HYDROLOGIC FEASIBILITY OF WATER-SUPPLY-DEVELOPMENT ALTERNATIVES IN CAPE MAY COUNTY, NEW JERSEY

By Frederick J. Spitz

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DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U. S. GEOLOGICAL SURVEY

Gordon P. Eaton, *Director*

For additional information write to:

District Chief
U. S. Geological Survey
Mountain View Office Park
810 Bear Tavern Road
Suite 206
West Trenton, NJ 08628

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

Multiply	By	To obtain
inch (in)	0.0254	meter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
inch per year (in/yr)	2.54	centimeter per year
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
square foot per day (ft^2/d)	0.0929	square meter per day
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

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

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

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ABSTRACT

Increasing public-supply withdrawals in Cape May County, New Jersey, associated with increasing residential and seasonal tourist populations have led to regionally lowered ground-water levels, a reversal of ground-water flow directions to onshore, and landward encroachment of saltwater in the shallow aquifer system. The three aquifers composing the shallow system are, in order of increasing depth, the unconfined Holly Beach water-bearing zone and the confined estuarine sand and Cohansey aquifers. The changes to the ground-water system have been greatest in the confined aquifers near the three major well fields on the Cape May peninsula. Formerly productive water-supply wells have been abandoned because of saltwater contamination. Concern about anthropogenic contamination has prevented shifting of withdrawals to the unconfined aquifer. Further development on the peninsula involving increased water demand will exacerbate the current saltwater-encroachment problems.

The purpose of this study was to test the feasibility of possible water-supply-development alternatives by use of predictive ground-water flow simulations. The alternatives involve (1) injection of tertiary-treated wastewater to replenish aquifer storage and create a hydraulic barrier to saltwater encroachment, (2) withdrawal of brackish water in order to create a hydraulic barrier, (3) conjunctive use of ground water and surface water, enabling the reduction of ground-water withdrawals, and (4) redistribution of withdrawals inland to the unconfined aquifer. Results of these simulations can potentially be used in the design of a water-supply-development strategy that preserves supply and a monitoring program that ensures early warning of saltwater encroachment, thereby allowing sufficient time for development of an alternative supply.

The water-supply-development alternatives were evaluated by comparison of results of predictive simulations made with a previously calibrated ground-water flow model of the shallow aquifer system. The quasi-three-dimensional sharp-interface model was calibrated to 1988 annual average hydrologic conditions. The planning period for the predictive simulations is 1989-2049. For the planning period, total public-supply withdrawals were increased 95 percent over average 1983-88 withdrawals. Results of a baseline simulation involving only the increased withdrawals were compared to each of the simulated alternatives, which also include the withdrawals. Hydraulic heads, saltwater-freshwater interface movement, and ground-water flows were compared.

Simulation results indicate that the barrier-injection or barrier-withdrawal scheme could be useful in managing the water supply for a specific location. The conjunctive-use scheme would provide a marginal regional hydrologic benefit. Redistribution of withdrawals appears to be the only regional alternative that would result in recovery of ground-water levels and would substantially slow saltwater encroachment; however, the introduction of anthropogenic contaminants from the land surface to the unconfined aquifer would have to be considered if the redistribution alternative is acted upon.

INTRODUCTION

Cape May County is the southernmost county in New Jersey (fig. 1). Water demand in the county varies seasonally because of the resort-oriented economy. The highest water demand is in the summer. Ground water is the primary source of potable water. Surface-water sources have supplied only a small amount of water because of the few streams, low relief, and porous surficial sediments in the area. The shallow aquifer system is composed of, in order of increasing depth, the unconfined Holly Beach water-bearing zone, the confined estuarine sand aquifer, and the confined Cohansey aquifer (table 1 and fig. 2). From 1926 through 1986, about one-half of the water used in the county for public-supply, commercial, domestic, industrial, and irrigation purposes was supplied by the shallow aquifer system (P.J. Lacombe, U.S. Geological Survey, written commun., 1994). The remainder of the supply came primarily from deeper aquifers.

Increases in the permanent population of the county to 95,000 in 1990, augmented by the summer influx of tourists to approximately 530,000 in 1990, have increased public-supply withdrawals from the shallow aquifer system to more than 6 Mgal/d, excluding domestic use. Withdrawals from the deep aquifers have not increased, mainly because of the high cost of drilling new wells (P.J. Lacombe, U.S. Geological Survey, oral commun., 1994). Public-supply withdrawals from the shallow aquifer system have come mainly from the confined aquifers. These withdrawals have led to a regional decline in water levels in these aquifers in the southern part of the peninsula. The region of lowered water levels is thought to be caused by the merging of two local cones of depression around the Rio Grande well field and the Cape May City wells (fig. 6, farther on). The cones of depression are persistent because more water is being withdrawn from the confined aquifers than is being recharged. Water levels in the unconfined aquifer have changed little as a result of population increases and associated land development.

During the period of increasing population and ground-water withdrawals, water quality has been degraded by increasing ion concentrations resulting from saltwater encroachment. Chloride and sodium concentrations in the water exceed National Secondary Drinking Water Standards established by the U.S. Environmental Protection Agency (1991b) of 250 mg/L and 50 mg/L, respectively. In addition, the change in water quality contributes to changes in ecological communities and deterioration of domestic plumbing and municipal waterworks equipment. Saltwater encroachment occurs when the volume of freshwater discharge from a coastal aquifer system decreases, allowing landward movement of the saltwater-freshwater interface. Saltwater encroachment also includes movement due to tides, seasonal and annual hydrologic conditions, or long-term climatic and sea-level fluctuations.

Public-supply wells in Cape May City and Cape May Point have been abandoned and replaced with new wells drilled farther inland to avoid the advancing salty ground water. These communities have also had to purchase water from other municipalities. Because the county's water supply is finite, particularly on the peninsula, water managers are concerned about when the demand will exceed the capacity. The permanent population of the county is expected to increase by 60 percent and the summer population by 10 percent by 2040 (Roger Tsao, New Jersey Department of Environmental Protection, written commun., 1989). Further development on the peninsula and a corresponding increase in water demand will exacerbate the existing saltwater-encroachment problems. Several alternatives have been proposed for preserving and protecting the freshwater supply of the area. A 1-year simulation study of these proposed alternatives was begun in 1990 by the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers and the N.J. Department of Environmental Protection (NJDEP). The purpose of the study was to evaluate the response of the hydrologic system to ground-water-development strategies that will allow for increased water withdrawal while limiting saltwater encroachment. Examination of the increased freshwater supply and (or) reduced saltwater encroachment from the simulations provides a means for evaluating the alternatives.

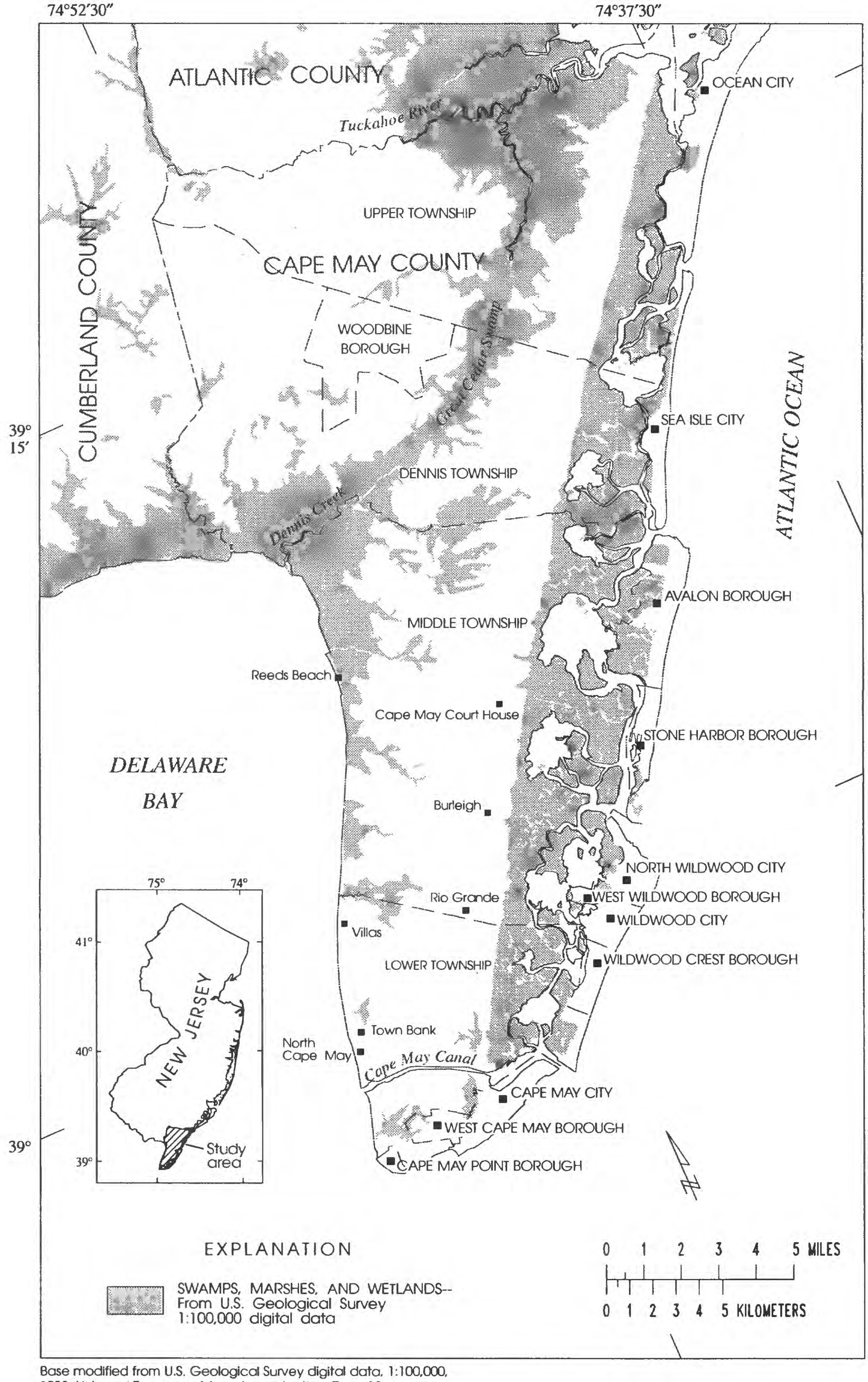

Figure 1. Location of study area.

Table 1. Geologic and hydrogeologic units in the shallow aquifer system in Cape May County, New Jersey

[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="6">Quaternary</td><td rowspan="3">Holocene</td><td>Alluvial deposits</td><td rowspan="7">Holly Beach water-bearing zone</td><td>Alluvial deposits</td><td rowspan="4">Holly Beach water-bearing zone</td></tr>
<tr><td rowspan="2">Beach and dune deposits</td><td>Beach and dune deposits</td></tr>
<tr><td>Intertidal sands</td></tr>
<tr><td rowspan="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="5">Tertiary</td><td rowspan="5">Miocene</td><td>Bridgeton Formation</td><td rowspan="4">Cohansey Sand</td></tr>
<tr><td rowspan="2">Cohansey Sand</td><td>Confining unit</td><td>Confining unit</td></tr>
<tr><td rowspan="2">Cohansey aquifer</td><td rowspan="2">Cohansey aquifer</td></tr>
<tr><td rowspan="2">Kirkwood Formation</td></tr>
<tr><td>Confining unit</td><td>Kirkwood Formation</td><td>Confining unit</td></tr>
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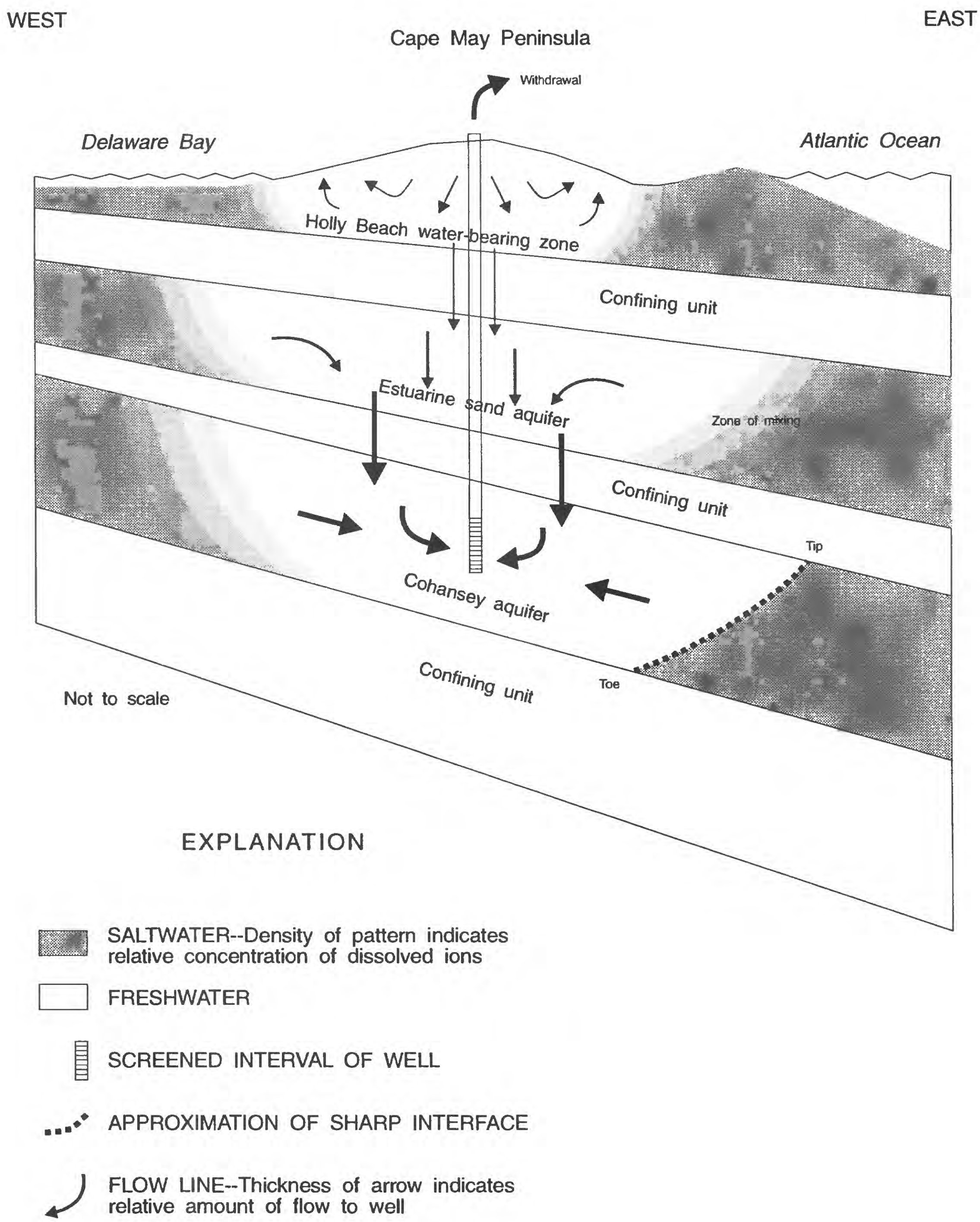


Figure 2. Diagrammatic section of flow in the shallow aquifer system across the Cape May peninsula, New Jersey.

Purpose and Scope

This report describes the results of the simulated water-supply-development alternatives that have been proposed for preserving ground-water supply and protecting ground-water quality from saltwater in the shallow aquifers of Cape May County, New Jersey. The proposed alternatives include (1) use of artificial ground-water recharge to create a hydraulic barrier; (2) withdrawal of brackish ground water, also to create a hydraulic barrier; (3) conjunctive use of ground water and surface water as a periodic supplement to withdrawals; and (4) redistribution of withdrawals. These alternatives were deemed the most hydrologically practical in addressing the water-supply problems of Cape May County. The alternatives were tested individually, but they could be used in combination.

A sharp-interface ground-water flow model of the region, created by Spitz and Barringer (1992), was used to evaluate the effectiveness of the alternatives. Predictive simulations for a 1989-2049 planning period were made that include a projected 100-percent increase in total withdrawals from the shallow aquifer system. Results of the simulations are discussed in terms of the probable hydrologic response with respect to water levels, flows, and saltwater encroachment.

Study Area

Cape May County, which is part of the Coastal Plain Physiographic Province, consists of a low-lying, gently rolling mainland and peninsula covering an area of 263 mi^2 (fig. 1). Great Cedar Swamp separates the peninsula part from the mainland part of the county. The mainland is a nearly level sandy plain with a maximum altitude of approximately 60 ft. The peninsula is an area of low topographic relief consisting of gently rolling sandy hills, tidal salt marshes, and wetlands. Land-surface altitudes range from sea level to more than 20 ft above sea level near the center of the peninsula. The east coast of the county consists of barrier islands that separate the Atlantic Ocean from areally extensive tidal estuaries. The west and south coasts abut the Delaware Bay. Most of the streams in the county are tidal in their lower reaches. The county has a temperate climate. Annual precipitation ranges from 41 to 45 in/yr (R.D. Schopp, U.S. Geological Survey, written commun., 1987).

Acknowledgments

Data on wastewater effluents and requirements for minimum surface-water flows were obtained from the NJDEP. Ground-water withdrawal projections were supplied by the Cape May County Planning Board (CPCPB). All other data were provided by the USGS.

GROUND-WATER HYDROLOGY

Details on the hydrogeology and the hydraulic properties of the shallow aquifers and confining units are documented in Spitz and Barringer (1992). The interpreted hydrogeologic framework is based on work done by Schuster and Hill (1995). Recent updates to the framework by P.J. Lacombe (U.S. Geological Survey, written commun., 1994) were made after the model was constructed by Spitz and Barringer (1992).

Aquifers and Confining Units

The three aquifers that compose the shallow aquifer system in Cape May County are, in order of increasing depth, the Holly Beach water-bearing zone, the estuarine sand aquifer, and the Cohansey aquifer (table 1). The aquifers consist of sand, gravel, and silt sediments. The aquifers are separated by leaky, sometimes discontinuous, low-permeability clay confining units. The Holly Beach is an unconfined aquifer, whereas the estuarine sand and Cohansey are confined aquifers. The extent of the estuarine sand aquifer and estuarine clay confining unit is limited to the Cape May peninsula and offshore. (Onshore hydrostratigraphic trends in the aquifers and confining units were extended offshore because of the paucity of data for areas under the Delaware Bay and Atlantic Ocean.) The bottom of the shallow aquifer system ranges in depth from 125 ft below sea level in the northwestern part of the county to 375 ft below sea level in the southeastern part. The shallow aquifer system overlies the deep aquifer system (including the Kirkwood aquifers). The confining unit separating the shallow and deep systems ranges in thickness from 75 to 175 ft (P.J. Lacombe, U.S. Geological Survey, written commun., 1994) and is considered to transmit little water (Gill, 1962, p. 110).

Average thicknesses of the Holly Beach water-bearing zone, estuarine sand aquifer, and Cohansey aquifer are 60, 80, and 120 ft, respectively. Average thicknesses of the estuarine clay confining unit and the confining unit overlying the Cohansey aquifer are 55 and 25 ft, respectively. Reported hydraulic conductivites of the aquifers range from 10 to 250 ft/d, whereas hydraulic conductivities of the confining units are typically 1,000 times smaller.

Water Use

Water use in Cape May County for public supply has increased throughout this century because of increased residential and seasonal tourist populations. Surface-water sources have been little used. Currently, about half of the withdrawals are from the shallow aquifer system and the other half from the deep aquifer system. The high cost of drilling wells and the worsening saltwater-encroachment problem have limited withdrawals from the deep aquifer system. Of the total ground-water withdrawal from the shallow aquifer system in 1990, about two-thirds was from the Cohansey aquifer. The remaining one-third was from the estuarine sand aquifer and Holly Beach water-bearing zone.

Two-thirds of the public-supply withdrawals from the shallow aquifer system have been made by Wildwood Water Department at the Rio Grande well field (fig. 1). Average withdrawal was 3.9 Mgal/d during 1983-88 and most of this withdrawal was made from the Cohansey aquifer. Much of the remaining public-supply withdrawals have been made from wells screened in the Cohansey aquifer operated by the Cape May City Water Department (average use, 1.2 Mgal/d during 1983-88) and the Lower Township Municipal Utilities Authority (average use, 0.6 Mgal/d during 1983-88). Most of the withdrawals from the shallow confined aquifers are consumptive, eventually being discharged to the ocean through waste-water-treatment outfalls. Withdrawals from the unconfined aquifer, however, are nonconsumptive, because the water is returned to the ground-water system nearby.

Flow System

Development of public-supply withdrawals from the shallow confined aquifers in Cape May County has significantly lowered ground-water levels. Current water levels in the Cohansey aquifer are at least 10 ft below sea level over most of Lower Township. These water levels had been above sea level before ground-water development in the late 1800's (Spitz and Barringer, 1992). Lateral ground-water flow in the confined aquifers has reversed from the predevelopment direction and is now toward onshore. Downward vertical leakage to the confined aquifers also has increased.

Ground-water flow in the unconfined aquifer, however, has changed little since predevelopment. The large difference in water levels in the unconfined and confined parts of the shallow aquifer system emphasizes the hydrologic separation between the two parts of the system, whereas the similarity in water levels in the two confined aquifers illustrates the interconnection of flow between these aquifers (fig. 6). The large decline in water levels associated with a small amount of withdrawals from the estuarine sand aquifer indicates that the aquifer is affected hydrologically by withdrawals from the Cohansey aquifer. Water levels in both confined aquifers are also affected by season; recovery during the winter at the withdrawal centers is greater than 10 ft in the Cohansey aquifer and about 5 ft in the estuarine sand aquifer (Spitz and Barringer, 1992, figs. 7 and 8).

A water budget can be used to estimate recharge to the shallow aquifer system (table 2). This budget is for annual average hydrologic conditions within the peninsular area. Evapotranspiration and surface runoff are subtracted from precipitation to calculate recharge to the ground-water zone. Inflow components of the water budget for the ground-water zone are recharge and lateral flow to the peninsula from all directions. Outflow components are discharge to streams and freshwater wetlands, discharge to tidal wetlands, and withdrawals. Budget components for both zones are based on data from Spitz and Barringer (1992) and G.B. Carleton (U.S. Geological Survey, written commun., 1994). Lateral flow and discharge to tidal wetlands are estimated. Approximate recharge and discharge areas on the peninsula used in the analysis are 65 and 49 mi^2, respectively.

The water-budget analysis highlights the importance of precipitation as the main source of recharge to the shallow aquifer system on the peninsula. The small amount of lateral ground-water inflow from the mainland to the peninsula (Spitz and Barringer, 1992, p. 51) indicates that the peninsula is hydrologically isolated from the mainland. Near the center of the peninsula, the unconfined aquifer discharges about 58 percent of the recharge to streams and freshwater wetlands. Nearshore, the unconfined aquifer discharges another 30 percent of the recharge to tidal wetlands. Less than 10 percent of the remaining recharge leaks down to the estuarine sand aquifer, and only part of this 10 percent leaks down to the Cohansey aquifer. Although leakage to the confined aquifers is only a small amount of the total recharge to the ground-water system, it can supply a large amount of the withdrawals.

Saltwater Encroachment

In coastal aquifers, freshwater generally grades into saltwater, depending on geologic material; across the gradient or interface, chloride concentration increases steadily, from below the 250- mg/L limit for potable water (U.S. Environmental Protection Agency, 1991b) to 19,000 mg/L for seawater. Because of the density difference between the freshwater and saltwater, the toe of the interface within the aquifer generally lies farther landward than does the tip (fig. 2). As more water from the shallow aquifer system is used consumptively for public supply, less water is left to help maintain high water levels that slow the inland movement of saline ground water, and less is left to discharge to streams and freshwater wetlands to inhibit increases in surface-water salinity. Reduction in ground-water levels due to withdrawals has three effects: water comes out of aquifer storage, leakage between aquifers or aquifers and surface-water bodies increases, and water moves laterally toward withdrawal locations. The release of freshwater from aquifer storage as the interface advances, and leakage between freshwater aquifers, can retard the encroachment. The saltwater zone also responds slowly because of low horizontal and vertical hydraulic conductivities that impede the lateral flow of saltwater into the zone of mixing. Therefore, the full extent of the encroachment due to withdrawals is delayed.

In southern Cape May County, predevelopment flow directions have been reversed, and freshwater has been moving away from the saltwater-freshwater interface toward major water-supply wells. The interface boundary will not stop moving until it reaches the low point of the cone of depression--that is, the center of withdrawals. As a result of these conditions, saltwater encroachment on the Cape May peninsula has been documented for more than 50 years. In the Holly Beach water-bearing zone, from which no

Table 2. Estimated hydrologic budget for the freshwater zone on the Cape May peninsula, New Jersey

[Modified from Spitz and Barringer, 1992, figure 6; positive values represent inflows and negative values represent outflows; in/yr, inches per year; Mgal/d, million gallons per day]

Budget component	Amount		Percentage of precipitation
	in/yr	Mgal/d	
Unsaturated zone			
Precipitation	42	128	100
Evapotranspiration	-23	-70	55
Runoff	-2	-6	5
Recharge to ground-water zone[1]	-17	-52	40
Total	0	0	
Ground-water zone			
Recharge	17	52	40
Discharge to streams and freshwater wetlands	-7	-22	17
Discharge to tidal wetlands	-5	-16	12
Net lateral flow (includes change in storage)[2]	-2	-5	4
Withdrawals (includes domestic use)	-3	-9	7
Total	0	0	

[1]Recharge to tidal wetlands is a component of the budget for the saltwater zone
[2]Mainly in confined aquifers; little saltwater encroachment in unconfined aquifer.

major withdrawals have been made and to which significant recharge is present, little lateral saltwater encroachment has occurred. Chloride concentrations increase abruptly near the back bays of barrier islands, but tend to be less than 50 mg/L inland on the peninsula. Elevated or increasing chloride concentrations have been measured near tidal wetlands on the west coast. The aquifer is susceptible to saltwater from leakage through the bottoms of the saline-water bodies and from flooding of nearshore land.

Saltwater encroachment in the confined aquifers is more severe (fig. 6). Along the west coast of the peninsula, particularly at Villas, non-potable chloride concentrations have been measured since the mid-1960's in ground water from many domestic wells screened in the estuarine sand aquifer; many of these wells have been abandoned (Lacombe and Carleton, 1992). From 1960 through 1990, the average rate of movement of the nonpotable saline water in the aquifer in this area was approximately 125 ft/yr. In 1987, the nonpotable saline ground water in this aquifer was 4,500 ft inland from the Delaware Bay (David Rutherford, Cape May County Planning Board, written commun., 1987) and was a potential threat to the Rio Grande well field. In Town Bank, near the Lower Township public-supply wells, no chloride concentrations greater than 250 mg/L have been measured in the aquifer.

Saltwater encroachment in the aquifer has occurred around the tip of the peninsula, affecting the public-supply wells belonging to the Cape May City Water Department (fig. 6, farther on). Wells at Columbia (well number 9-12) and Lafayette Avenues (9-14) have been abandoned as a result of water with chloride concentrations exceeding 250 mg/L in 1950 and 1963, respectively (Lacombe and Carleton, 1992). (A USGS well number consists of a county-code prefix followed by a unique sequence number for the well in that county.) Water from the next most inland well, 9-27, reached the non-potable chloride limit in 1984 after a period of heavy pumping. Well 9-45, located farther inland, has withdrawn water with increasing chloride concentrations, but the concentrations are below the limit for potable water. The most inland well, 9-43, produces water with chloride concentrations less than 25 mg/L. The position of the saltwater-freshwater interface in Villas is estimated to be at the shoreline and moving at a slower rate than the interface in the estuarine sand aquifer. The Lower Township public-supply wells produce water with chloride concentrations less than 50 mg/L. On Wildwood Island, approximately 10 public- and industrial-supply wells have been abandoned because of water containing high chloride concentrations.

HYDROLOGIC FEASIBILITY OF WATER-SUPPLY-DEVELOPMENT ALTERNATIVES

The shallow aquifer system of Cape May County was simulated previously by Spitz and Barringer (1992) using the SHARP (Essaid, 1990) computer code. SHARP is a Fortran code for a quasi-three-dimensional, finite-difference model that simulates fresh and salt ground-water flow and the movement of a sharp interface separating the two zones. Although the sharp-interface approximation can be less accurate than the variable-density approximation, it is less restrictive, requires fewer unknowns, is easier to implement, and is less intensive computationally. A simple cross-sectional application of the SHARP code on the Cape May peninsula (Hill, 1988) yielded estimates of interface position that are nearer to shore than did SUTRA (Voss, 1984), a variable-density code.

The model is a discrete representation of the geometry, boundaries, and water-transmitting properties of the shallow aquifer system. To apply the SHARP code, the ground-water system is divided into an areal grid of mutually exclusive cells designated by row, column, and layer to which cell-averaged hydrogeologic properties are assigned. Withdrawal stresses to the system are applied by means of pumping periods of average withdrawals. Each cell has a node at its center where heads are simulated by use of ground-water-flow equations for fresh and salty water. Saltwater-freshwater interface elevations are then simulated by use of a coupling equation representing the pressure boundary condition at the interface. Further discussion of the SHARP code can be found in Essaid (1990).

Model Limitations and Assumptions

Limitations and assumptions of the numerical analysis of the ground-water system affect conclusions made about the system and the certainty of predictive simulations made with the model. Limitations fall into three categories: those due to data, computer code, and model formulation. Principal data limitations are lack of data (for example, on the saltwater-freshwater interface) and inaccuracy of data (for example, recharge and withdrawal estimates). An additional data limitation is the error associated with field measurements of parameters.

Some limitations due to the SHARP computer code are that flow in confining units, upconing of saltwater beneath well screens, and tidal effects are not explicitly represented. The subsurface geometry of the shallow aquifer system is assumed to be composed of layered units. Confining units are not represented as layers in the model but rather as vertical leakances between aquifer layers. Discretization of the study area causes an approximation of hydraulic properties, recharge, and streamflow in grid cells. Discretization also creates an offset between observations at actual well locations and calculations at model nodes. Moreover, discretization can place more than one well in a grid cell.

The mixing zone between freshwater and saltwater is assumed to be narrow compared to the thickness of the aquifer in the SHARP code. This means that the interface separates fresh ground water from salty ground water abruptly, with no transition. In reality, the transition is gradual (fig. 2). In Cape May County, the mixing zone can be several thousand feet wide, as indicated by chloride concentrations in well water. The density gradient present over a wide mixing zone translates into higher heads on the freshwater side of the sharp interface and the interface located farther seaward. However, this density effect is small in locations where ground-water chloride concentrations are only a few thousand mg/L (Reilly, 1993, table 18-3). This finding also implies that dilute saline water, with chloride concentrations above the 250- mg/L limit for potable water, is advancing in front of the simulated sharp interface (approximately 10,000 mg/L). Because of different ground-water flow velocities in the mixing zone, estimates of sharp-interface movement can be much slower than estimates of 250-mg/L-isochlor (line of equal chloride concentration) movement.

Limitations due to model formulation are partly the result of simplifying assumptions required by the model. Leakage is chosen to be restricted in the SHARP code, which prevents saltwater leakage into the freshwater zone. This code option is recommended for ground-water systems with considerable vertical leakage (Essaid, 1990, p. 56). Using this option counterbalances the purported conservative positioning of the saltwater in the SHARP code when compared to a variable-density code (Hill, 1988). Finally, all aquifers are assumed to be isotropic, and annual average conditions, not seasonal or other short-term effects, are simulated.

Model Design and Calibration

The details regarding design and calibration of the Cape May model are given in Spitz and Barringer (1992). The model was constructed as an irregular grid consisting of 42 rows, 40 columns, and 3 aquifer layers representing an area of approximately 782 mi^2 (fig. 3). The smallest grid-cell size, 0.15 mi^2, is in the southern part of the peninsula. Boundary conditions for the model are shown areally in figure 3 and vertically in figure 4. Constant freshwater heads representing surface-water bodies and wetlands were assigned on the basis of long-term average water level and water-table elevation, respectively. A leakance for sediments at the bottom of the surface-water bodies and the wetlands was applied to represent the interaction with the unconfined aquifer below. Constant-head boundaries for saltwater were represented as the equivalent freshwater head. Saltwater heads were assigned on the basis of bathymetry

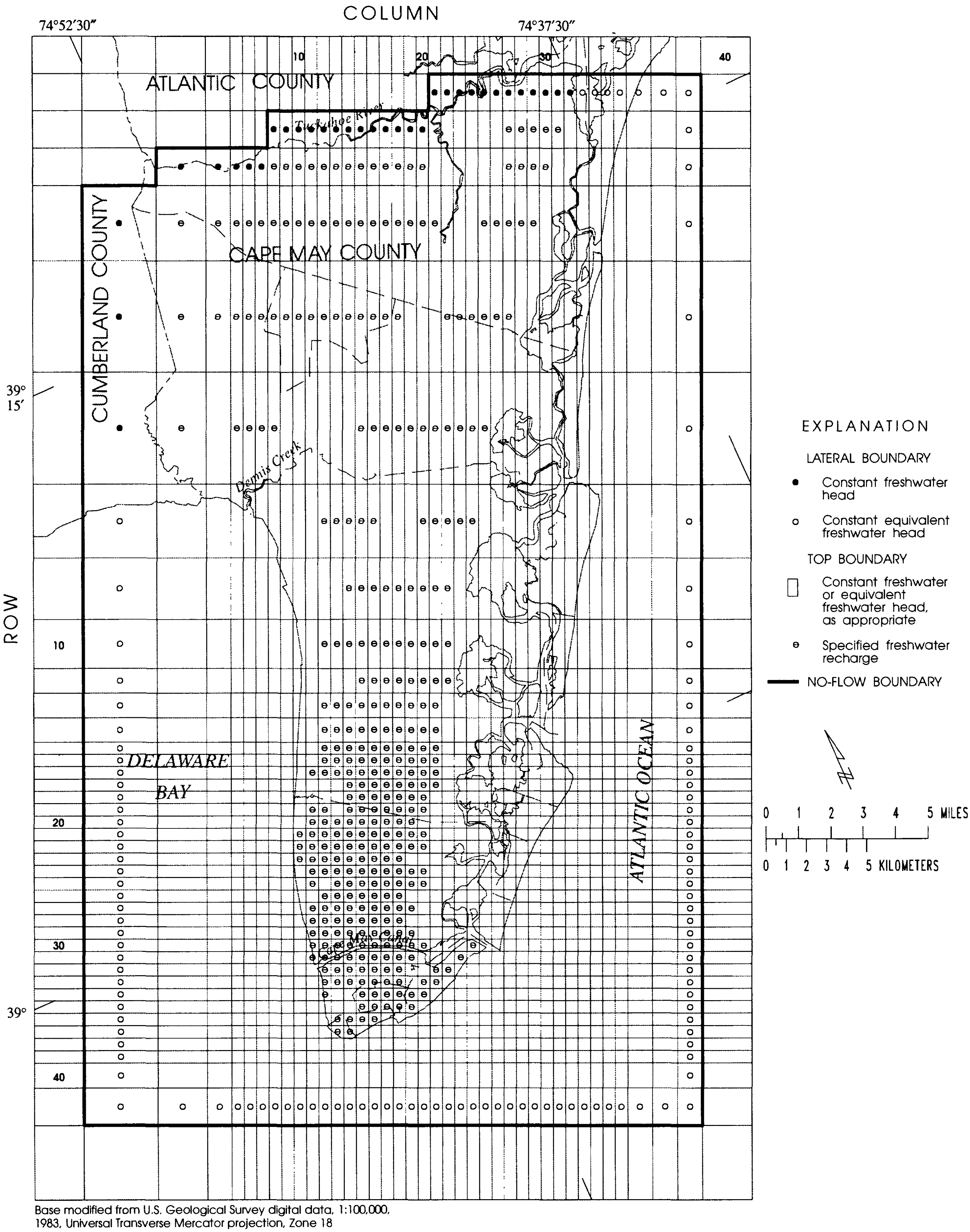


Figure 3. Grid and boundary conditions for model of Cape May County, New Jersey (modified from Spitz and Barringer, 1992, fig. 10).

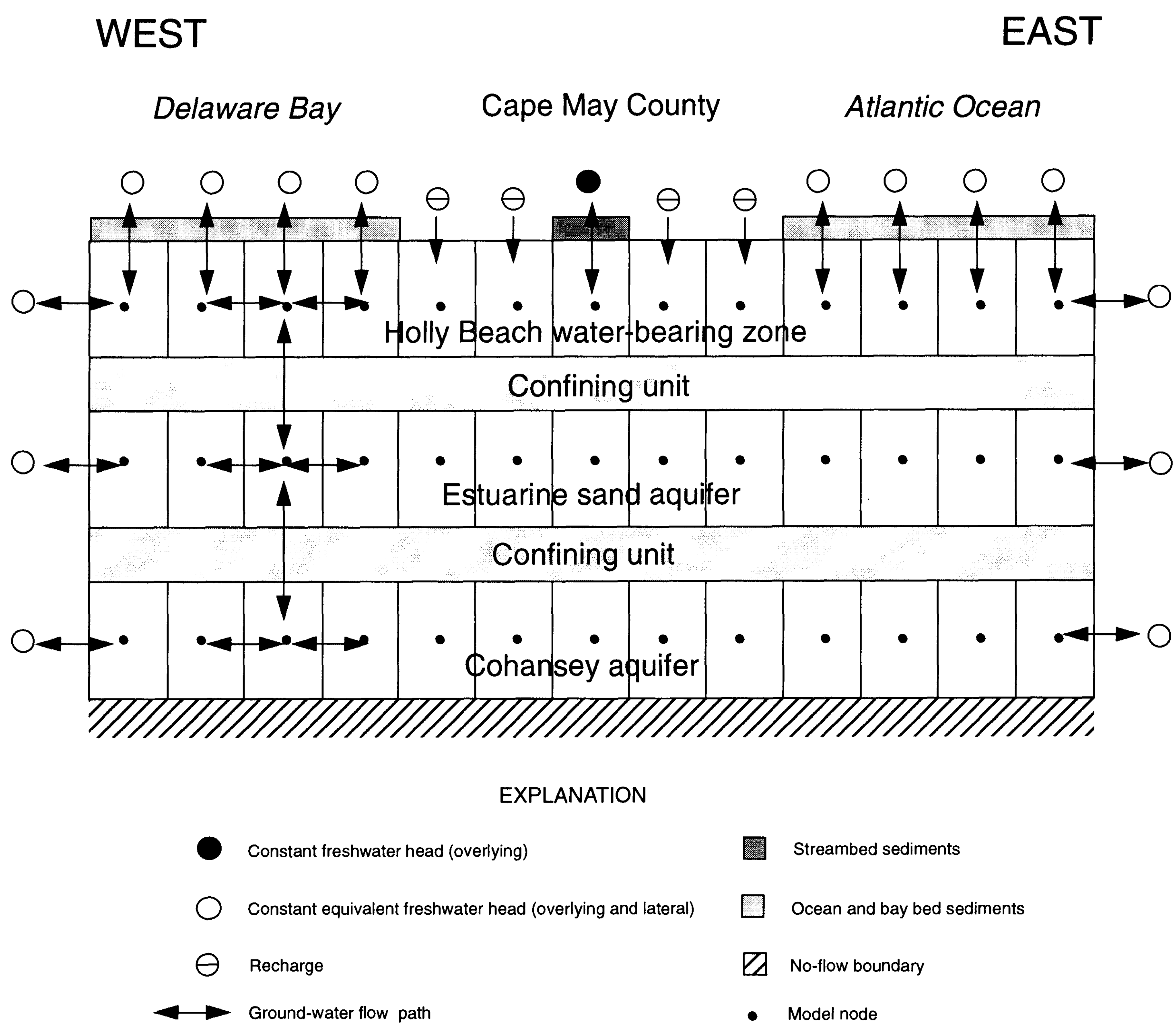


Figure 4. Schematic diagram along a row of the model of the Cape May peninsula, New Jersey (modified from Spitz and Barringer, 1992, fig. 11).

elevation, and a bottom leakance was applied to represent interaction with the underlying aquifer. The model's bottom boundary was assumed to be a no-flow boundary representing the tight confining unit separating the shallow aquifer system from the deep aquifer system.

Predevelopment (about 1890) and stressed (1890-1989) conditions in the shallow aquifer system were simulated. The predevelopment simulation provided the initial conditions for the stressed simulation. Heads and positions of the sharp interface between saltwater and freshwater were calibrated mainly by trial-and-error adjustment of aquifer horizontal hydraulic conductivities and confining-unit leakances. Recharge, horizontal hydraulic conductivity of the unconfined aquifer, and leakance of the confining unit beneath the aquifer were the most sensitive parameters. The calibrated values for all parameters were generally within the ranges of measured values, except for the hydraulic conductivity of the unconfined aquifer and the leakance of the bottom sediments of surface-water bodies, which were approximately 10 times greater than measured values.

The difference between measured and simulated heads for the three aquifers was generally within 5 ft, except in the cone of depression of the major well fields, where the difference was increased due to discretization error. The simulated hydrologic budget for the Cape May peninsula in 1989 (Spitz and Barringer, 1992, fig. 21) corresponds to the estimated hydrologic budget shown in table 2; however, the model indicated that about half of the water in the unconfined aquifer flowed laterally off the peninsula, rather than discharging upward. Downward vertical flow predominates in the confined aquifers, and lateral flow in these aquifers is landward.

Because nearly all of the chloride concentrations measured in the county are less than the concentration approximating a sharp front between freshwater and saltwater (10,000 mg/L), close calibration of the interface was not possible. Lower measured chloride concentrations were used to infer the position of the interface. The simulated interface in the Holly Beach water-bearing zone and estuarine sand aquifer generally correspond to measured chloride concentrations. In the Cohansey aquifer, however, the simulated interface is too far onshore in the southern part of the peninsula. Correction of the discrepancy was not possible during calibration. Locations where measured chloride concentrations were elevated or rising coincide with areas where movement of the saltwater-freshwater interface was simulated. Estimated movement of the 250-mg/L isochlor (Lacombe and Carleton, 1992), which represents the limit for potable water, was approximately 10 times greater than simulated movement of the sharp interface in the confined aquifers. Simulated and estimated movement were both small in the unconfined aquifer. Differences between simulated and estimated movement reflect differences in flow velocities in the mixing zone, model limitations and inaccuracies, and inaccuracies in interpretation of chloride isochlors from measured point concentrations.

Predictive Simulations of Alternatives

Predictive simulations were used to compare ground-water-system responses to alternative water-management plans. The calibrated ground-water flow model of the shallow aquifer system in Cape May County by Spitz and Barringer (1992) was used to make the predictive simulations. Results of the simulations were evaluated by comparing ground-water levels, ground-water flows, and saltwater encroachment. Although the simulations adequately portray changes in ground-water levels and flows, they permit only the inference of changes in saltwater encroachment. Inaccuracy in the movement of the saltwater results partly from discrepancies in model calibration and partly from limitations of the modeling approach, which cannot represent variations in water density and solute dispersion. Despite these considerations, predicted saltwater encroachment can be compared among the simulation results.

The proximity of the Cape May County to saltwater bodies and the hydrology of the shallow aquifer system restrict the number of water-supply-development alternatives. Those alternatives deemed hydrologically impractical were not simulated. For example, artificial recharge basins were not simulated because the low permeability confining unit beneath the unconfined aquifer would impede leakage to the wells screened in the confined aquifers. The alternatives include two local options (barrier injection and barrier withdrawal) and two regional options (conjunctive use and redistribution).

A summary of all the predictive simulations made with the Cape May model is given in table 3. The planning period (1989-2049) used in this study is the same as that used by Spitz and Barringer (1992). The end of the stressed simulation (1890-1989) provided the initial conditions for the predictive simulations. Historical and projected public-supply withdrawals from the shallow confined aquifers at the three major well fields are shown in figure 5. Increased public-supply withdrawals in Cape May City, Rio Grande (including the Cape May Court House Water District), and Lower Township are based on the projected percent increases in dwelling-unit construction or sewer capacity, whichever of the two criteria is the larger during 1989-2019 and 2020-2049. This represents 90-, 60-, and 310-percent increases in withdrawals at the well fields, respectively, or a 95-percent increase in total public-supply withdrawals over the planning period. Withdrawals were gradually increased over six 10-year pumping periods through 2049. All other withdrawals continued at average 1983-88 rates. A constant time step of 1 year during the pumping periods was applied to allow for accurate tracking of the saltwater-freshwater interface. The withdrawal projections apply to all the predictive simulations made in this study.

No Action

The first simulation involved only the projected increases in withdrawals and is used as a baseline for comparison with the alternatives. Comparison of the simulated shallow aquifer system for 1989 (fig. 6) with the no-action simulation (fig. 7) shows that heads in the southern part of the peninsula decline up to 40 ft in the confined aquifers over the planning period. Changes to heads in the unconfined aquifer are negligible, as is the case for all the simulated alternatives.

Saltwater encroachment can be compared by examination of movement of the simulated saltwater-freshwater interface toe. The interface toe--the intersection of the interface with the bottom of the aquifer--is the most landward extent of the interface (fig. 2). In the Cohansey aquifer, the interface toe moves approximately 580 ft toward the Cape May City wells and 750 ft toward the Rio Grande well field over the planning period (fig. 8 and table 4). Interface movement in this aquifer toward the Lower Township wells was not estimated because of inaccuracies in the calibrated position of the interface (Spitz and Barringer, 1992, p. 55); however, simulated movement toward the wells is inferred to be less than the 1,740 ft of movement simulated in the estuarine sand aquifer. In the estuarine sand aquifer, the interface toe moves approximately 1,350 ft toward the Cape May City wells and 1,680 ft toward the Rio Grande well field over the planning period. Interface-toe movement in the unconfined aquifer is negligible in this simulation, as it is in all the simulated alternatives.

Simulated ground-water budgets for the shallow aquifers on the Cape May peninsula for 1989 and for the no-action simulation in 2049 are shown in figure 9. The ground-water system supplies the projected increased withdrawals through increased downward leakage through the confining units and the release of water from aquifer storage as the interface advances. Increased leakage from the unconfined aquifer to the confined aquifers supplies much of the increased withdrawals. Some of the imbalance between total inflow to and total outflow from the aquifers is caused by the difference in the way flow components and storage are calculated. Flow components are calculated at the end of a pumping period, whereas the rate of change in storage is calculated as the average over the period. Generally, the average change in storage over the period is larger than the change in storage at the end.

Table 3. Summary of predictive simulations made with the ground-water flow model for Cape May County, New Jersey

Scenario name	Withdrawal	Principal water-source area affected	Shallow aquifers used
Spitz and Barringer (1992)			
No action	Current rate	Current wells	Estuarine sand and Cohansey
Increased demand	Decreased	Current wells	Estuarine sand and Cohansey
Decreased demand	Increased	Current wells	Estuarine sand and Cohansey
Aggregated demand	Current rate	Rio Grande well field	Estuarine sand
Redistribution	Increased[1]	Center of peninsula	Cohansey
Current study			
No action	Increased[1]	Current wells	Estuarine sand and Cohansey
Barrier injection	Increased[1]	Rio Grande well field	Estuarine sand and Cohansey
Barrier withdrawal	Increased[1]	Cape May City wells	Estuarine sand and Cohansey
Conjunctive use	Increased[1]	Tuckahoe River	Estuarine sand and Cohansey
Redistribution	Increased[1]	Center of peninsula	Holly Beach

[1]Projected increased withdrawal plus increases for Cape May Court House Water District (involves a 10-percent increase to projections for Rio Grande).

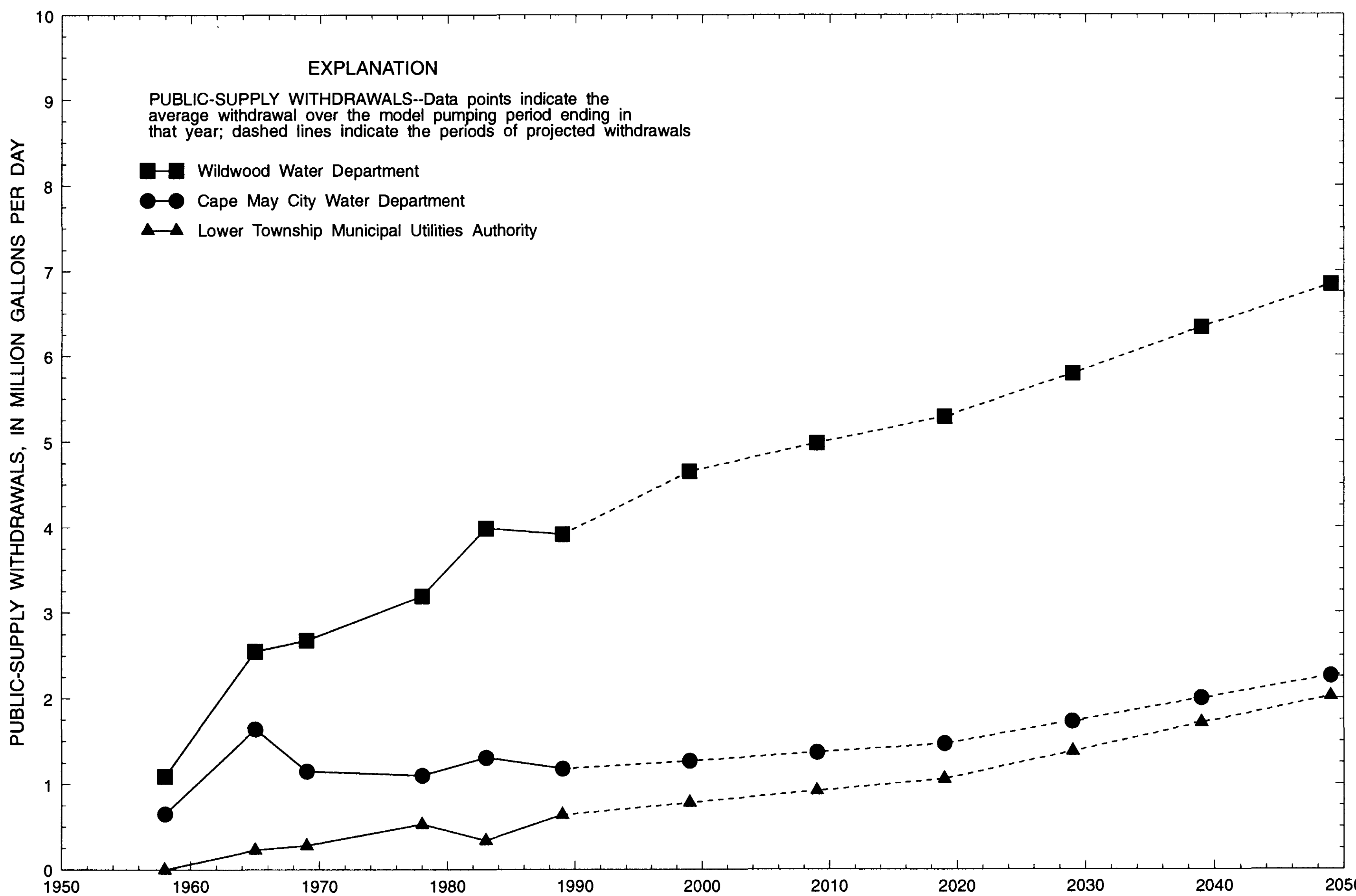
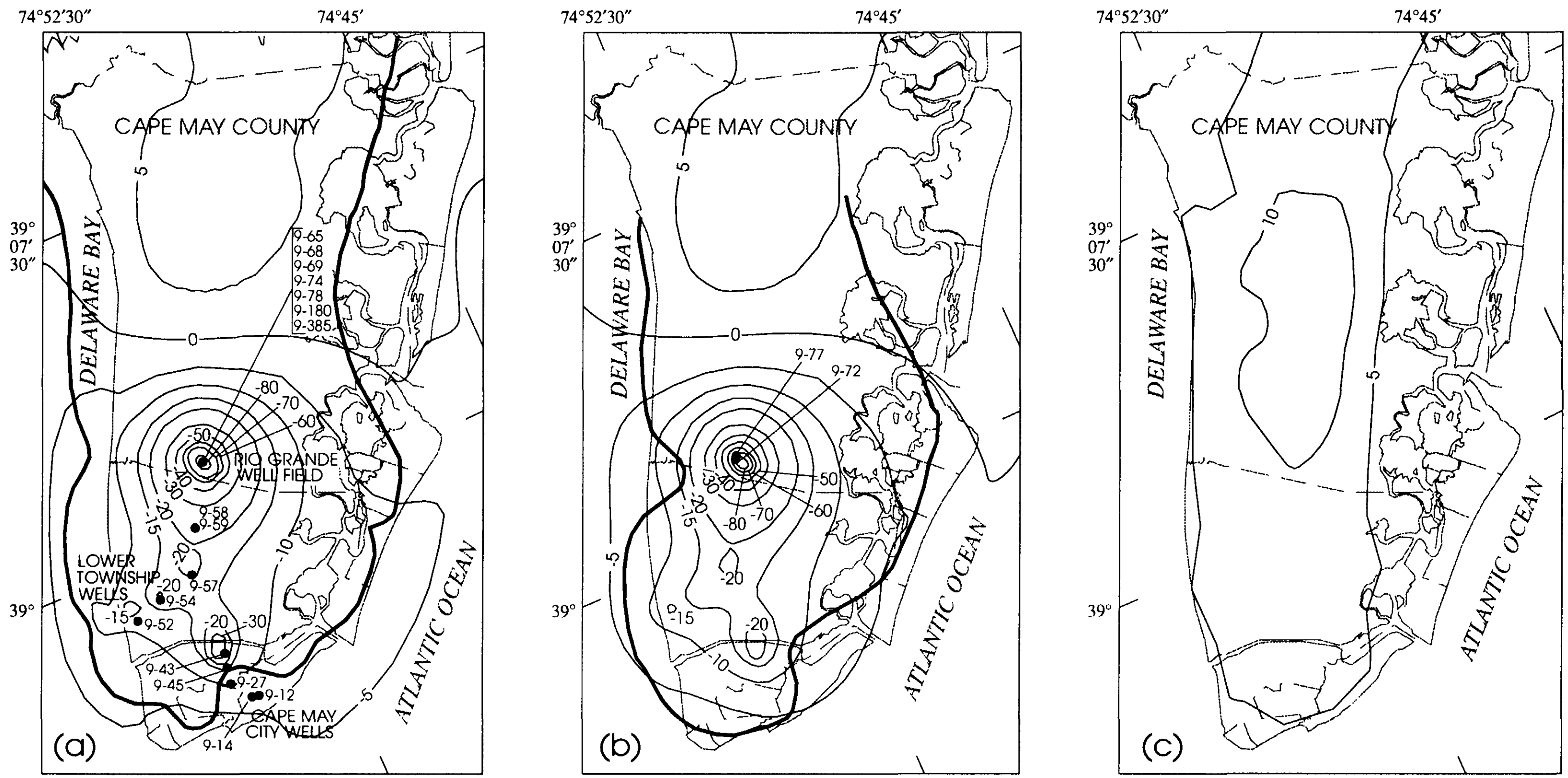


Figure 5. Partial historical withdrawals and projected future withdrawals from the shallow aquifer system in Cape May County, New Jersey.



Base modified 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--Altitude of simulated water-table or potentiometric surface in 1989. Contour interval, in feet, is variable. Datum is sea level

INTERPRETED POSITION OF NON-POTABLE SALINE WATER--Chloride concentration equal to 250 milligrams per liter in the middle of the aquifer in 1992. Estimate from P.J. Lacombe, U.S. Geological Survey, written commun., 1994

• 9-57 WATER-SUPPLY WELL LOCATION AND NUMBER

Figure 6. Simulated water-table and potentiometric surfaces for 1989 and locations of the 250-milligram-per-liter isochlor for 1992 in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone, Cape May County, New Jersey (modified from Spitz and Barringer, 1992, fig. 17).

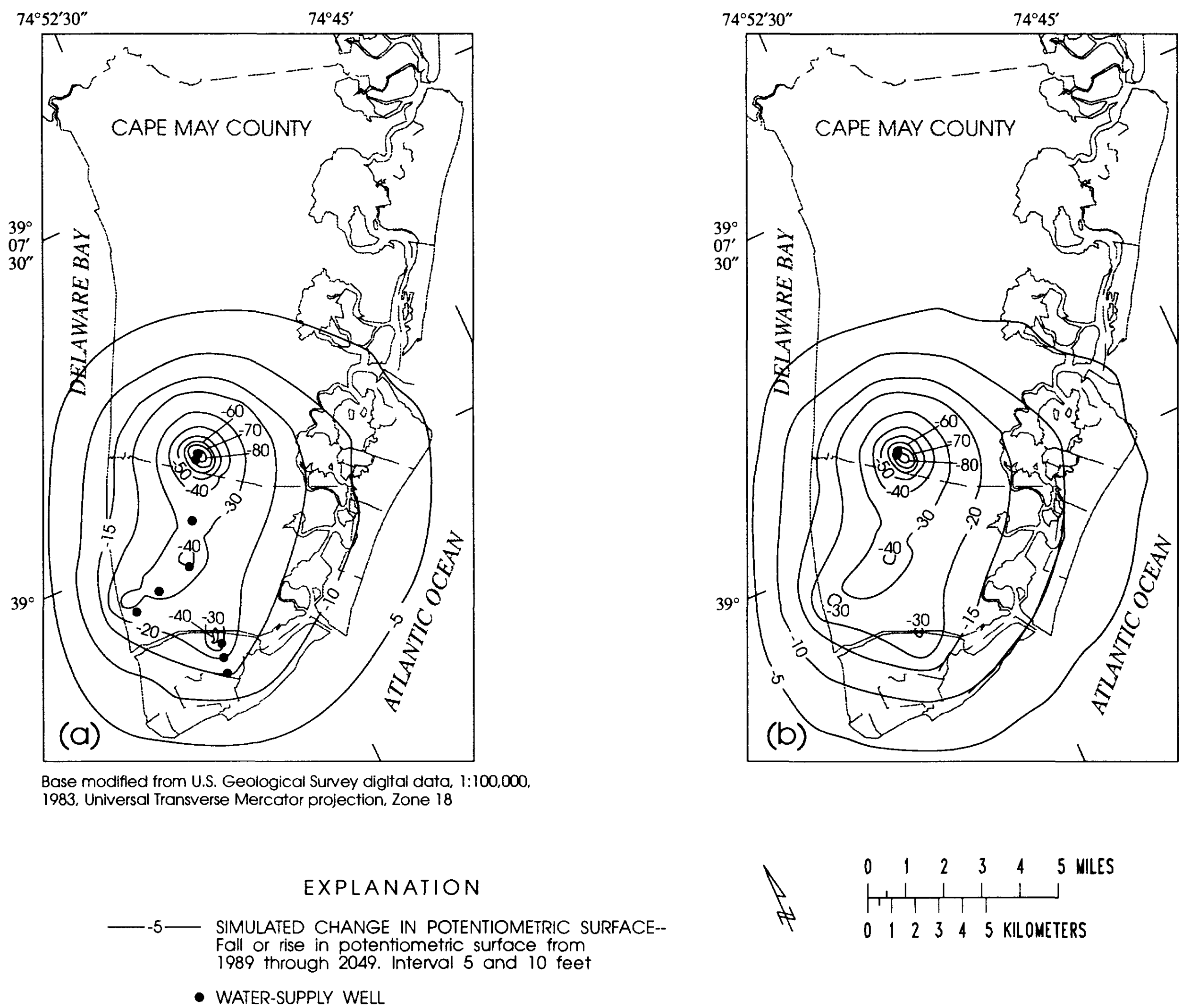


Figure 7. Simulated change in potentiometric surface for the no-action alternative in the (a) Cohansey aquifer and (b) estuarine sand aquifer, Cape May County, New Jersey.

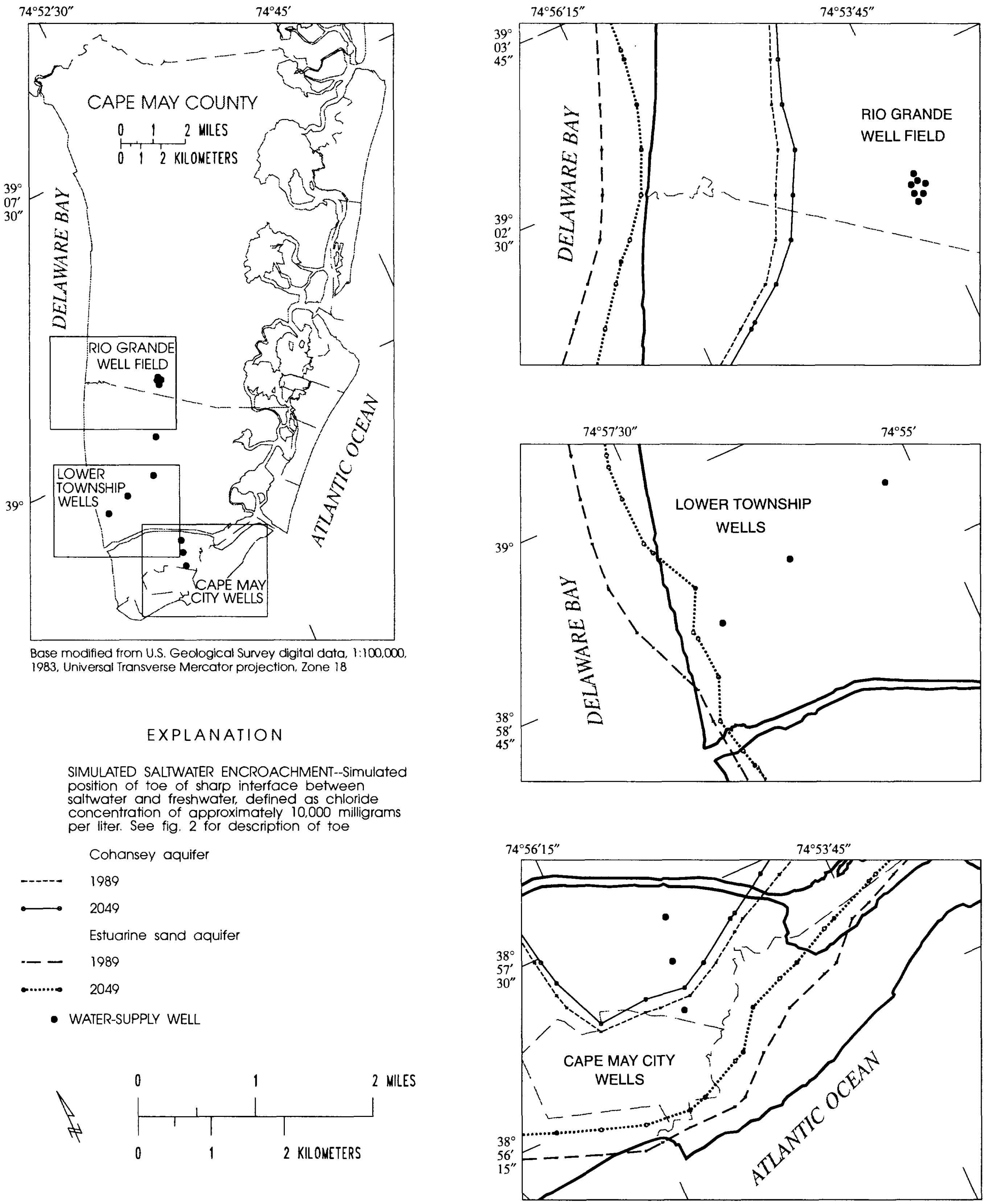
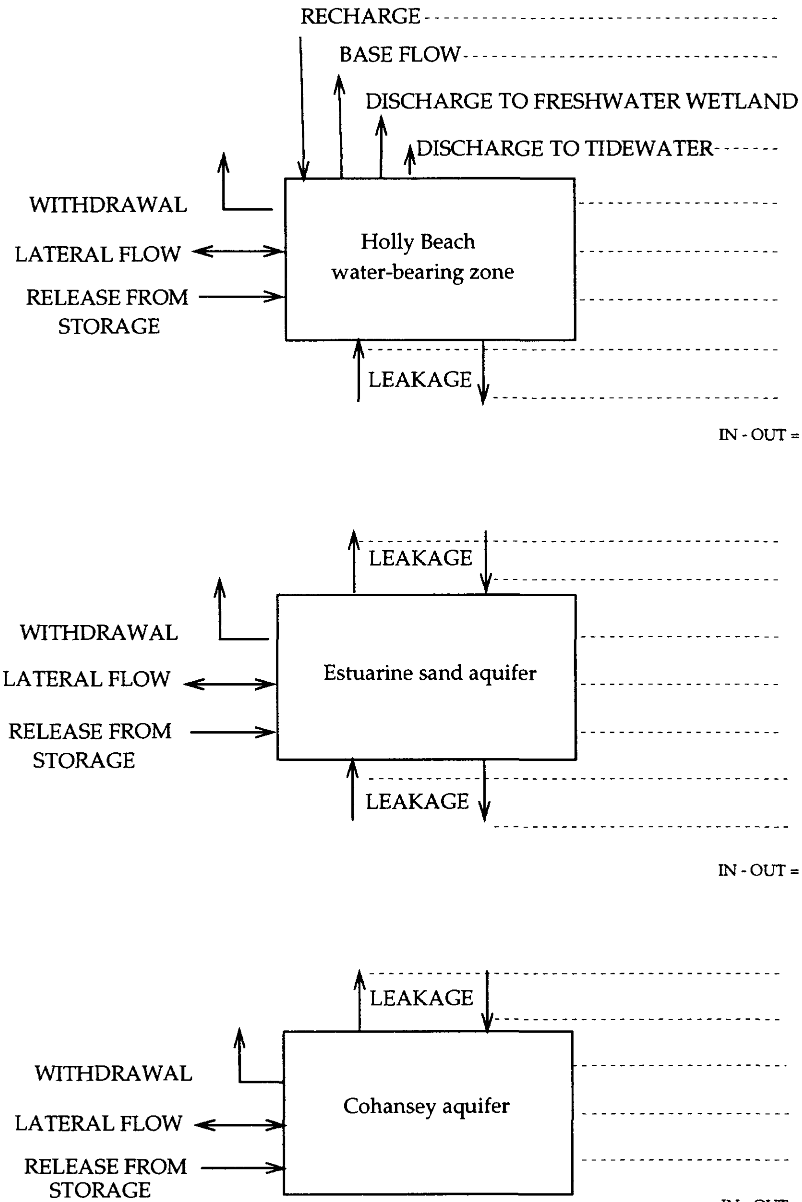


Figure 8. Simulated saltwater encroachment for the no-action alternative in the Cohansey and estuarine sand aquifers, Cape May County, New Jersey.

Table 4. Predicted movement of the saltwater-freshwater interface toe from 1989 through 2049 for simulated water-supply-development alternatives, Cape May County, New Jersey

[Interface defined as chloride concentration of approximately 10,000 milligrams per liter; movement to ± 50 feet of value shown; <, less than]

Greatest advance toward closest well at--	Simulated alternative				
	No Action	Barrier injection	Barrier withdrawal	Conjunctive use	Redistribution
Estuarine sand aquifer					
Rio Grande	1,680	750	1,870	1,290	<50
Lower Township	1,740	1,740	1,950	1,580	120
Cape May City	1,350	1,340	0	1,210	560
Cohansey aquifer					
Rio Grande	750	730	800	630	120
Cape May City	580	570	630	510	150



	1989	2049				
		No action	Barrier injection	Barrier withdrawal	Conjunctive use	Redistribution
Holly Beach water-bearing zone						
RECHARGE	49.2	49.2	49.2	49.2	49.2	49.2
BASE FLOW	-4.4	-4.4	-4.4	-4.3	-4.4	-3.6
DISCHARGE TO FRESHWATER WETLAND	--	--	--	--	--	--
DISCHARGE TO TIDEWATER	-18.7	-15.3	-15.4	-14.9	-16.0	-16.1
WITHDRAWAL	-.1	-.1	-.1	-.1	-.1	-11.8
LATERAL FLOW	-22.2	-21.7	-22.0	-21.8	-22.0	-22.4
RELEASE FROM STORAGE	1.4	1.7	1.7	1.6	1.4	5.9
LEAKAGE	.1	.1	.1	.1	.1	.2
LEAKAGE	-4.5	-8.5	-8.3	-8.7	-7.4	-.7
IN - OUT =	.8	1.0	.8	1.1	.8	.7
Estuarine sand aquifer						
LEAKAGE	-.2	-.1	-.1	-.1	-.1	-.3
LEAKAGE	4.5	8.5	8.3	8.7	7.4	.7
WITHDRAWAL	-.4	-.8	-.5	-.8	-.6	0
LATERAL FLOW	.7	1.7	1.6	1.7	1.4	-.4
RELEASE FROM STORAGE	.3	1.2	1.1	1.0	.9	.1
LEAKAGE	.3	.3	.3	.3	.3	.3
LEAKAGE	-5.4	-10.8	-10.8	-10.9	-9.5	-.4
IN - OUT =	-.2	0	-.1	-.1	-.2	0
Cohansey aquifer						
LEAKAGE	-.3	-.3	-.3	-.3	-.3	-.3
LEAKAGE	5.4	10.8	10.8	10.9	9.5	.4
WITHDRAWAL	-5.5	-11.1	-11.1	-11.0	-9.8	-.3
LATERAL FLOW	0	.1	.1	.1	.1	0
RELEASE FROM STORAGE	.3	.5	.5	.3	.4	.1
IN - OUT =	-.1	0	0	0	-.1	0

EXPLANATION

——> INFLOWS AND OUTFLOWS OF WATER--In million gallons per day.

- - - - NOT SIMULATED

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 9. Simulated ground-water budgets for the Cape May peninsula, New Jersey, in 1989 and 2049 for the water-supply-development alternatives.

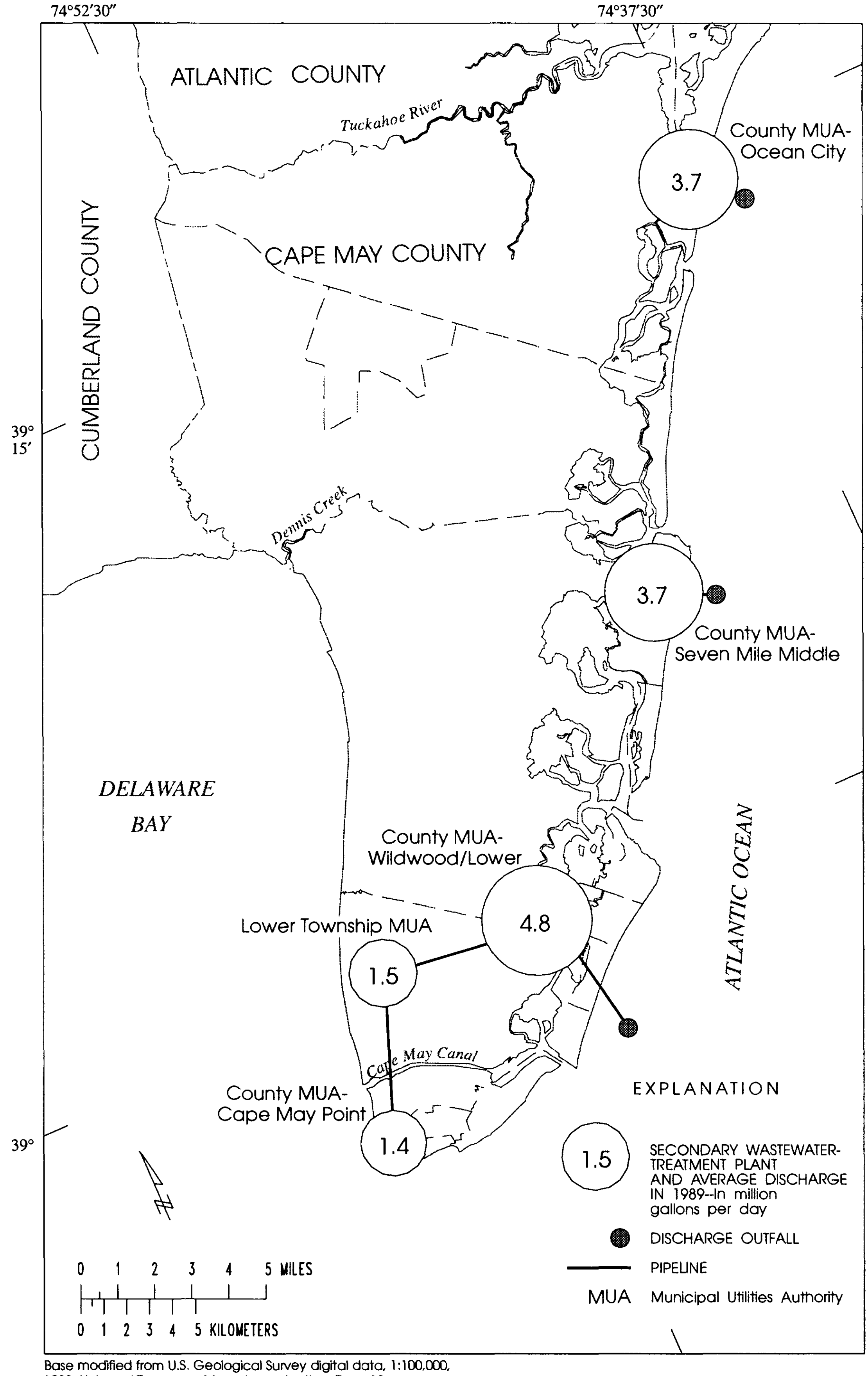
Barrier-Injection Wells

Artificial recharge is the method of replenishing the ground-water system by increasing aquifer storage (Kimrey, 1989). The method can also create a hydraulic barrier to saltwater encroachment (Wedding and Kondru, 1982). Additional benefits of the use of the method include the reduction in the operating costs of existing wells by raising water levels, elimination of well-field expansion costs resulting from premature abandonment of wells, and increased ground-water storage capacity (Driscoll, 1986). The three main sources of water for artificial recharge are reclaimed water, such as tertiary-treated wastewater, and natural ground water or surface water. Considerations related to the source water are where to obtain it, when it would be available, and how much could be added to and recovered from to the ground-water system. Other considerations in the use of the method include construction of water works and treatment facilities; environmental consequences and permitting problems; and aquifer-clogging problems related to quality and chemistry of the injected water (O'Hare and others, 1986).

The two main types of artificial recharge are recharge basins and injection wells. In New Jersey, injection wells have been used at few locations (Pucci and others, 1994; Signor and others, 1970; Todd, 1959), whereas recharge basins have been used more extensively (Pucci and others, 1994; Parker and others, 1964). Application of artificial-recharge methods in the State has declined in recent years. In Cape May County, the Wildwood Water Department has withdrawn ground water at the Rio Grande well field during the nonsummer months and then piped and injected it into the Cohansey aquifer beneath Wildwood Island to help supply summer peak withdrawals. Wells in North Wildwood, Wildwood, Wildwood Crest, and just south of Wildwood Crest are used for injection at rates that were typically 0.15-0.20 Mgal/d during 1990. Chlorine is added to the water prior to injection for disinfection, and daily back-flushing of the wells is necessary to prevent clogging of the well screens. More recently, Cape May City Water Department has injected ground water purchased from Lower Township into well 9-45 (fig. 6) to help meet summer peak water demand. Typical rates of injection were 0.3-0.5 Mgal/d during 1994 (P.J. Lacombe, U.S. Geological Survey, oral commun., 1994).

Reclaimed water is another possible source of water for artificial recharge in Cape May County. Secondary-treated wastewater is discharged in highest quantity concurrently with peak water demand. Five large wastewater-treatment plants operate in the county (J.C. Jessel, New Jersey Department of Environmental Protection, written commun., 1991). The three southernmost plants discharge through a common pipeline to an ocean outfall near Wildwood Island (fig. 10). Monthly average discharge for 1989 from these plants are shown in figure 11. Total discharge from these plants ranges from 7.5 Mgal/d in the winter to 24 Mgal/d in the summer. The addition of tertiary treatment would enhance secondary-wastewater quality for 5-day biochemical oxygen demand, suspended solids, pH, and bacteria (U.S. Environmental Protection Agency, 1989). Tertiary treatment typically consists of nitrogen addition or removal, phosphorus removal, removal of refractory organic or inorganic substances, or disinfection (Metcalf & Eddy, 1979). By adding the tertiary-treated wastewater to the ground-water system, it would mix with the natural water and be further filtered. Tertiary-treated wastewater also has been reused directly in the United States without causing any health problems (Johnson and Finlayson, 1988; Metcalf & Eddy, 1979; Culp and others, 1978).

The use of barrier wells to inject tertiary-treated wastewater is a possible water-supply-development alternative for Cape May County. The predictive simulation for this alternative was identical to the baseline simulation discussed earlier except for the addition of two hypothetical injection wells screened in the estuarine sand aquifer located at the bayshore west of the Rio Grande well field. The Rio Grande well field accounts for the largest withdrawals from the shallow aquifer system, and saltwater is encroaching fastest in the estuarine sand aquifer near the well field. Hypothetical barrier-well locations are shown in figure 12. The use of two wells is chosen to prevent saltwater from moving around one well to



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

Figure 10. Locations of secondary wastewater-treatment plants and discharge outfalls in 1989, Cape May County, New Jersey.

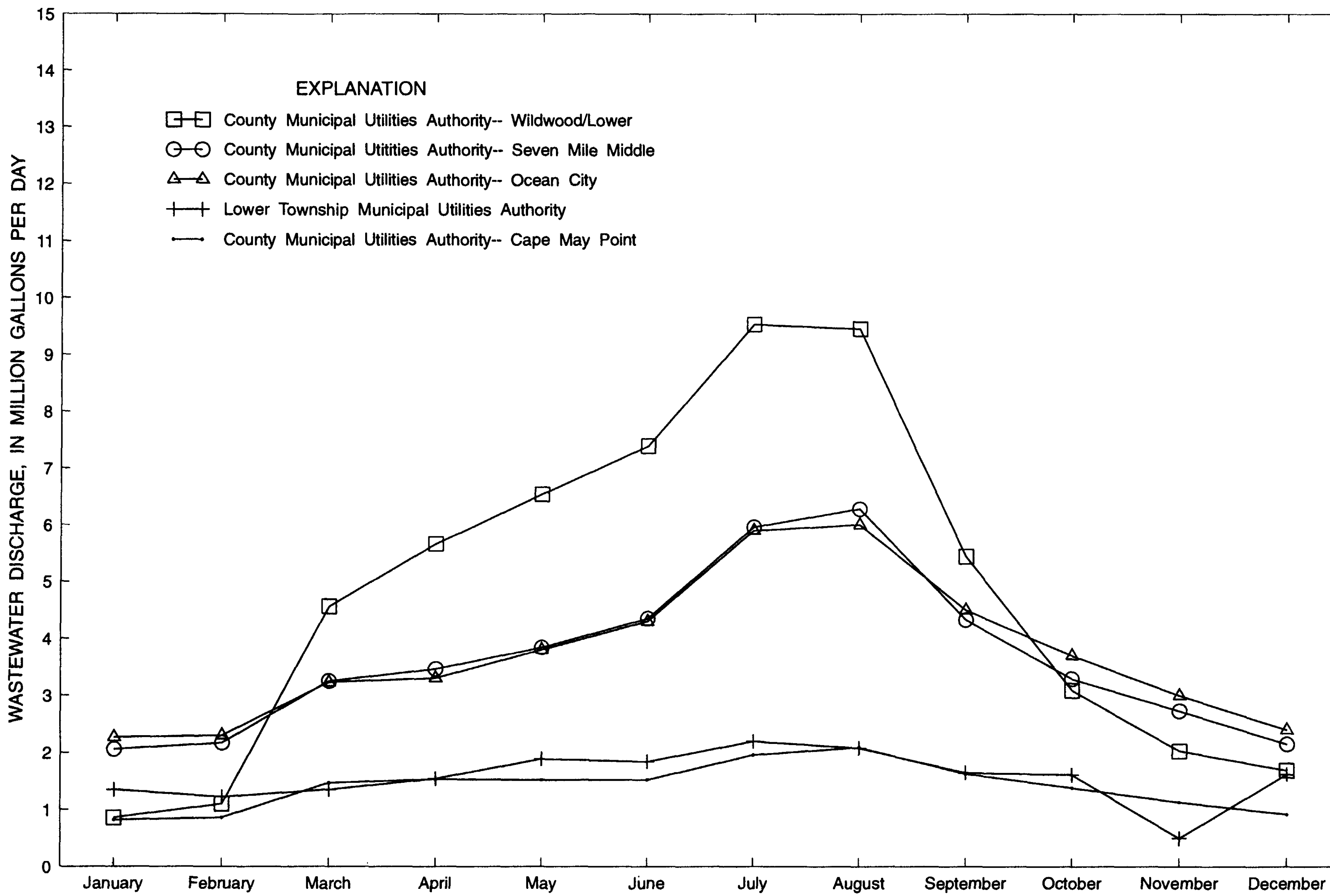


Figure 11. Monthly discharge of secondary-treated wastewater in Cape May County, New Jersey, 1989.

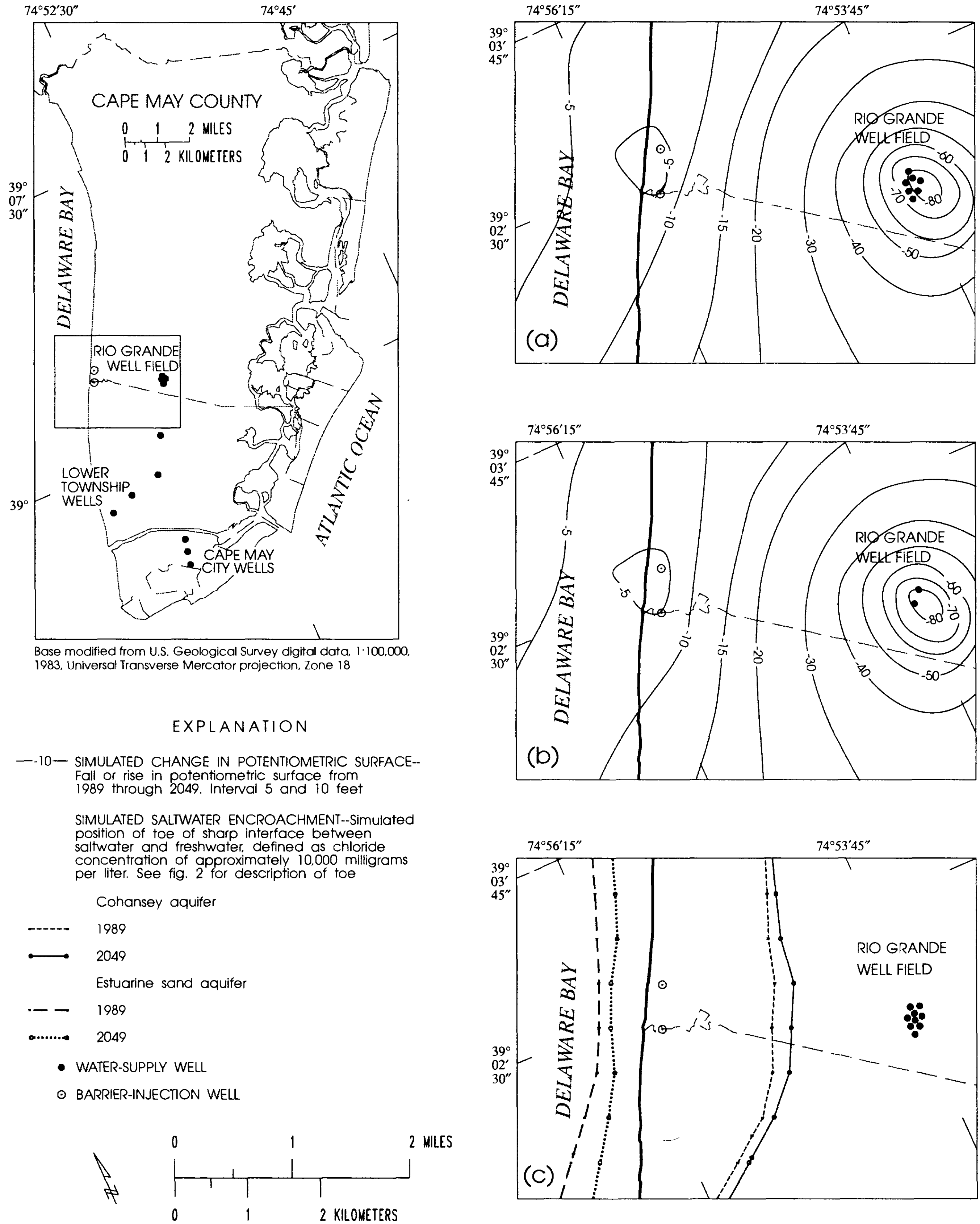


Figure 12. Simulated change in potentiometric surface for the barrier-injection alternative in the (a) Cohansey aquifer and (b) estuarine sand aquifer; and simulated saltwater encroachment in the (c) Cohansey and estuarine sand aquifers, Cape May County, New Jersey.

the well field. The hypothetical wells inject water at an average rate of 0.16 Mgal/d, the same rate currently used on Wildwood Island. The well-separation distance is restricted by the model discretization. Any of the five large secondary wastewater-treatment plants in the county would provide sufficient water for subsequent tertiary treatment and year-round injection. If one applies Darcy's Law for ground-water flow and assumes a hydraulic conductivity for the aquifer of 100 ft/d, a porosity of 0.3, and a hydraulic gradient of 10 ft/4,000 ft, then the injected water would take almost 40 years to reach the well field.

A comparison of the hydrologic response of the baseline simulation (figs. 7 and 8) and the barrier-injection simulation (fig. 12) indicates little difference in heads in the shallow aquifers. Heads near the hypothetical injection wells are 5 to 10 ft greater in both confined aquifers. A significant difference between the two simulations is the 55-percent reduction in movement of the saltwater-freshwater interface toe toward the Rio Grande well field in the estuarine sand aquifer (table 4). In the other aquifers and locations, saltwater encroachment remains about the same. Comparison of the two simulations shows no significant differences between the ground-water budgets (fig. 9). These results emphasize the local effect of this water-supply-development alternative.

Barrier-Withdrawal Wells

Wells withdrawing brackish water between public-supply wells and the coastline can also create a hydraulic barrier to saltwater encroachment. Continual withdrawals of brackish water can stabilize the saltwater-freshwater interface position. The brackish water could then be discharged to sea or possibly desalinated. Conversion of brackish water whose chloride concentrations are greater than 500 mg/L to freshwater has been mainly a problem of cost, and this cost has decreased over time (Buros, 1989; Metcalf & Eddy, 1979). Another problem affecting desalination is the maintenance of a brackish feedwater source with stable chloride concentrations. If the zone of brackish water is not sufficiently stable, product water can be blended with withdrawals from nearby wells. Disposal of the brine byproduct is another problem associated with desalination. Membrane processes are the most commonly used desalination processes in the United States. These processes use mechanical energy; compared to processes that use thermal energy, membrane processes cost less, provide a higher rate of recovery, function more reliably, and precipitate out a smaller amount of brine. However, membrane processes are more sensitive to feedwater sources and permit less blending of product water.

The predictive simulation for the barrier-withdrawal alternative was identical to the baseline simulation discussed earlier except for the addition of four hypothetical barrier wells screened in the Cohansey aquifer at Cape May City. The Cape May City Water Department has had a long-standing problem of chloride contamination of its well water. Construction of a 1- to 2-Mgal/d membrane desalination plant has been proposed for the area (American Water Works Service Company, Inc., 1993) and pilot-plant testing has been done. Hypothetical barrier-well locations are shown in figure 13. Each well withdraws an average of 0.15 Mgal/d. The total brackish water withdrawal of 0.6 Mgal/d is equal to one-third of the projected freshwater withdrawal from the main public-supply wells (9-43 and 9-45). If a higher withdrawal rate is used for this barrier-well configuration, the wells will begin to remove a significant amount of freshwater. This feedwater-quality limit is analogous to a shifting ground-water divide.

For the barrier-withdrawal simulation (fig. 13), heads in the confined aquifers in Cape May City are 5 to 15 ft lower than for the baseline simulation (fig. 7). Movement of the saltwater-freshwater interface toe in the Cohansey aquifer is approximately 50 ft more than in the baseline simulation (table 4). In the estuarine sand aquifer, interface movement toward the Cape May City wells ceases; however, interface movement toward the other well fields increases by approximately 200 ft compared to the baseline simulation as a result of the barrier withdrawals. The interface advances more in the estuarine sand aquifer than in the Cohansey aquifer, despite the withdrawals from the Cohansey aquifer, because of

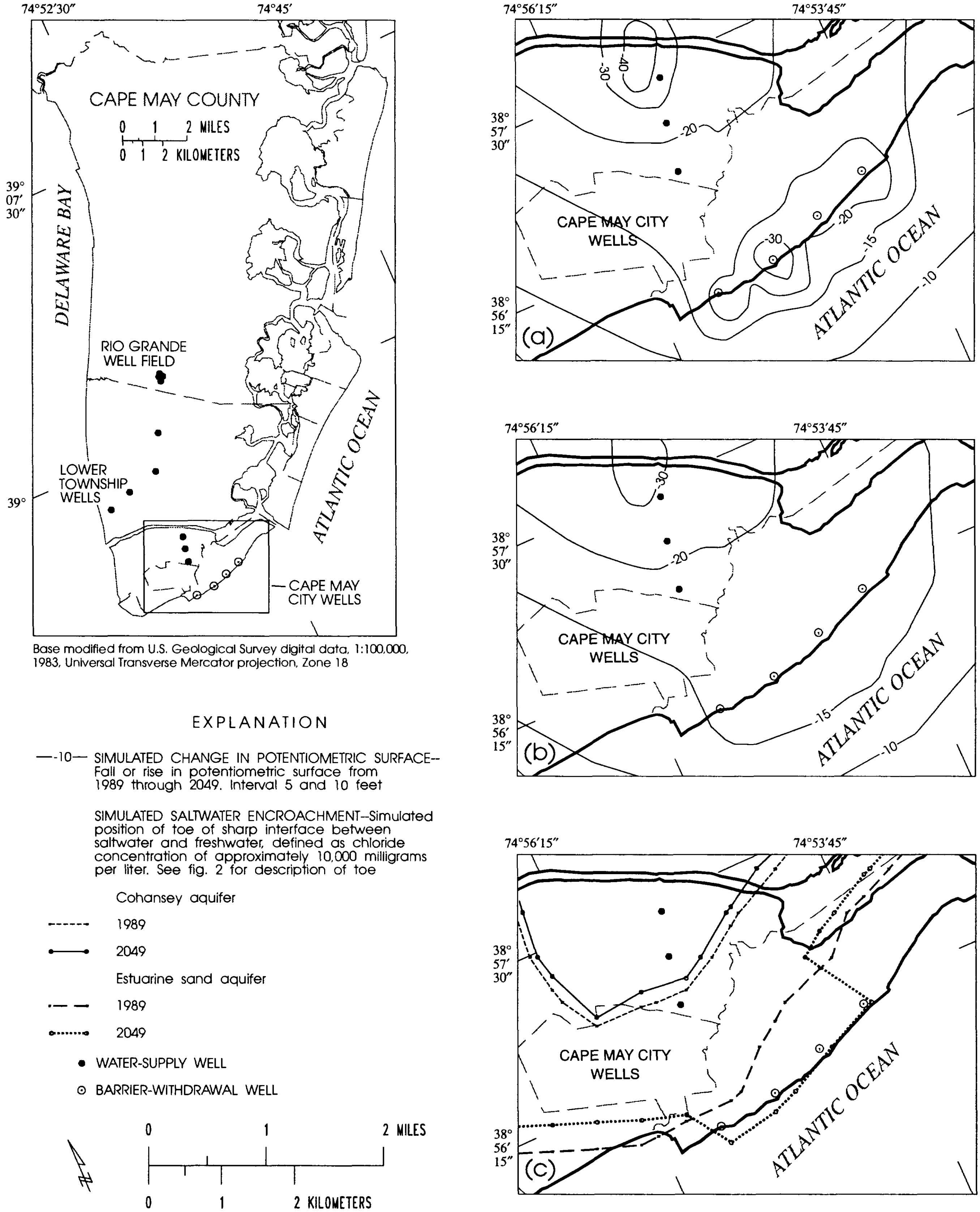


Figure 13. Simulated change in potentiometric surface for the barrier-withdrawal alternative in the (a) Cohansey aquifer and (b) estuarine sand aquifer; and simulated saltwater encroachment in the (c) Cohansey and estuarine sand aquifers, Cape May County, New Jersey.

the proximity of the interface in the estuarine sand aquifer to the barrier wells, the inland calibrated interface position in the Cohansey aquifer, and the significant leakage between the two aquifers. There are no significant differences between the ground-water budgets for this simulation and the baseline simulation (fig. 9). (Withdrawal from the saltwater zone is not reflected in the freshwater budget.) These results emphasize the local effect of this water-supply development alternative.

Conjunctive Use of Ground Water and Surface Water

The conjunctive use of ground water and surface water for water supply would allow for the reduction of withdrawals from public-supply wells, thus lessening the withdrawal stress on aquifers. Considerations in the use of this method are available surface-water quantity, the environmental consequences of reducing surface-water volume, the problems of establishing and maintaining an additional water-distribution system, and the treatment of the surface water.

In Cape May County, this method could take advantage of the seasonal variability of surface water, although the lagtime between the largest quantity of this water and peak water demand is considerable. Surface-water volume is greatest during late winter and spring but is minimal in the summer, when demand is highest. The lag-time problem could be resolved through storage or artificial recharge, however treatment and direct use of the surface water would be easier. Furthermore, the quantity of excess surface water is not large enough to permit the reduction of withdrawals and use of artificial recharge or aquifer storage concurrently.

Although several sand and gravel companies operating in northern Cape May County discharge large amounts of water onto land surface, location of the companies in the protected Pinelands Natural Reserve Area make use of this surface water unlikely. The Tuckahoe River (fig. 1), however, is a potential fresh surface-water source. Table 5 describes a method for estimating excess water in the river. Minimum monthly discharge during 1970-90 and monthly average discharge are shown in the table. Various methods have been used to estimate minimum flow requirements for New Jersey rivers and streams, including those based on drainage area and flow-frequency analysis (R.D. Schopp, U.S. Geological Survey, oral commun., 1990). Estimates based on the logarithm of the most commonly occurring (modal) flow have been proposed recently. These estimates are considered to be the most conservative. For the Tuckahoe River, the modal flow is 16 ft^3/s (10.3 Mgal/d). The difference of average monthly minimum flow minus modal flow is shown in the table. An additional conservative decision that could be made is to use only 20 percent of this difference. None of the calculated volumes exceeds the minimum flow for that month over the period of record.

Average monthly public-supply withdrawals from the shallow aquifer system over the last calibrated pumping period 1983-88 are also included in table 5. Comparison of the calculated excess surface water volume with the total withdrawal for January, for example, shows that a 58-percent reduction in withdrawals is possible during that month. Comparisons for the other months indicate that excess water is plentiful during the winter, whereas no excess water is available in August and September (fig. 14).

Water-quality data for the Tuckahoe River during 1959-82 are available from the National Water Data Storage and Retrieval System, an unpublished data base on file at the New Jersey District Office of the USGS. Concentrations of common constituents indicate that river-water quality is between that of precipitation and that of undeveloped ground water. Concentrations of most constituents meet U.S. Environmental Protection Agency primary (1991a) and secondary (1991b) standards for potable water. The median iron concentration of 415 mg/L, however, exceeds the secondary standard of 300 mg/L. River water also contains fecal coliform and fecal streptococcus bacteria from sources outside the county, at

Table 5. Discharge data for the Tuckahoe River at Head of River, New Jersey, and calculation of surface-water supplement for the conjunctive-use simulation

[All flows in cubic feet per second; - -, no available supplement]

Month	Low flow during period of record, 1970-90[1]																					Aver-age low flow	Average low flow minus required minimum flow[2]	Twenty percent of difference (excess)	Consumptive withdrawals for 1983-88[3]				Percentage of total withdrawal satisfied by excess
	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90				Rio Grande	Cape May City	Lower Town-ship	Total	
January	44	25	47	55	29	27	44	18	43	50	30	13	26	18	49	22	22	50	22	22	41	33	17	3.4	4.0	1.2	.7	5.9	58
February	42	25	46	64	24	46	47	18	42	44	30	16	35	25	46	28	39	50	30	24	36	36	20	4.0	3.5	1.1	.7	5.3	75
March	40	39	56	47	24	43	35	21	42	77	26	24	29	46	69	26	33	45	27	39	32	39	23	4.6	3.9	1.2	.7	5.8	79
April	47	33	54	53	24	43	28	21	46	60	61	23	23	105	76	13	30	54	29	38	27	42	26	5.2	4.5	1.4	.8	6.7	78
May	38	30	48	48	23	44	23	16	42	55	38	23	28	57	45	12	23	31	28	57	26	35	19	3.8	7.4	1.9	1.0	10.3	37
June	27	15	32	28	20	36	17	10	37	42	20	16	17	28	38	15	15	20	12	38	21	24	8	1.6	9.1	2.4	1.3	12.8	12
July	27	11	23	23	12	29	11	12	22	25	24	12	15	19	29	11	13	15	9	29	16	18	2	.4	10.8	3.2	1.5	15.5	2
August	13	14	15	13	12	17	7	13	18	25	6	13	12	16	23	15	13	11	6	28	15	15	-1	- -	10.7	3.2	1.5	15.4	- -
September	10	26	15	10	18	14	12	13	16	19	1	11	11	15	18	10	12	11	9	26	15	14	-2	- -	7.4	2.2	1.0	10.6	- -
October	11	28	16	12	15	25	16	12	18	23	11	10	12	16	18	19	14	13	11	37	14	17	1	.2	4.9	1.6	.9	7.4	3
November	17	39	32	15	17	31	18	14	20	31	22	16	21	23	20	20	21	15	18	45	18	23	7	1.4	3.9	1.4	.9	6.2	23
December	20	50	54	15	20	29	18	30	34	31	15	20	22	47	23	25	34	20	22	32	18	28	12	2.4	3.6	1.2	.9	5.7	42

[1]From Automated Data Processing System, unpublished data base on file at the New Jersey District Office of the U.S. Geological Survey
[2]Required minimum flow is 16 cubic feet per second (R.D. Schopp, U.S. Geological Survey, oral commun., 1990)
[3]From Site Specific Water-Use Data System, unpublished data base on file at the New Jersey District Office of the U.S. Geological Survey

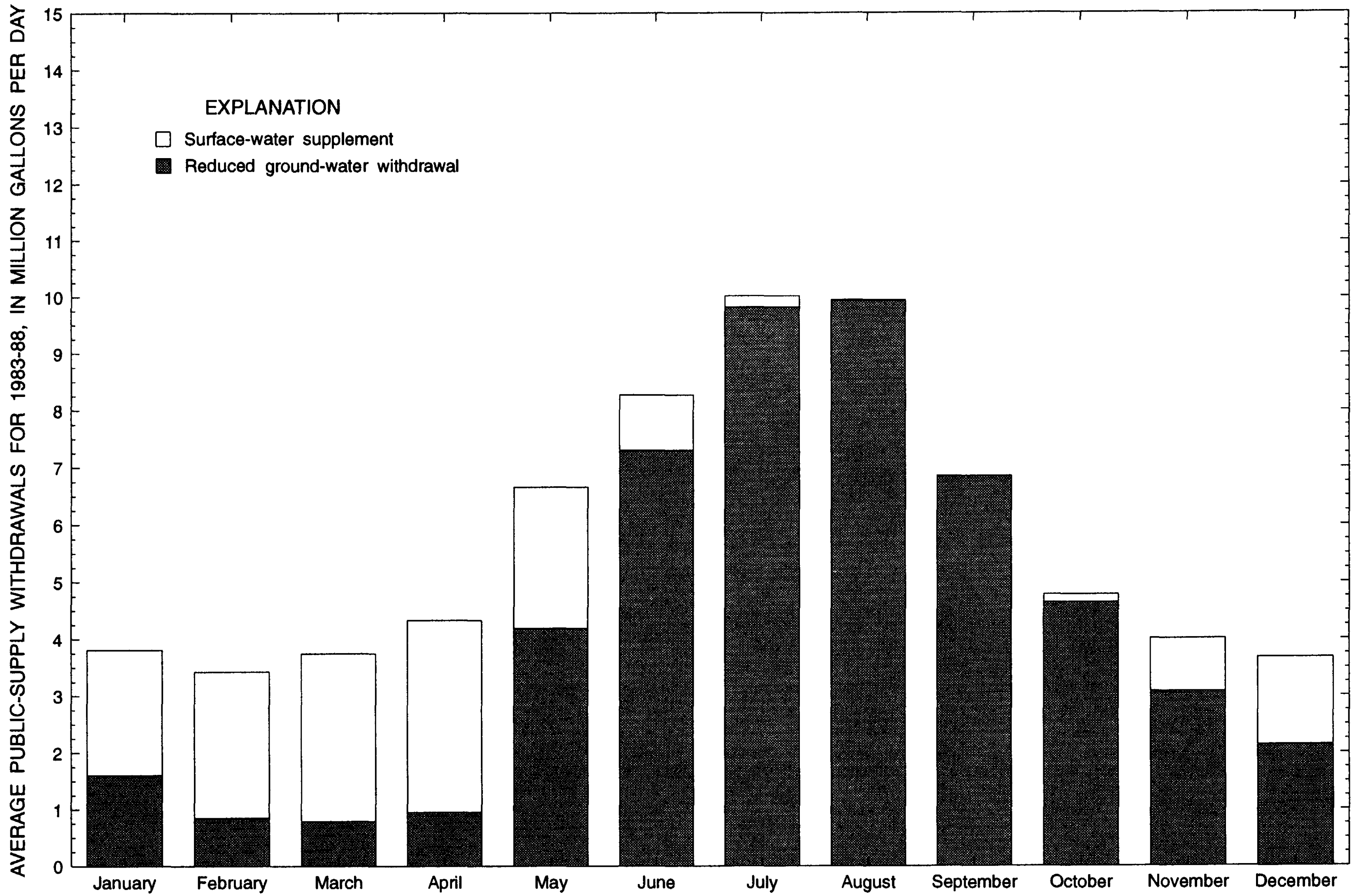


Figure 14. Monthly reduced withdrawal from the shallow aquifer system and estimated surface-water supplement from the Tuckahoe River, Cape May County, New Jersey. (Stacked bars of total withdrawal show the availability of surface water in reducing the demand for ground water.)

levels exceeding State surface-water-quality standards of 200 colonies per 100 milliliters (New Jersey Department of Environmental Protection, 1989). Potential contamination from nearby point and nonpoint sources would require investigation if the Tuckahoe River actually were to be used as a water source.

A predictive simulation was made to test the conjunctive use of ground water and surface water as a periodic supplement to withdrawals. Withdrawals at individual wells at the major well fields are reduced by applying the percent reduction for the well field to the percent of total well field withdrawals for individual wells. This approach results in a more general response of the shallow aquifer system to the conjunctive-use alternative than does the preferential shutdown of well fields. Although withdrawals increase over the planning period according to the projections for the baseline simulation discussed earlier, the surface-water supplement remains constant. Because the model simulates annual average hydrologic conditions, reduced monthly withdrawal rates are converted to annual values by (1) multiplying monthly surface-water supplement rates by the number of days in the month to yield monthly volumes, (2) summing the monthly volumes to obtain an annual volume, and (3) subtracting this volume from the total annual withdrawal volume to obtain a reduced annual withdrawal volume. This difference is then converted to a rate and apportioned among the well fields.

The hydrologic response to the conjunctive-use simulation is less dramatic than that to the baseline simulation. Heads in the confined aquifers for the conjunctive-use simulation (fig. 15) are only 5 ft higher in most areas, excluding the Rio Grande well field, than in the baseline simulation (fig. 7). Movement of the saltwater-freshwater interface toe toward the well fields in the confined aquifers is reduced by an average of 15 percent in the conjunctive-use simulation (fig. 16 and table 4) compared to the baseline simulation (fig. 8). The ground-water budget for the peninsula for the conjunctive-use simulation shows slightly less leakage from the unconfined aquifer compared to that for the baseline simulation (fig. 9). Discharge to tidal wetlands is also increased.

Redistribution of Withdrawals

To prolong the water-supply capability of and lessen the saltwater encroachment problem in the shallow aquifer system, municipalities could redistribute public-supply withdrawals to new locations. The logical relocation of withdrawals is to areas where ground-water levels are highest and saltwater encroachment is furthest. Placement of wells northward and inland along the centerline of the peninsula would satisfy these criteria.

A predictive simulation testing the redistribution of withdrawals in the Cohansey aquifer was made previously by Spitz and Barringer (1992). Of the predictive simulations in that study, redistribution resulted in the least drawdown and saltwater encroachment. In that simulation, total public-supply withdrawals for Lower Township, Rio Grande, and Cape May City were redistributed to the Rio Grande well field and two hypothetical well fields near Burleigh and Cape May Court House (see fig. 1 for locations). Withdrawals at Lower Township and Cape May City were ceased, as was injection operations at Wildwood Island. The simulated withdrawals were apportioned at a ratio of 1:2:3 from Rio Grande, Burleigh, and Cape May Court House, respectively.

This redistribution design can be further enhanced by shifting the withdrawals from the confined aquifer to the unconfined aquifer. Currently, the unconfined aquifer is underutilized and is subject to little saltwater encroachment. The unconfined aquifer also has a high specific yield, contains most of the water in the shallow aquifer system, and is more economical to use than deeper aquifers are; its use would help to reduce the pumping stress on the confined aquifers.

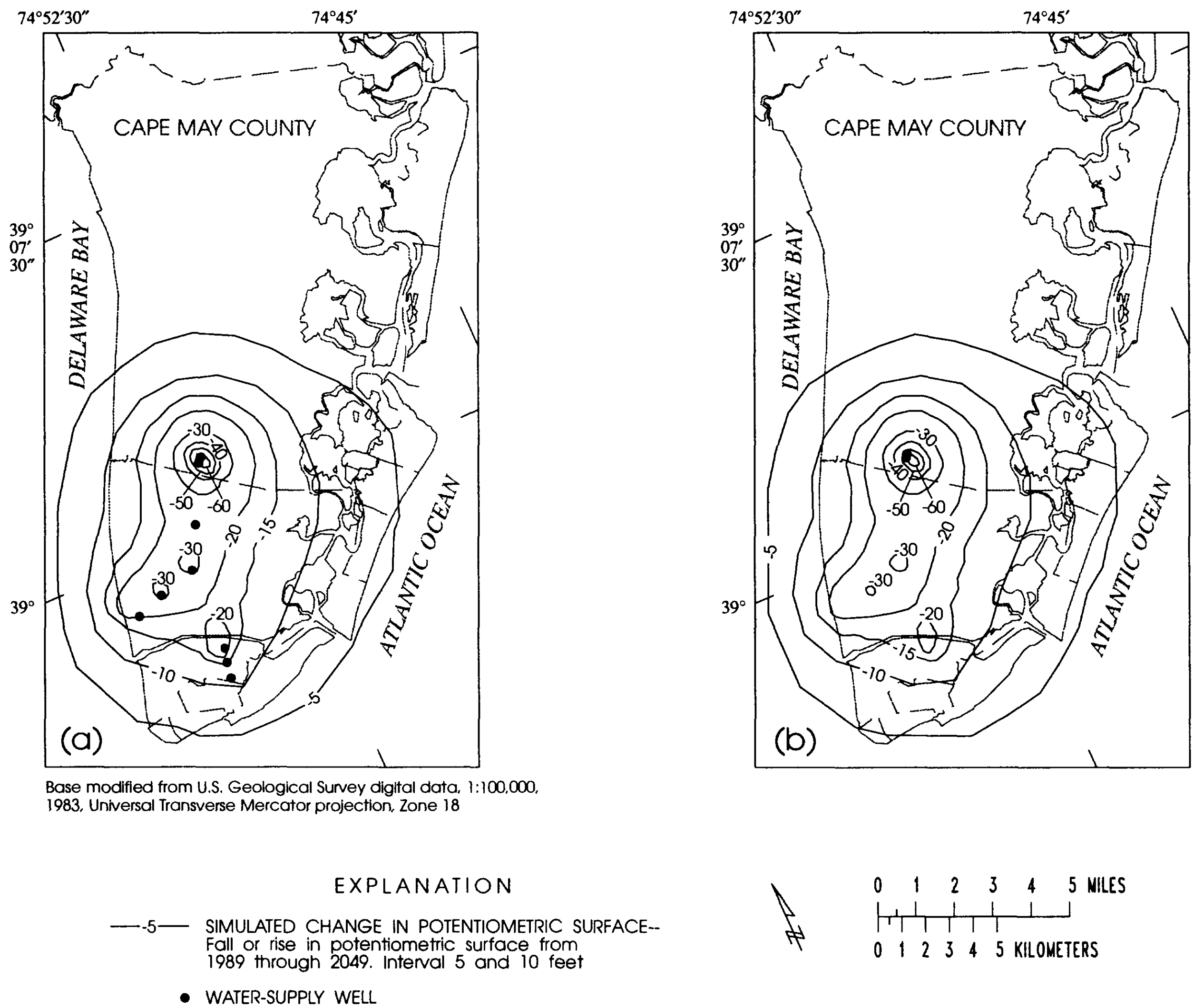


Figure 15. Simulated change in potentiometric surface for the conjunctive-use alternative in the (a) Cohansey aquifer and (b) estuarine sand aquifer, Cape May County, New Jersey.

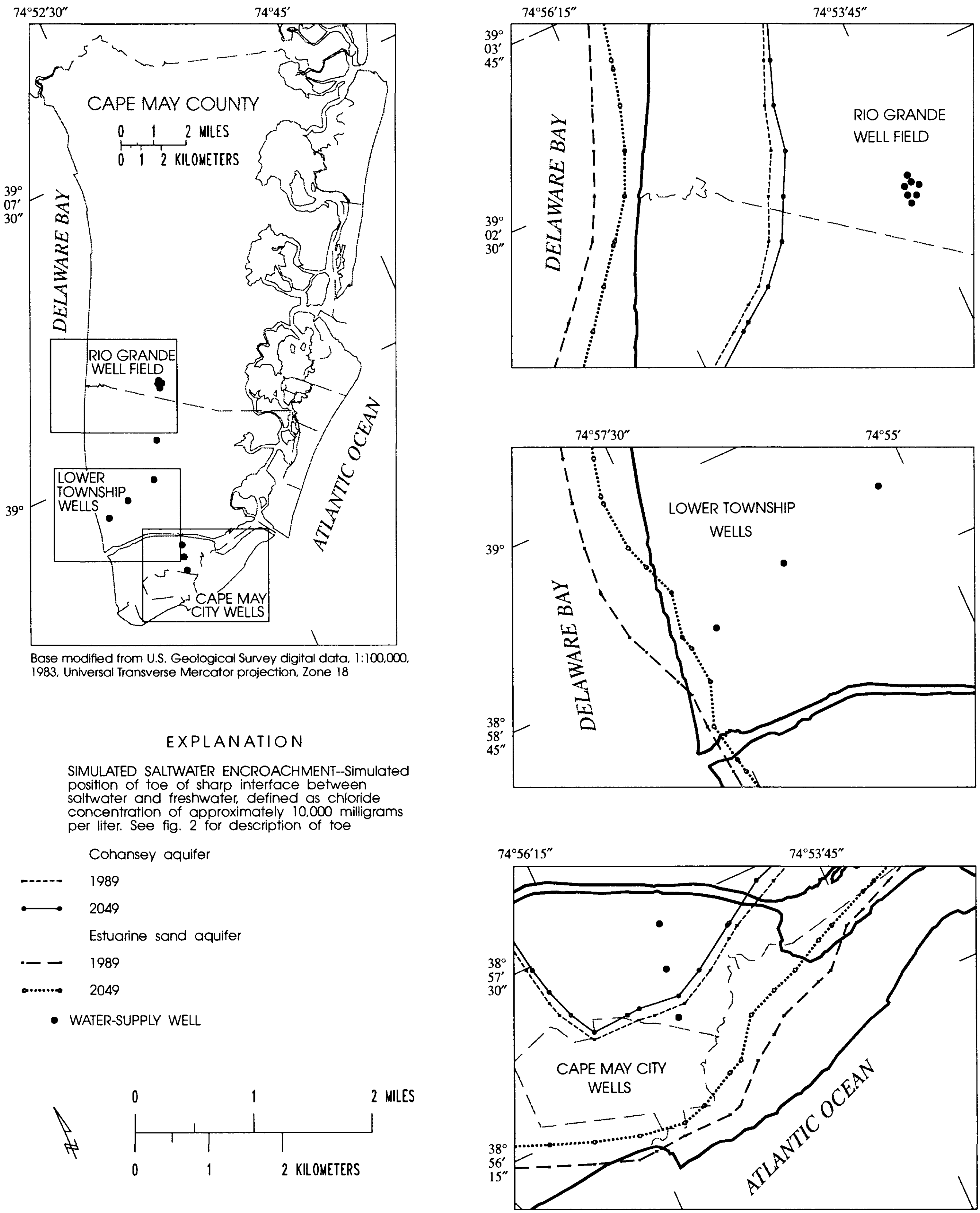


Figure 16. Simulated saltwater encroachment for the conjunctive-use alternative in the Cohansey and estuarine sand aquifers, Cape May County, New Jersey.

Unfortunately, anthropogenic contamination would be a concern if the unconfined aquifer were developed for water supply. Pristine areas are necessary for locations of shallow wells, and local water quality would need to be thoroughly investigated if the aquifer were to be used. Locations of both nonpoint- and point-source contamination are widespread in the county, particularly in the developed areas south of Great Cedar Swamp (G.B. Carleton, U.S. Geological Survey, written commun., 1994; Cape May County Planning Board, 1979). Shallow wells at the Rio Grande well field are susceptible to contamination by leachate from the old Lower Township Landfill, located between Rio Grande and Villas. The hypothetical well field at Burleigh is southeast of the old Middle Township Landfill. The hypothetical well field at Cape May Court House is south of one of the USEPA Superfund sites in the county. Other less significant sources of contamination could be closer to these well fields. Therefore, implementation of the redistribution alternative would require continued monitoring of the water quality near the shallow-well fields.

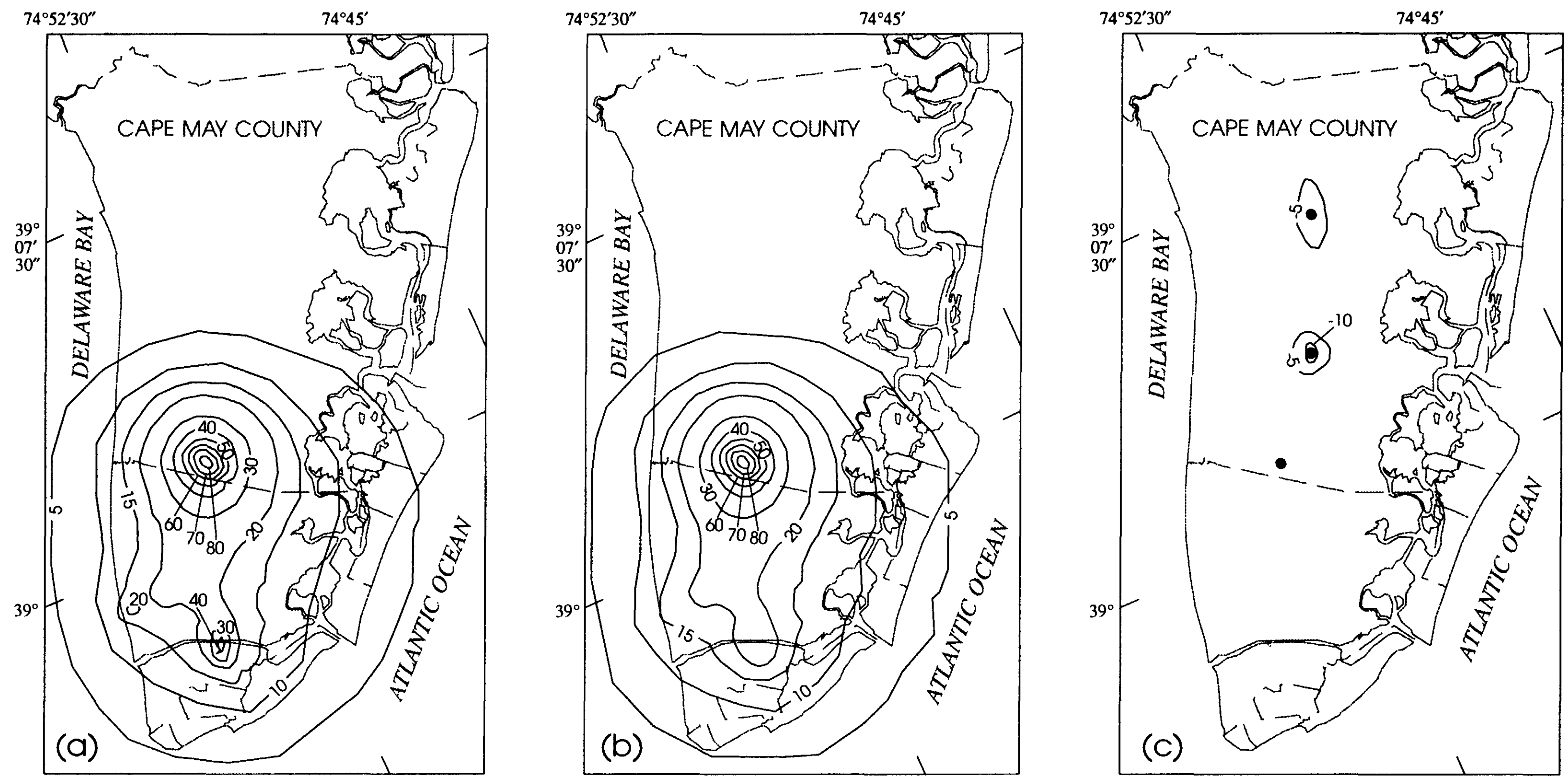
A predictive simulation was made by using the well-field design of Spitz and Barringer (1992), but with the projected withdrawals shifted to the unconfined Holly Beach water-bearing zone. The hydrologic response for this simulation is dramatic compared to the baseline simulation. Heads in the confined aquifers in the redistribution simulation recover to near sea level on most of the peninsula (fig. 17) and are 10 to 75 ft higher than corresponding heads for the baseline simulation (fig. 7). Heads in the unconfined aquifer for the redistribution simulation are only slightly lowered at the well fields. This is the only water-supply-development alternative tested that addresses the cause of the saltwater encroachment, which is ground-water levels that are below sea level.

Movement of the saltwater-freshwater interface toe toward the existing well fields in the confined aquifers nearly ceases (fig. 18 and table 4), except toward Cape May City in the estuarine sand aquifer. Simulated interface movement at this location is reduced 60 percent compared to that in the baseline simulation. Simulated interface movement for the redistribution simulation in this study is 40 percent less than movement for the redistribution simulation in Spitz and Barringer (1992, table 9). Interface movement toward the hypothetical well fields in the unconfined aquifer is less than 100 ft and is not shown. Redistribution causes the most significant changes to the ground-water budget of all the simulated alternatives compared to the baseline simulation (fig. 9): nearly twice as much water is released from storage, leakage to the confined aquifers is significantly reduced, and lateral inflow from offshore ceases.

Comparison of Results of Predictive Simulations

In the baseline simulation where no action is taken to change the rate and distribution of projected water-supply withdrawals, heads in the confined aquifers decline up to 40 ft in the southern part of the peninsula over the planning period. Heads in the unconfined aquifer change little in all of the simulated water-supply-development alternatives over the planning period. In comparing heads in the confined aquifers for the simulated alternatives with heads for the baseline simulation, the redistribution alternative results in the greatest regional recovery (10-75 ft). Simulated heads are 5 ft higher regionally for the conjunctive-use alternative, 5 to 10 ft higher locally for the barrier-injection alternative, and 5 to 15 ft lower locally for the barrier-withdrawal alternative compared to the baseline simulation.

The simulated saltwater-freshwater interface toe in the estuarine sand aquifer advanced approximately 1,350, 1,740, and 1,680 ft toward the Cape May City wells, the Lower Township wells, and the Rio Grande well field, respectively, for the baseline simulation over the planning period. Simulated interface movement in the Cohansey aquifer toward the well fields was about half that in the estuarine sand aquifer. Interface movement in the unconfined aquifer was negligible in this simulation, as it was in all the simulated alternatives. In comparing interface movement in the confined aquifers in the simulated alternatives with movement in the baseline simulation, the redistribution alternative results in the least regional



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

EXPLANATION

——-5—— SIMULATED CHANGE IN WATER-TABLE OR POTENTIOMETRIC SURFACE-- Fall or rise in water-table or potentiometric surface from 1989 through 2049. Interval 5 and 10 feet

● WATER-SUPPLY WELL

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

Figure 17. Simulated change in water-table and potentiometric surfaces for the redistribution alternative in the (a) Cohansey aquifer, (b) estuarine sand aquifer, and (c) Holly Beach water-bearing zone, Cape May County, New Jersey.

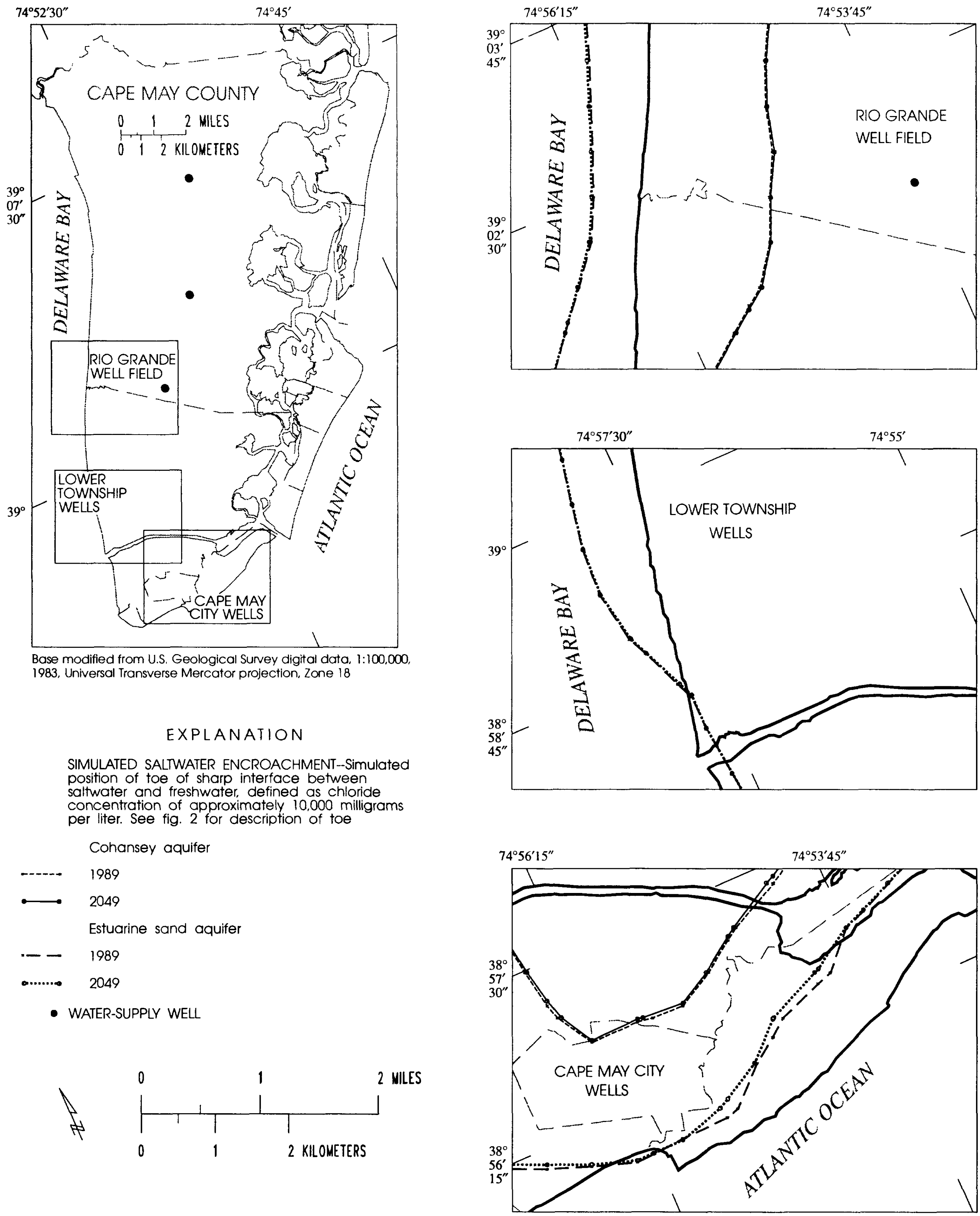


Figure 18. Simulated saltwater encroachment for the redistribution alternative in the Cohansey and estuarine sand aquifers, Cape May County, New Jersey.

movement (85 percent less than baseline). There is no interface movement in the estuarine sand aquifer toward the Cape May City wells, a 5-percent increase in movement in the Cohansey aquifer toward the same wells, and a 10-percent increase in movement in the confined aquifers toward the other well fields for the barrier-withdrawal alternative compared to the baseline simulation. Simulated interface movement in the estuarine sand aquifer is reduced 55 percent toward the Rio Grande well field and is unchanged toward the other well fields, and in the Cohansey aquifer is unchanged toward the well fields for the barrier-injection alternative compared to the baseline simulation. Simulated interface movement in the confined aquifers is reduced by about 15 percent regionally in the conjunctive-use simulation compared to the baseline simulation.

Changes in ground-water flows over the planning period for the baseline simulation are a 90-percent increase in downward leakage to the confined aquifers, a 15-percent decrease in discharge to tidal wetlands, and a 70-percent increase in water released from storage (fig. 9). Comparison of flows for the simulated alternatives with flows for the baseline simulation shows that the redistribution alternative results in the most benefit to the ground-water budget. Simulated leakage is significantly reduced, lateral inflow from offshore ceases, and release of water from storage is increased 80 percent compared to the baseline simulation. Simulated leakage is reduced by 15 percent for the conjunctive-use alternative compared to the baseline simulation. Change in flows in the two barrier alternatives are negligible compared to the baseline simulation.

Lateral saltwater encroachment is the dominant hydrologic process in the ground-water system nearshore. Leakage is the dominant hydrologic process in the cones of depression around the major well fields, even though the leakage is impeded by low-permeability confining units. Vertical gradients are much greater than lateral gradients in the cones of depression. Induced leakage of saline water can also contaminate an aquifer. Travel times for freshwater leakage through the confining units at the well fields can be computed from simulated leakage rates. Travel times through the estuarine clay confining unit and the confining unit overlying the Cohansey aquifer in 1989 average 17.1 and 0.5 years, respectively. Travel times through the estuarine clay confining unit in 2049 averaged half as long as in 1989 for most of the simulated alternatives. However, for the redistribution alternative, travel times are longer than in 1989. For the confining unit overlying the Cohansey aquifer, travel times are also reduced by half, except at Lower Township, where they are reduced by two-thirds. The difference at Lower Township is related to the weak calibration of interface position in the Cohansey aquifer in this location. For the redistribution alternative, travel times are significantly longer than in 1989.

SUMMARY AND CONCLUSIONS

Cape May County is the southernmost county in New Jersey. Much of the county is a peninsula of low topographic relief with tidally influenced wetland along its coast. Increasing residential and seasonal tourist populations have increased the water demand in the county. Withdrawals from the shallow confined aquifers have supplied more than half of this demand, the rest coming from withdrawals from deeper aquifers. Surface-water sources have not been available. Three aquifers, in order of increasing depth, make up the shallow aquifer system: the unconfined Holly Beach water-bearing zone and the confined estuarine sand and Cohansey aquifers.

Precipitation accounts for most of the ground-water recharge, and ground-water discharge occurs mainly in the unconfined part of the system. Concern about anthropogenic contamination has precluded substantial use of the unconfined aquifer for supply. Withdrawals from the shallow confined aquifers have caused a regional lowering of ground-water levels, a reversal of flow directions, and saltwater encroachment in the southern part of the peninsula. For example, nearshore water-supply wells in Cape

May City have been abandoned because of increasing chloride concentrations, and new wells have been drilled inland. Further development in the county, and a corresponding increase in water demand, will exacerbate the current saltwater-encroachment situation.

The purpose of this study was to test the hydrologic feasibility of possible water-supply-development alternatives by use of predictive ground-water flow simulations. The goal of the alternatives is to preserve and protect the existing water-supply capability of the area. The alternatives include application of hydraulic barriers created by artificial recharge or withdrawal of brackish water, conjunctive use of ground water and surface water as a supplement to withdrawals, and redistribution of withdrawals. The hydrogeology of the area constrains the number of alternatives to be tested. Some of the alternatives will provide only interim solutions to the water-supply problem, because withdrawals on the peninsula currently exceed long-term recharge. Results of these simulations can potentially be used in the design of a water-management strategy that preserves supply and a monitoring program that ensures early warning of saltwater encroachment, thereby allowing sufficient time for development of an alternative supply.

The predictive simulations describe the hydrologic response of the shallow aquifer system through changes in heads, flows, and saltwater encroachment. A previously calibrated quasi-three-dimensional ground-water flow model was used for the predictive simulations. Limitations and assumptions of the model are presented. The planning period for the simulations was 1989 to 2049. For each simulation, current public-supply withdrawals at Cape May City, Lower Township, and Rio Grande were increased according to projected percent increases in dwelling-unit construction or sewer capacity. The percent increases vary with location and time and, combined, represent a 95-percent increase in total public-supply withdrawals over the planning period.

In comparing the calibrated shallow aquifer system for 1989 with results of a baseline simulation involving only the projected withdrawals, heads in the southern part of the peninsula decline up to 40 ft in the confined aquifers, whereas heads in the unconfined aquifer change only slightly. Encroachment of the saltwater-freshwater interface in the estuarine sand aquifer is 1,350 ft toward Cape May City, 1,740 ft toward Lower Township, and 1,680 ft toward Rio Grande. Interface movement in the Cohansey aquifer toward these well fields is about half that in the estuarine sand aquifer. Interface movement in the Holly Beach water-bearing zone is negligible. Surficial discharge decreases, downward leakage to the confined aquifers increases, and release of water from aquifer storage increases for the baseline simulation compared to the 1989 simulation.

Results of the baseline simulation are used to compare the four simulated water-supply-development alternatives. The first alternative involves use of injection wells and tertiary-treated wastewater. This method of artificial recharge replenishes the ground-water system by adding to aquifer storage and creates a hydraulic barrier to saltwater encroachment. Two hypothetical wells screened in the estuarine sand aquifer, each injecting 0.15 Mgal/d, were simulated near the Rio Grande well field. This design was chosen because saltwater encroachment is fastest in this aquifer and the well field is the location of the largest withdrawals from the shallow aquifer system. In this simulation, heads in the confined aquifers are 5 to 10 ft higher locally, and saltwater encroachment in the estuarine sand aquifer is 55 percent less than in the baseline simulation locally. The response in the unconfined aquifer for this and the other simulated alternatives is small. Differences in ground-water flows from the baseline simulation also are small.

The second simulated alternative involves withdrawal of brackish water in an area already experiencing saltwater encroachment. This method creates a hydraulic barrier which can stabilize the position of the saltwater-freshwater interface. The brackish water could then possibly be desalinated. Four hypothetical wells screened in the Cohansey aquifer, each withdrawing 0.15 Mgal/d, were simulated between the Cape May City wells and the saltwater-freshwater interface. In this simulation, heads in the confined aquifers in the vicinity of the barrier wells are 5 to 15 ft lower than in the baseline simulation. Saltwater encroachment ceases in the estuarine sand aquifer and increases 5 percent in the Cohansey aquifer toward the Cape May City wells in this simulation. Encroachment in the confined aquifers toward the other well fields increases by 10 percent. Differences in ground-water flows from the baseline simulation are small.

The third simulated alternative is the conjunctive use of ground water and surface water in order to lessen the withdrawal stress on the shallow aquifer system. Excess surface water from the Tuckahoe River, when available, could be treated and used directly or stored for water supply. About 20 percent of the difference between average monthly low flow and the State-required minimum flow would be used from the river. Using this amount of surface water would allow withdrawals at the three major well fields to be reduced by 15 percent annually, based on withdrawals in 2049. In this simulation, heads in the confined aquifers on the peninsula are 5 ft higher regionally than in the baseline simulation. Saltwater encroachment in the confined aquifers toward the well fields is reduced an average of 15 percent compared to the baseline simulation. Changes to ground-water flows are less than those in the baseline simulation.

The fourth simulated alternative involves the redistribution of withdrawals inland and to the unconfined aquifer in order to alleviate the withdrawal stress on the confined aquifers. The Rio Grande well field and two hypothetical well fields at Burleigh and Cape May Court House were simulated for this alternative. In this simulation, heads in the confined aquifers on the peninsula recover significantly, whereas heads in the unconfined aquifer are only slightly lower than in the baseline simulation. Saltwater encroachment toward the well fields is small in the confined aquifers. Twice as much water is released from storage, leakage to the confined aquifers is significantly reduced, and lateral inflow from offshore ceases in this simulation.

Results of the predictive simulations indicate that the barrier-injection scheme could be useful in managing the water supply at a specific location. Likewise, the barrier-withdrawal scheme could preserve and protect the water supply locally but could exacerbate saltwater encroachment in other locations. The conjunctive-use scheme would provide a marginal regional hydrologic benefit. Redistribution of withdrawals inland and from the confined aquifers to the unconfined aquifer appears to be the only regional alternative that would result in recovery of ground-water levels and would substantially lessen saltwater encroachment; however, anthropogenic contamination of the unconfined aquifer would have to be considered if the alternative is acted upon.

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