for the entire planning period varied by time and township; for example, the smallest increase (21 percent) is for Wildwood from 1989-2019, whereas the largest increase (90 percent) is for Lower Township from 2019-2049.

By 2019 (not shown), the extent of the two main cones of depression in the estuarine sand and Cohansey aquifers are greater than those simulated in scenario 1 for 2049. Simulated potentiometric surface maps for 2049 are shown in figure 30. A comparison of the saltwater-freshwater interface-toe positions for scenarios 1 and 3 shows more landward movement in the confined aquifers toward the Rio Grande well field for scenario 3 (fig. 31 and table 9). Near the Lower Township wells, interface movement for scenario 3 more than doubles in the estuarine sand aquifer. Near Cape May City, movement of the interface in both aquifers is less affected by the increase in withdrawals. The ground-water budget for the peninsula in 2049 for scenario 3 (fig. 27) shows a reduction in upward discharge to tidewater, an increase in the amount of water released from storage, and increased downward leakage through the confining units compared with scenario 1. Leakage travel times at the major withdrawal centers through the two confining units calculated from simulated leakage rates (not shown and which vary by unit and center), are generally cut by half compared to scenario 1 (which are the same as for 1989).

Scenario 4: Aggregated Demand

Scenario 4 was designed to investigate the effect of aggregating the public-supply withdrawals of City of Cape May, City of Wildwood, and Township of Lower at Rio Grande well field and shifting the withdrawals from the Cohansey aquifer to the less-used estuarine sand aquifer. Thus, the purpose is to alleviate the pumping stress on hydraulic head in the southern part of the peninsula, at the expense of an increase in the extent of the Rio Grande cone of depression. Compared to scenario 1, heads in the estuarine sand and Cohansey aquifers near the tip of the peninsula recover from 5 to 15 ft with the cessation of pumping of the Cape May City and Lower Township wells (fig. 32). The simulated saltwater-freshwater interface-toe movement almost tripled in both confined aquifers toward Rio Grande (fig. 33 and table 9). Movement in this area for this scenario was the greatest of all the scenarios, but corresponding movement near Cape May City and Lower Township were among the smallest. The ground-water budget for the peninsula in 2049 (fig. 27) shows that upward leakage



EXPLANATION

— 5 — SIMULATED POTENTIOMETIC CONTOUR--Shows altitude of simulated potentiometric surface in 2049. Contour interval 10 and 25 feet. Datum is sea level

⊙ WATER-SUPPLY WELL

Figure 30.--Simulated potentiometric surface, Scenario 3, 2049, in the (a) Cohansey aquifer and (b) estuarine sand aquifer.

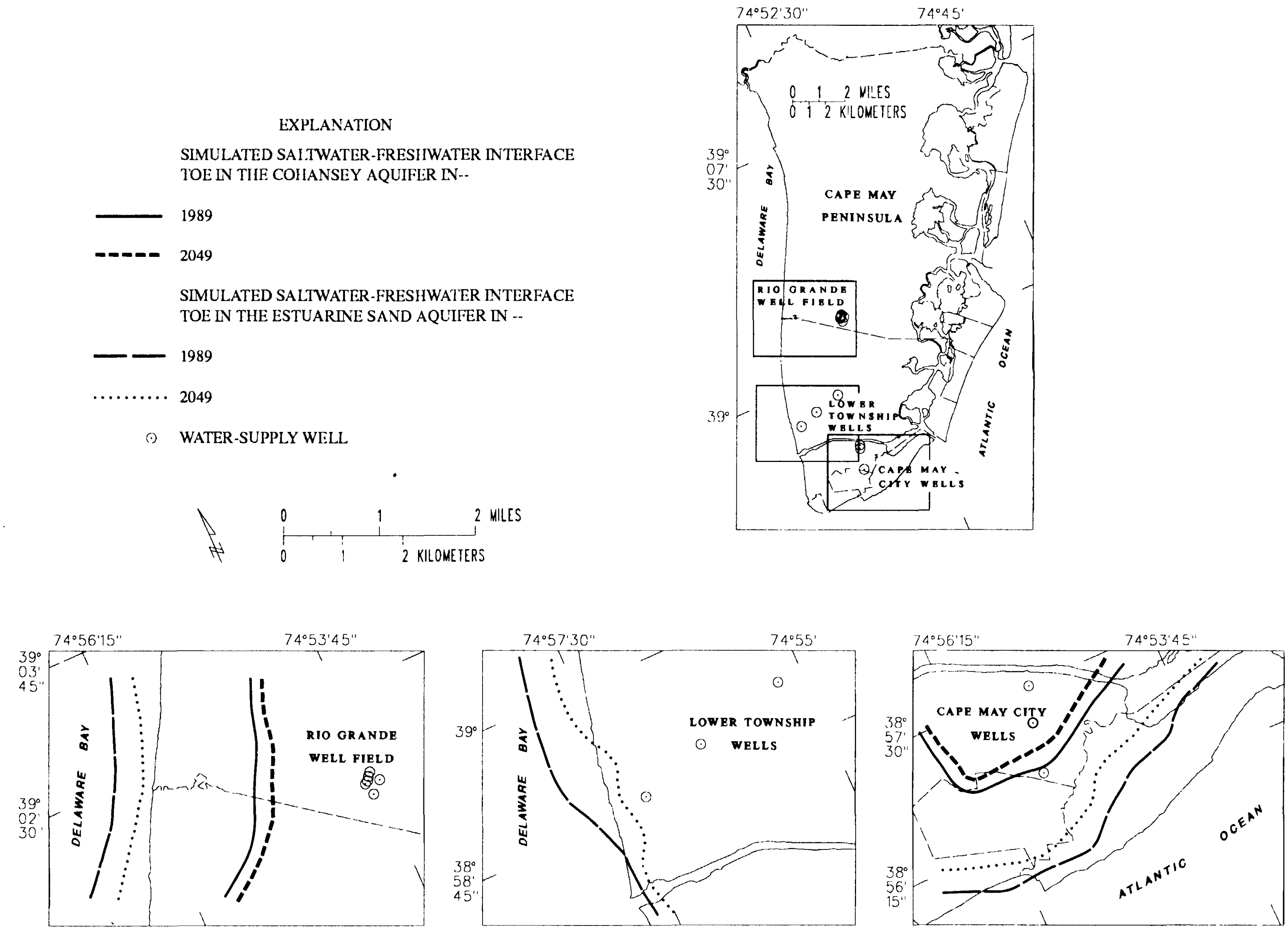


Figure 31.--Simulated positions of the saltwater-freshwater interface toe, 1989 and Scenario 3, 2049, in the Cohansey and estuarine sand aquifers.

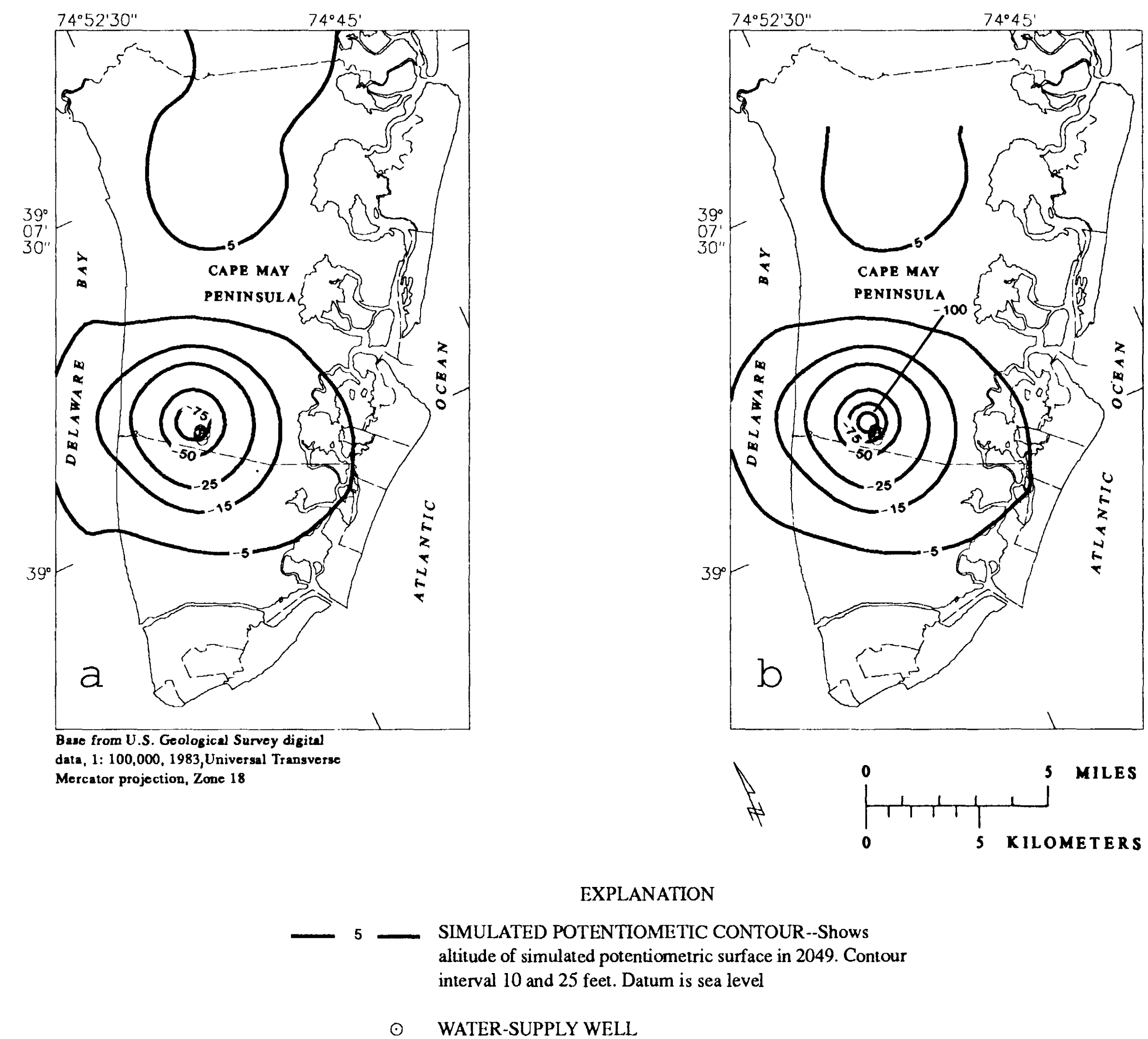


Figure 32.--Simulated potentiometric surface, Scenario 4, 2049, in the (a) Cohansey aquifer and (b) estuarine sand aquifer.

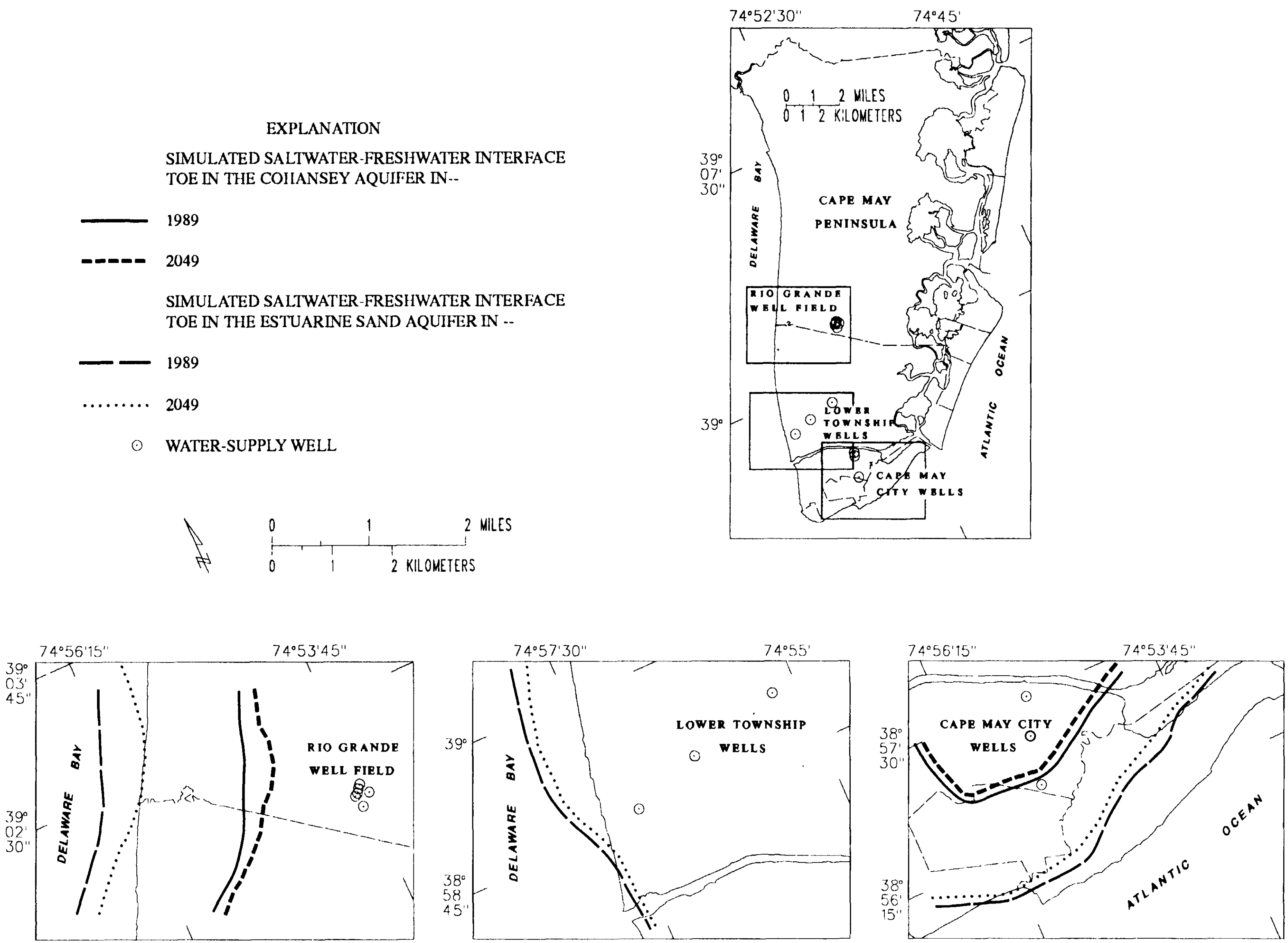


Figure 33.--Simulated positions of the saltwater-freshwater interface toe, 1989 and Scenario 4, 2049, in the Cohansey and estuarine sand aquifers.

from the Cohansey aquifer to the estuarine sand aquifer increases, whereas downward leakage between the two aquifers decreases.

Scenario 5: Increased and Redistributed Demand

This scenario was designed to investigate the effect of water-supply development of the peninsula's shallow aquifers in a redistributed withdrawal system. Percentage growth withdrawal estimates from scenario 3 are used, which are further augmented by those projected for the Cape May Court House Water District. Public-supply withdrawals are made at the existing Rio Grande well field (withdrawals at the Cape May City well field, Lower Township wells, and the injection at Wildwood ceases) and two arbitrarily chosen sites far from saltwater encroachment along the high in the water table that follows with the peninsula's longitudinal axis (fig. 34). The new sites are near Burleigh and just north of Cape May Court House.

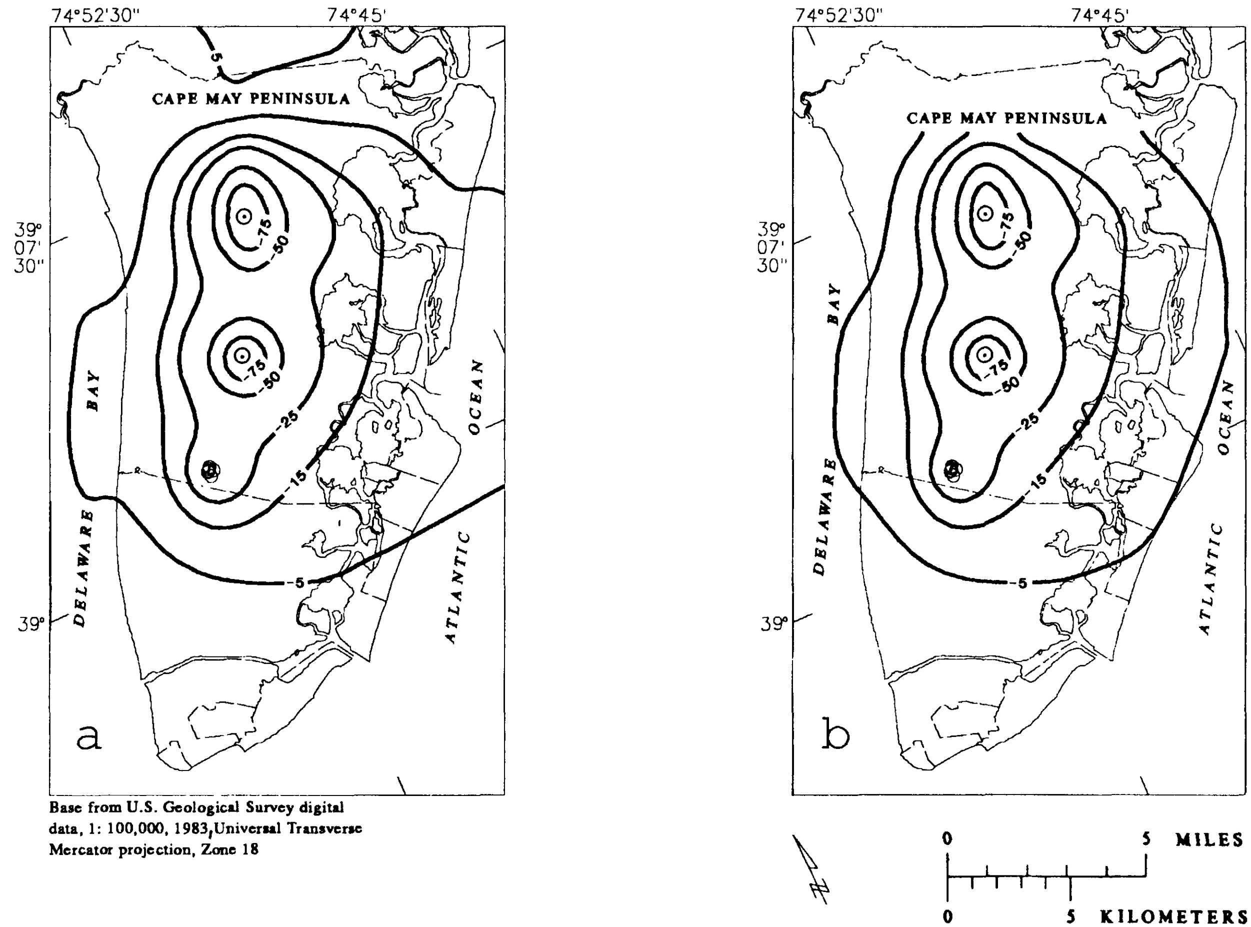
The withdrawals, made from the Cohansey aquifer at a ratio of 1:2:3 from Rio Grande, Burleigh, and Cape May Court House, respectively, cause three cones of depression to develop. Saltwater-freshwater interface-toe movement (fig. 35 and table 9) is reduced by more than half toward Cape May City and Lower Township wells and is decreased toward Rio Grande wells from that in the baseline scenario. The ground-water budget for the peninsula in 2049 (fig. 27) shows the greatest decrease in surficial discharge than any scenario, with reductions in both base flow and discharge to tidewater. Scenario 5 contains the greatest downward leakage in response to the highest withdrawals. Freshwater storage in aquifers also decreases. Leakage travel times in the southern part of the peninsula across the confining units were expectedly the longest of all the scenarios.

Comparison of Results of Predictive Simulations

Simulated hydraulic-head distributions, ground-water flows, and movement of the saltwater-freshwater interface can be evaluated as a means of comparing the results of the ground-water-management plans. Changes in head over the 60-year planning period are greatest for the scenarios involving increased or aggregated withdrawals; these changes occur in the confined aquifers.

Comparison of the ground-water budgets for the peninsula in 2049 for each scenario (fig. 27) shows that increased withdrawal results in reduced upward discharge to the peninsula's tidewater areas; discharges to other surface-water bodies are affected less. These natural discharges support hydrologic conditions (that is, water levels above sea level) that impede encroachment of saltwater in the aquifers. To supply the source water to wells, downward leakage increases, lateral inflow increases, and aquifer storage decreases. Ground-water withdrawals in 1989 comprise about 12 percent of the peninsula's total recharge of 78 ft^3/s. Withdrawals in scenario 3 are about 21 percent of this total recharge and scenario 5 withdrawals are almost 25 percent (19 ft^3/s) of total recharge.

Movement of the saltwater-freshwater interface toe from 1989 through 2049 toward the major well fields for all the scenarios is summarized in table 9. Although scenario 5 results in the smallest interface movements, Scenario 2,



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

EXPLANATION

— 5 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated potentiometric surface in 2049. Contour interval 10 and 25 feet. Datum is sea level

⊙ WATER-SUPPLY WELL

Figure 34.--Simulated potentiometric surface, Scenario 5, 2049, in the (a) Cohansey aquifer and (b) estuarine sand aquifer.

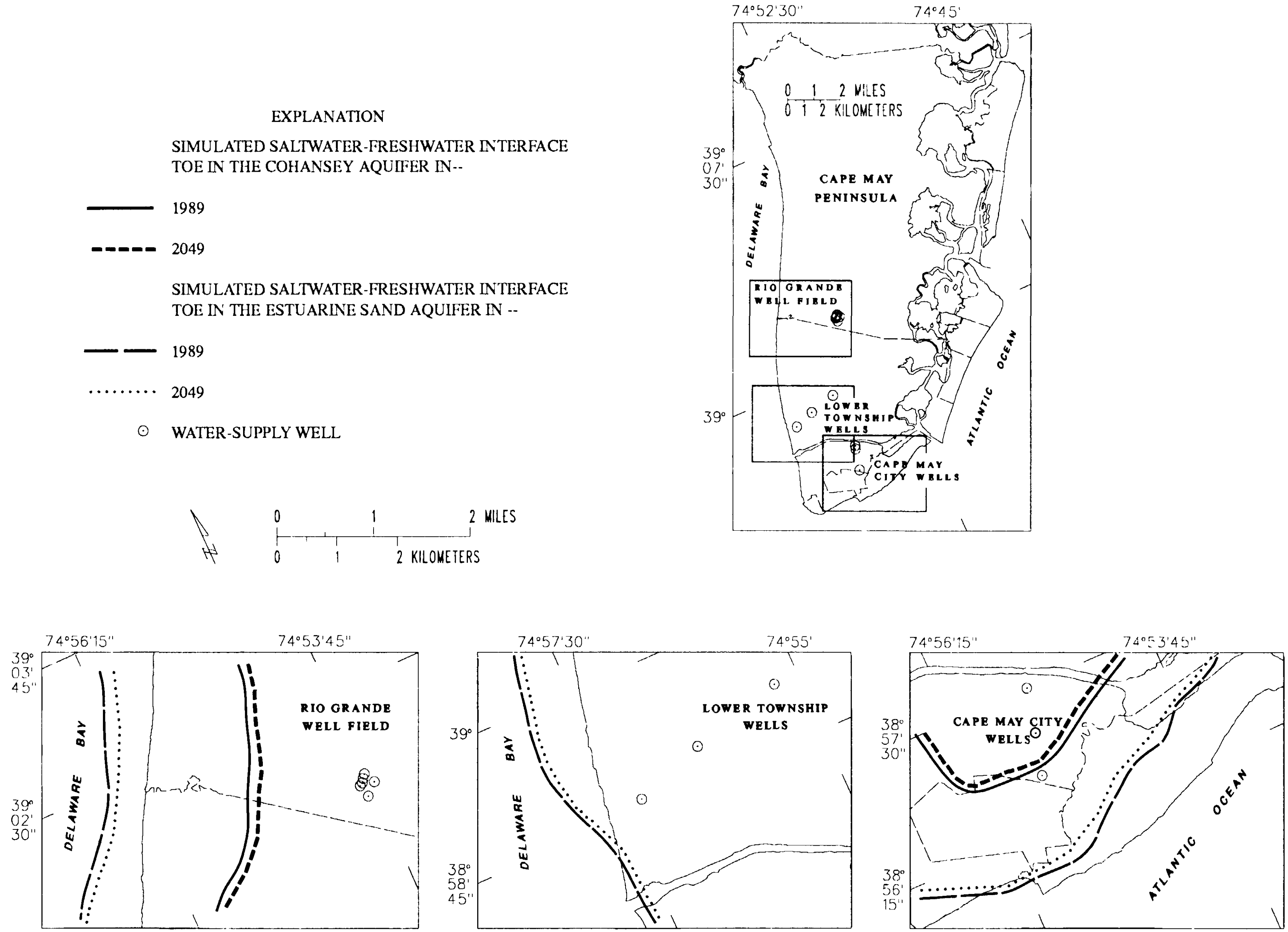


Figure 35.--Simulated positions of the saltwater-freshwater interface toe, 1989 and Scenario 5, 2049, in the Cohansey and estuarine sand aquifers.

in which the least overall pumping stress is placed on the shallow aquifer system, is associated with the smallest combined effect on interface movement, ground-water heads, and flows. Landward movement of the interface is expected to continue, regardless of the withdrawal scheme, as a result of the current water-level distributions in the aquifers.

SUMMARY AND CONCLUSIONS

Increasing withdrawals of ground water from the shallow aquifer system on the peninsula of Cape May County, New Jersey, has led to a regional lowering of ground-water levels, encroachment of saltwater into public-supply wells, and subsequent abandonment and sealing of formerly productive freshwater wells in those areas. A study was undertaken to predict the movement of the saltwater-freshwater interface in response to future ground-water-management plans. A computer model of the shallow aquifer system was constructed to analyze the flow system from the predevelopment through the present (1989). The model then was used to predict the hydrologic effects of five scenarios for ground-water withdrawals through the year 2049.

The three aquifers in the shallow aquifer system of the peninsular part of Cape May County are, in order of increasing depth, the Holly Beach water-bearing zone, the estuarine sand aquifer, and the Cohansey aquifer. The aquifers are separated by leaky confining units, but in the northern, mainland part of the County, confining material is discontinuous. The Holly Beach water-bearing zone is considered an unconfined aquifer; precipitation falling on the land surface percolates through the unsaturated zone and recharges the water table. The estuarine sand and Cohansey aquifers are overlain by confining units.

Ground-water flow from the northern part of the County to the peninsula accounts for only a small percentage of the peninsular ground-water budget; the amount of ground water beneath the peninsula is limited by the amount of precipitation that falls directly on it. Under predevelopment conditions, most of the water that recharged the shallow aquifer system remained in the Holly Beach water-bearing zone. Only a small fraction of the water leaked downward to the estuarine sand aquifer, and only part of that amount penetrated to the Cohansey aquifer. The high transmissivity of the Holly Beach water-bearing zone permits water to flow easily to the shoreline; the low vertical hydraulic conductivity of the underlying confining unit restricts downward leakage to the confined aquifers.

Natural discharge from the ground-water system supports various fresh- and brackish-water ecological communities and helps balance the position of the saltwater-freshwater interface. In inland areas, ground water discharges to streams and freshwater wetlands. Nearshore, ground water discharges primarily to tidal wetlands, the bay, and the ocean; a small amount mixes with saline ground water and is lost from the freshwater system. Withdrawal of ground water causes a decrease in natural discharge, a lowering of water levels, and an attendant landward movement of the interface.

Increasing residential and seasonal tourist populations since early in this century have placed ever-greater demands on the peninsula's ground-water resources. Ground-water levels have declined rapidly in response to pumping, whereas the attendant saltwater-freshwater interface movement has occurred more slowly, as freshwater is displaced by saltwater. Withdrawals (9.2 ft^3/s) include only small amounts of water from the Holly Beach water-bearing zone; some domestic wells located near the shore have been affected by saltwater (chloride) contamination. Large consumptive withdrawals from the two confined aquifers at the Rio Grande, Cape May City, and Lower Township well fields have caused significant drawdown in water levels that extends offshore, inducing vertical leakage downward to these aquifers, and landward migration of salty ground water toward these well fields. Elevated and rising chloride concentrations in well water are evident near these locations.

The shallow aquifer system was simulated to improve understanding of the hydrology of, and saltwater encroachment in, Cape May. This was accomplished by using a quasi-three-dimensional sharp-interface ground-water computer model. The model is a discrete representation of the subsurface geometry, boundaries, and water-transmitting characteristics of the aquifer system, and simulates the flow of freshwater and saltwater that results from changing hydrologic conditions within the system. Predevelopment and present-day (1989) ground-water levels, flows, and the position and movement of the saltwater-freshwater interface were simulated for the shallow aquifer system.

Simulated hydraulic heads in all three aquifers were calibrated to measured water levels from wells. Generally, the difference between simulated heads and measured water levels was less than 5 ft. The simulated position of the saltwater-freshwater interface also was compared to available water chloride-concentration data from wells screened in the aquifers. The simulated interface moved inland during the development period by as much as 1,500 ft in the estuarine sand aquifer and 690 ft in the Cohansey aquifer toward the Cape May City wells. Movement toward the other two major withdrawal centers (the Rio Grande and Lower Township wells) in the same aquifers was less than 850 ft.

The model approximates the interface as an abrupt (sharp) transition from freshwater to saltwater. In reality, the interface is a gradual transition that, on the basis of lines of equal chloride concentration interpreted from results of analyses of well water in Cape May County, probably is several thousand feet wide. Model predictions must be evaluated with the understanding that saline ground water is advancing faster in front of the simulated interface, where chloride concentrations are low, than at the simulated interface, where chloride concentrations are high. Consequently, the model yields much smaller estimates of interface movement than estimates made from dilute chloride concentrations measured at the front of the transition zone.

On the basis of the simulated ground-water budget for the peninsula in 1989, average consumptive pumpage (9.2 ft^3/s, or 12 percent of the total recharge to the peninsula) caused a decrease of 3.8 ft^3/s in discharge to streams and tidewater from predevelopment conditions, suggesting that pumpage from the confined aquifers captures some of the discharge to the peninsula's surface-water bodies. Vertical leakage to the confined aquifers increased from 1.0 ft^3/s under predevelopment conditions (only 1 percent of the total peninsular recharge) to 6.9 ft^3/s under present conditions (almost 9 percent).

Results of these simulations indicate that (1) the shallow aquifer system on the Cape May peninsula is recharged primarily by precipitation (ground-water inflow from the northern part of the County is only 3 percent of the total recharge); (2) water-supply development of the confined aquifers has caused extensive drawdown in water levels, enabling saltwater encroachment; (3) these withdrawals have reduced discharge to surface-water bodies, increased downward leakage to the confined aquifers, increased lateral ground-water inflow to the peninsula, and caused displacement of freshwater from aquifer storage as the saltwater-freshwater interface advances landward; and (4) the interface in the Cohansey aquifer is onshore near water-supply wells in Cape May City and nearshore west of the Lower Township and Rio Grande wells.

The model was used to predict the hydrologic consequences of five hypothetical ground-water development scenarios for the period 1989-2049. The scenarios included projected water demand as well as variations in withdrawal locations. The simulation for each scenario estimates the change in ground-water levels, flows, and the movement of the saltwater-freshwater interface toward the major well fields. These results provide the hydrologic information necessary to design a water-supply-development strategy for the planning period that maintains the needed potable water and a monitoring program that ensures early warning of impending saltwater encroachment, allowing sufficient time for development of an alternative supply.

In the baseline scenario 1, withdrawal rates were assumed to remain at the average pumping rate for 1983-88 (9.2 ft^3/s). Withdrawal locations were left unchanged. Simulation results indicated that, during the planning period, the saltwater-freshwater interface moved toward the Lower Township wells 1,210 ft in the estuarine sand aquifer. The interface moved toward the Cape May City water-supply wells 1,030 and 400 ft in the estuarine sand and Cohansey aquifers, respectively. Movement toward the Rio Grande well field was less than 750 ft in the confined aquifers. Interface movement in the unconfined Holly Beach water-bearing zone, as for the other scenarios and during the development period, was negligible. The ground-water budget for the peninsula in 2049 was similar to the simulated budget in 1989, largely because the pumping rates did not change.

In scenario 2, ground-water withdrawals were reduced by 25 percent at the same locations. The extents of the local cones of depression at the major well fields were diminished slightly. Saltwater-freshwater interface movement in the confined aquifers toward the well fields decreased by an average of 40 percent from scenario 1. The ground-water budget for the peninsula in 2049 indicates more discharge to tidewater and less downward leakage through the confining units occurred than in scenario 1.

In scenario 3, public-supply withdrawals were increased in accordance with projected increases in County development. Withdrawals were estimated to increase by an average of more than 80 percent in Cape May City, in Lower Township, and in Wildwood. Withdrawal locations remained the same. This scenario resulted in the greatest and most extensive drawdown in water levels; movement of the saltwater-freshwater interface in the confined aquifers toward the major well fields also was the greatest, increasing by approximately 60 percent over scenario 1. The greatest movement (2,800 ft) was toward the Lower Township wells in the estuarine sand aquifer. Interface movement toward the Rio Grande well field was 1,240 and 630 ft in the estuarine sand and Cohansey aquifers, respectively; movement toward the Cape May City wells was 1,270 and 580 ft in these two aquifers, respectively. The ground-water budget for the peninsula in 2049 shows a decrease in discharge to tidewater, an increase in the amount of freshwater released from storage, and increased downward leakage through the confining units (65 percent greater than in scenario 1).

In scenario 4, current (1983-88) public-supply withdrawals were aggregated at the Rio Grande well field and made from the estuarine sand aquifer. The purpose of this scenario was to examine the effects of ceased withdrawals in the southern part of the peninsula (where saltwater encroachment is greatest) and aggregation of withdrawals at a central inland location. Drawdown in water levels decreased significantly in the south, but increased at the Rio Grande well field. Saltwater-freshwater interface movement in the confined aquifers toward the Cape May City and Lower Township wells decreased approximately 60 percent from scenario 1, whereas movement toward Rio Grande increased 300 percent, resulting in interface movement of 2,190 and 1,320 ft in the estuarine sand and Cohansey aquifers, respectively. Measured chloride-concentration data from well water indicate that the potable water interface currently is more than 2 mi from the well field. The ground-water budget for the peninsula in 2049 shows that downward leakage decreased and upward leakage into the estuarine sand aquifer increased compared to scenario 1.

In scenario 5, projections of increased public-supply withdrawals for Middle Township were added to projections for the Rio Grande well field used in scenario 3. Projections for Cape May City and Lower Township were the same as in that scenario. Withdrawals were redistributed northward to three sites in Middle Township along the axis of the peninsula made from the Cohansey aquifer. The Rio Grande well field was the southernmost and least pumped of the sites; the second site was at Burleigh, and the third was at Cape May Court House. At the end of the planning period, total withdrawals were projected to increase by 100 percent (equal to almost one-fourth of the total recharge to the peninsula) from 1989 rates.

Simulation of this scenario created a substantial reduction in drawdown in water levels in the southern part of the peninsula in the confined aquifers. Saltwater-freshwater interface movement in the estuarine sand aquifer toward the Lower Township wells was 140 ft, compared to 1,210 ft in scenario 1. Interface movement in the confined aquifers toward Cape May City was lowered more than 50 percent and toward the Rio Grande well field was lowered more than 25 percent compared to scenario 1. The ground-water budget for the peninsula in 2049 shows the greatest reduction in discharge to streams and tidewater of all the scenarios. The amount of freshwater released from storage and downward leakage to the Cohansey aquifer also were greatest for this scenario. Of the five ground-water-management plans, scenario 5 permitted a large amount of withdrawal combined with negligible interface movement, indicating that redistribution of withdrawals can significantly prolong the water supply in the shallow aquifers of the peninsula.

The greatest movement of the saltwater-freshwater interface in all the scenarios was predicted for the estuarine sand aquifer along the peninsula's southwestern coast, likely because of nearby pumping from the underlying Cohansey aquifer, the high permeability of the estuarine sand aquifer relative to that of the Cohansey aquifer, and the leaky nature of the confining unit (where flow travel times are only a few years) that separates the two aquifers. This saltwater encroachment through the estuarine sand aquifer can affect wells screened in the Cohansey aquifer. The interface will continue to advance toward well fields in the confined aquifers at varying rates. Water quality in areas found to be most susceptible to saltwater contamination under each of the scenarios can be monitored by measuring chloride concentrations in suitably placed observation wells.

Under continued current withdrawals, saltwater encroachment will most likely affect the Cape May City wells. The proximity of the interface to these wells at present and the predicted movement of the saltwater-freshwater interface indicates that they likely will be unsuitable for water supply by the end of the planning period. Saltwater encroachment will affect the Lower Township wells to a lesser degree, for similar reasons. However, saline ground water probably will reach the westernmost well during the planning period. Saltwater contamination of the Rio Grande well field, which is located about 2 mi inland, probably will not occur during the planning period because the current interface position is only at the shore in the estuarine sand aquifer, and possibly even offshore in the Cohansey aquifer.

The analysis of the predictive ground-water-development scenarios also indicates that maintenance of potable public-water supplies would be facilitated by (1) decreasing withdrawals, (2) moving withdrawals farther north on the peninsula and inland toward the centerline of the peninsula, and (or) (3) diverting withdrawals to the water-table aquifer; however, the potential for contamination from human activities also must be considered in this case.

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