EVALUATION OF SALTWATER INTRUSION AND TRAVEL TIME IN THE ATLANTIC CITY 800-FOOT SAND, CAPE MAY COUNTY, NEW JERSEY, 1992, BY USE OF A COUPLED-MODEL APPROACH AND FLOW-PATH ANALYSIS

By Lois M. Voronin, Frederick J. Spitz, and Steven D. McAuley

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U. S. GEOLOGICAL SURVEY

Gordon P. Eaton, *Director*

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ILLUSTRATIONS--Continued

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

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Transmissivity	
square foot per day (ft^2/d)[1]	0.09290	square meter per day

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.

Water-quality abbreviations:

mg/L - milligrams per liter

1.This unit is used to express transmissivity, the capacity of an aquifer to transmit water. Conceptually transmissivity is cubic feet (of water) per day per square foot (of aquifer area) times feet (of aquifer thickness), or (ft^3/d)/ft^2 x ft. In this report, this expression is reduced to its simplest form, ft^2/d.

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ABSTRACT

Regional and subregional ground-water-flow models were coupled, and the output was analyzed by a particle-tracking method. The results were then used to assess the effects of ground-water withdrawals on the flow of saltwater in the Atlantic City 800-foot sand in Cape May County, New Jersey, and to estimate the travel time from areas in which the chloride concentration of the ground water exceeds 250 milligrams per liter to the county's nearest public supply wells.

First, a quasi-three-dimensional finite-difference computer model of freshwater and saltwater flow that simulated regional ground-water flow through the unconsolidated materials underlying the New Jersey Coastal Plain was used to estimate flow at the boundaries of the subregional study area. The results of the regional simulation were used as input to a second quasi-three-dimensional finite-difference model that was used to simulate flow in the subregion, the Atlantic City 800-foot sand in Cape May County.

The results of the simulation of flow in the subregion were analyzed by a semianalytical particle-tracking method to estimate ground-water flow paths and travel time of ground water from areas in which chloride concentrations exceed 250 milligrams per liter to public supply wells located at Stone Harbor, New Jersey. Ground-water withdrawals from the Atlantic City 800-foot sand were assumed to be equal to those reported for 1991. Results of the analysis indicate that the time required for saltwater to reach the public supply wells is on the order of hundreds of years. These results, however, are based on the assumptions that the aquifer is homogeneous. The presence of zones of high permeability in the aquifer could reduce the predicted travel times of the saltwater from its present location to the supply wells. Travel times also could be reduced if ground-water withdrawals increase.

INTRODUCTION

Ground water is the most important source of public water supply in Cape May County, New Jersey (fig. 1). In the barrier-island communities, ground water is withdrawn from the regionally confined aquifer system, the Atlantic City 800-foot sand. Additional supplies are obtained and transported from the shallow ground-water system on the mainland. The presence of saline ground water (ground water in which the chloride concentration exceeds 250 mg/L) in Cape May County was documented in 1926 when water samples from a well screened in the Atlantic City 800-foot sand in Wildwood (fig. 1) were found to contain chloride in a concentration of 352 mg/L (Gill, 1962a, table 7). Water from a well sampled in 1957 in Cape May City contained chloride in a concentration of 1,510 mg/L (Gill, 1962, table 7) and confirmed the presence of saltwater in Cape May County. These data indicate that saltwater intrusion in the Atlantic City 800-foot sand had occurred prior to 1926, possibly as a result of the presence of a large zone of diffusion that broadened in response to sea-level fluctuations during the Pleistocene glacial periods (Meisler and others, 1985). The saltwater may be moving landward in response to ground-water withdrawals and (or) because the system is not in equilibrium as a result of these fluctuations.

Concern about the future adequacy of freshwater supplies from the Atlantic City 800-foot sand in Cape May County led the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, to undertake a study of saltwater intrusion in this aquifer in order to estimate the travel time of the saltwater from its present location to the public supply wells at Stone Harbor in Cape May County, New Jersey. This report presents the results of the study and describes the calibrated ground-water-flow model and the particle-tracking technique that were used to estimate travel time.

Approach

A regional and a subregional ground-water-flow model were coupled to assess the effects of ground-water withdrawals on the flow of saltwater in the Atlantic City 800-foot sand. Model coupling has been shown to be a useful approach to ground-water-flow simulation by Buxton and Reilly (1986). First, a regional model of ground-water-flow through the sediments of the New Jersey Coastal Plain (D.A. Pope, U.S. Geological Survey, written commun., 1991) was used to estimate the quantity and distribution of flow across the natural and artificial boundaries of the Cape May subregional model area. Next, the results of this simulation were input to the subregional model to refine the estimates of flow in the Atlantic City 800-foot sand in the smaller area of interest. Finally, a particle-tracking method was used to estimate ground-water-flow paths and travel time from parts of the aquifer that contain saltwater to the public supply wells at Stone Harbor, New Jersey (fig. 1).
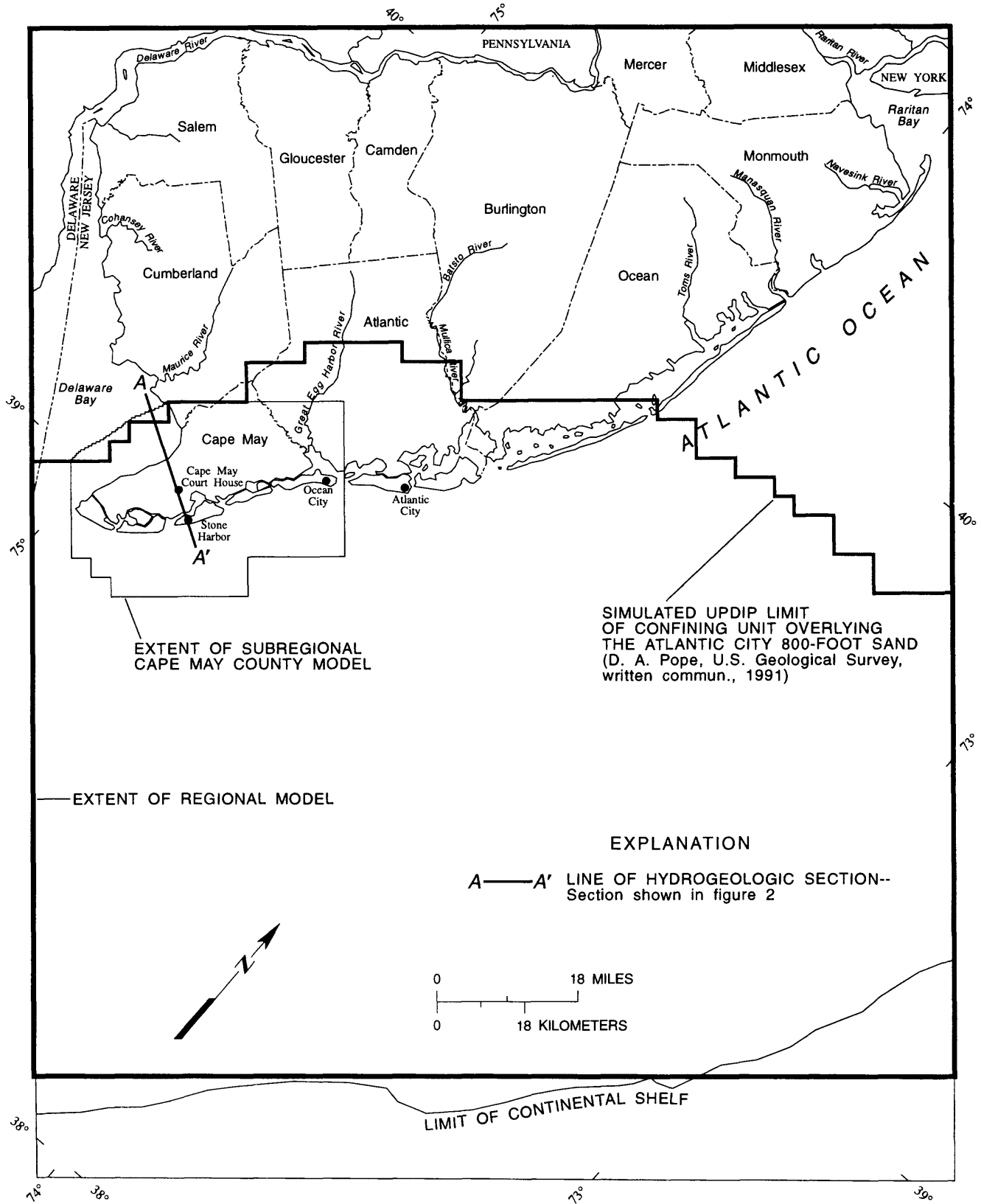
Figure 1. Location of study area in the New Jersey Coastal Plain.

The regional model extends to the natural boundaries of the Coastal Plain sediments at the outcrop to the northwest and the subcrop to the southeast, at the continental shelf (fig. 1). Its northeast and southwest boundaries are artificial boundaries in offshore areas where flows were calculated with a model of the Northern Atlantic Coastal Plain (Leahy and Martin, 1993). The regional model is coarsely discretized, with a grid-cell size of 13,200 ft on each side in the subregional model area. Ground-water flow in the regional model area was simulated by use of SHARP (Essaid, 1990), a quasi-three-dimensional finite-difference computer model of freshwater and saltwater flow separated by a sharp interface in a layered coastal aquifer system.

Results of the simulation with the SHARP model were used in the subregional model as simulated ground-water flow at the boundaries of the subregional model area. Ground-water flow in the Atlantic City 800-foot sand in the subregional model area (fig. 1) was simulated by the use of MODFLOW (McDonald and Harbaugh, 1988). The subregional model is more finely discretized than the regional New Jersey Coastal Plain model. The cell size in the subregional Cape May County model grid, 1,320 ft on each side, allows for a sufficiently detailed representation of local variations in thickness, water levels, and distribution of ground-water withdrawals to estimate travel time of saltwater moving toward public supply wells.

The regional model was used to simulate ground-water flow and movement of the freshwater-saltwater interface (10,000 mg/L chloride concentration), including the quantity and distribution of flow across the interface and accounted for density differences between freshwater and saltwater. The boundaries of the subregional model do not extend to the freshwater-saltwater interface in the Atlantic City 800-foot sand, but are located 9 mi or more from it. Therefore, the use of MODFLOW to simulate fresh ground-water flow in the Atlantic City 800-foot sand in Cape May County is valid.

Ground-water-flow paths and travel time from parts of the aquifer that contain saltwater to the public supply wells at Stone Harbor, New Jersey, were estimated by use of a semianalytical particle-tracking method. The method is used to calculate steady-state flow paths in a block-centered finite-difference ground-water-flow model. The interblock flows calculated with the subregional steady-state model were used as input to the particle-tracking method. The method incorporates the assumption that the velocity in each coordinate direction varies linearly between the velocities calculated by the flow model at each face of the finite-difference block. Under these conditions, an analytical expression is derived that describes the three-dimensional velocity field within each block. After the three-dimensional velocity distribution is calculated for each block in the flow model, the unique path of any particle within the model area can be determined. The mathematical derivation of and analytical expressions for the particle-tracking algorithm are given in Pollock (1989).

Flow paths calculated by the particle-tracking method are based on average linear velocities computed by the finite-difference model. Hydrodynamic dispersion (mixing or spreading) of a chemical species as a result of small-scale velocity variations is not considered. Although flow paths calculated with this method are accurate for the model representation of the ground-water-flow system, any numerical model is a simplification of the actual ground-water-flow system that can cause results to be inaccurate (Pollock, 1989).
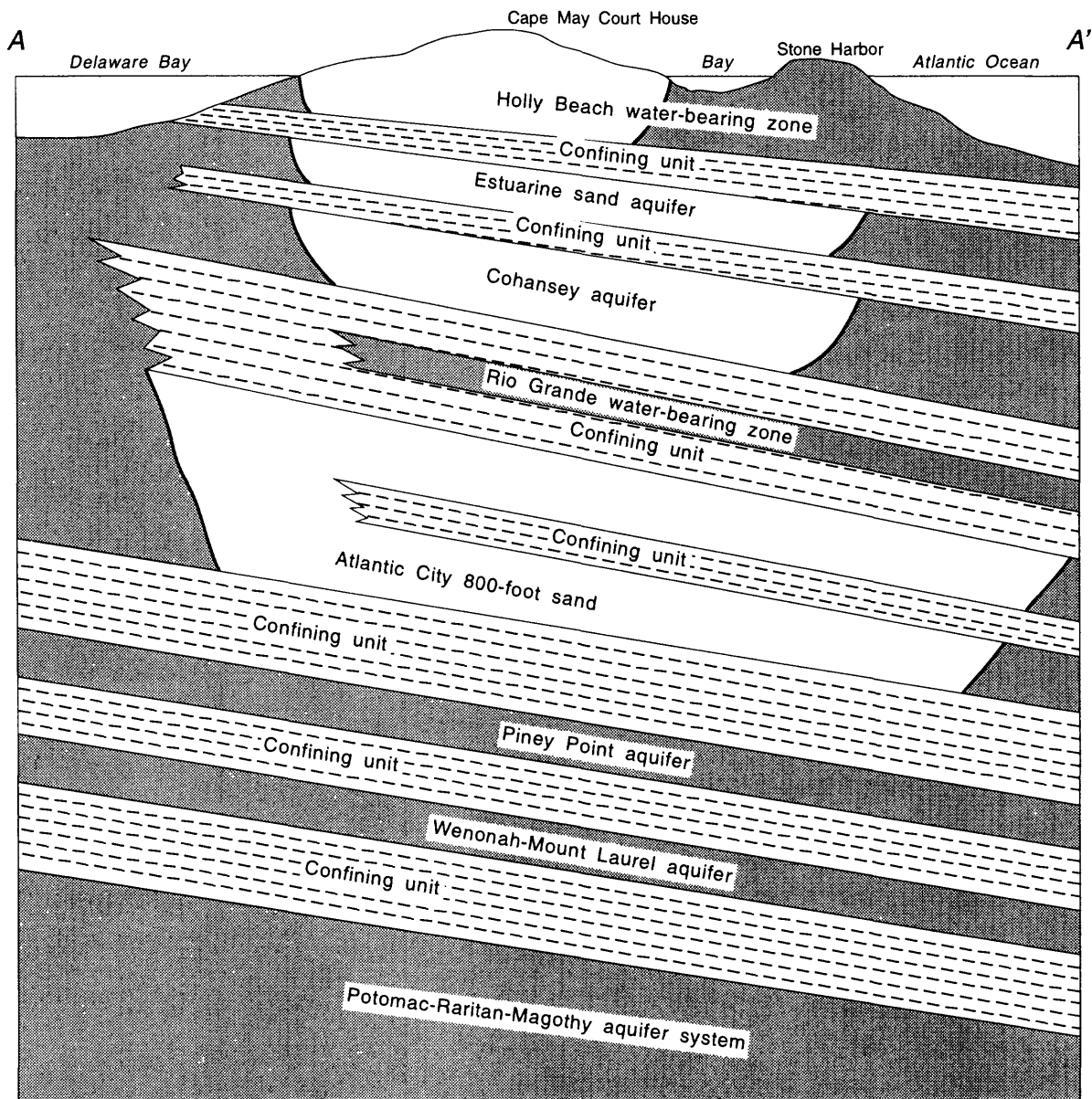
Hydrogeology

The Atlantic City 800-foot sand is located in New Jersey in the Coastal Plain Physiographic Province. The Coastal Plain sediments consist of layers of gravel, sand, silt, and clay that gently dip and thicken to the southeast. The Atlantic City 800-foot sand lies within the lower part of the Kirkwood Formation of middle Miocene age and is a regionally confined aquifer system (fig. 2) that is bounded above and below by thick confining units that attain maximum thicknesses of 200 and 140 ft, respectively (P.J. Lacombe and G.B. Carleton, U.S. Geological Survey, written commum., 1992). In Cape May County, the Holly Beach water-bearing zone, estuarine sand aquifer, Cohansey aquifer, and Rio Grande water-bearing zone overlie the Atlantic City 800-foot sand. The Piney Point aquifer, Wenonah-Mount Laurel aquifer, and Potomac-Raritan-Magothy aquifer system underlie it; these aquifers do not provide potable water for Cape May County and, therefore, are not discussed in detail in this report.

The confining unit overlying the Atlantic City 800-foot sand is described by Martin (in press), D.A. Pope (U.S. Geological Survey, written commun., 1991) and P.J. Lacombe (U.S. Geological Survey, written commun., 1992). For this study, the limit of this overlying confining unit is the same as that assumed by D.A. Pope (U.S. Geological Survey, written commun., 1991) for the New Jersey Coastal Plain regional model. The updip limit of the confining unit that overlies the Atlantic City 800-foot sand is west and north of Cape May County in Ocean, Burlington, Atlantic, and Cumberland Counties (fig. 1). In these areas, the Atlantic City 800-foot sand is in direct hydraulic connection with the overlying Kirkwood-Cohansey aquifer system. In areas where the confining unit overlying the Atlantic City 800- foot sand is truncated in the Delaware Bay or the Atlantic Ocean, offshore from Ocean County, the saltwater is hydraulically connected to the freshwater in the Atlantic City 800-foot sand (fig. 2). Directly to the east, the overlying confining unit is assumed to extend to the continental shelf (fig. 1) (D.A. Pope, U.S. Geological Survey, written commun., 1991).

Figure 2. Generalized hydrogeologic section through the Cape May peninsula, New Jersey, showing the approximate extent of freshwater and saltwater. (Location of section shown in fig. 1)

The altitude of the Atlantic City 800-foot sand in Cape May County ranges from 350 to 950 ft below sea level. For this study, the Atlantic City 800-foot sand was subdivided into two layers and an intervening confining unit on the basis of an analysis of geophysical logs (P.J. Lacombe and G.B. Carleton, U.S. Geological Survey, written commun., 1992). Zapecza (1989, p. 18) describes the Atlantic City 800-foot sand as a single unit; however, some discussion of the presence of an intervening clay is included. Geophysical borehole logs obtained from several wells in Cape May County (P.J. Lacombe and G.B. Carleton, U.S. Geological Survey, written commun., 1992) indicate that an intervening clay, ranging in thickness from 10 to 60 ft, is present along the barrier island and at some locations farther inland. The extent and integrity of this clay unit throughout Cape May County is poorly documented. For this study, the intervening clay is defined as a continuous confining unit throughout the Atlantic City 800-foot sand in Cape May County. The thickness of the upper layer of the Atlantic City 800-foot sand ranges from about 40 to 130 ft and the thickness of the lower layer ranges from about 30 to 130 ft.

In the description of the predevelopment potentiometric surface and flow directions for the Atlantic City 800-foot sand, Zapecza and others (1987, fig. 9) do not differentiate the Atlantic City 800-foot sand into two layers. Before development, recharge to the Atlantic City 800-foot sand occurred northwest of the Cape May peninsula in Atlantic County (fig. 3), beyond the limit of the overlying confining unit, where the aquifer is unconfined. Water levels in the Atlantic City 800-foot sand were 50 ft or more above sea level, and ground water flowed laterally downdip from the recharge area and discharged to the Delaware Bay and the Atlantic Ocean (fig. 3).

The potentiometric surface of, and flow directions in, the Atlantic City 800-foot sand in 1988 are shown in figure 4 (modified from Rosman and others, 1996, pl. 1). Water levels have declined more than 110 ft near the center of the regional cone of depression near Atlantic City as a result of ground-water withdrawals. In Cape May County, water levels have declined as much as 95 ft near Ocean City and 50 ft near Stone Harbor.

Ground-water flow directions also have changed in response to ground-water withdrawals. Ground water flows laterally downdip from the recharge area at the limit of the overlying confining unit toward public supply wells along the Atlantic Coast. Before pumping, ground water discharged to the ocean east of New Jersey and to the Delaware Bay west of Cape May County (fig. 3). By 1988, however, water levels had declined to below sea level throughout much of the offshore area both east of New Jersey beneath the Atlantic Ocean and west of Cape May County under the Delaware Bay. Ground water no longer flows seaward; instead it flows updip from the Atlantic Ocean and downdip from the Delaware Bay toward the public supply wells.
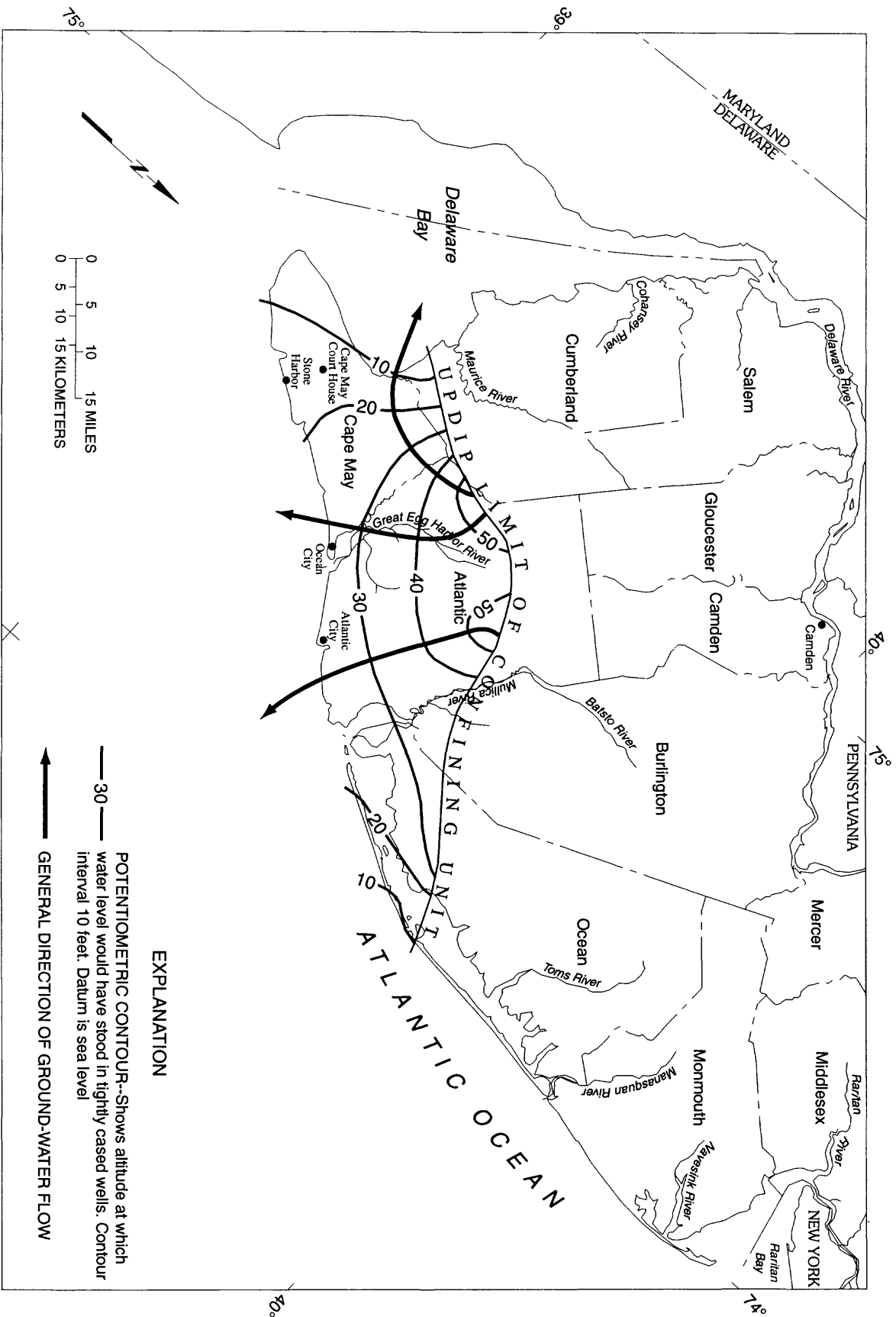
Figure 3. Predevelopment potentiometric surface in the Atlantic City 800-foot sand in the New Jersey Coastal Plain. (Modified from Zapecza and others, 1987, fig. 9)

Base from U.S. Geological Survey digital data, 1:2,000,000, 1993
Universal Transverse Mercator projection, Zone 18

EXPLANATION

—30— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 10 feet. Datum is sea level

GENERAL DIRECTION OF GROUND-WATER FLOW
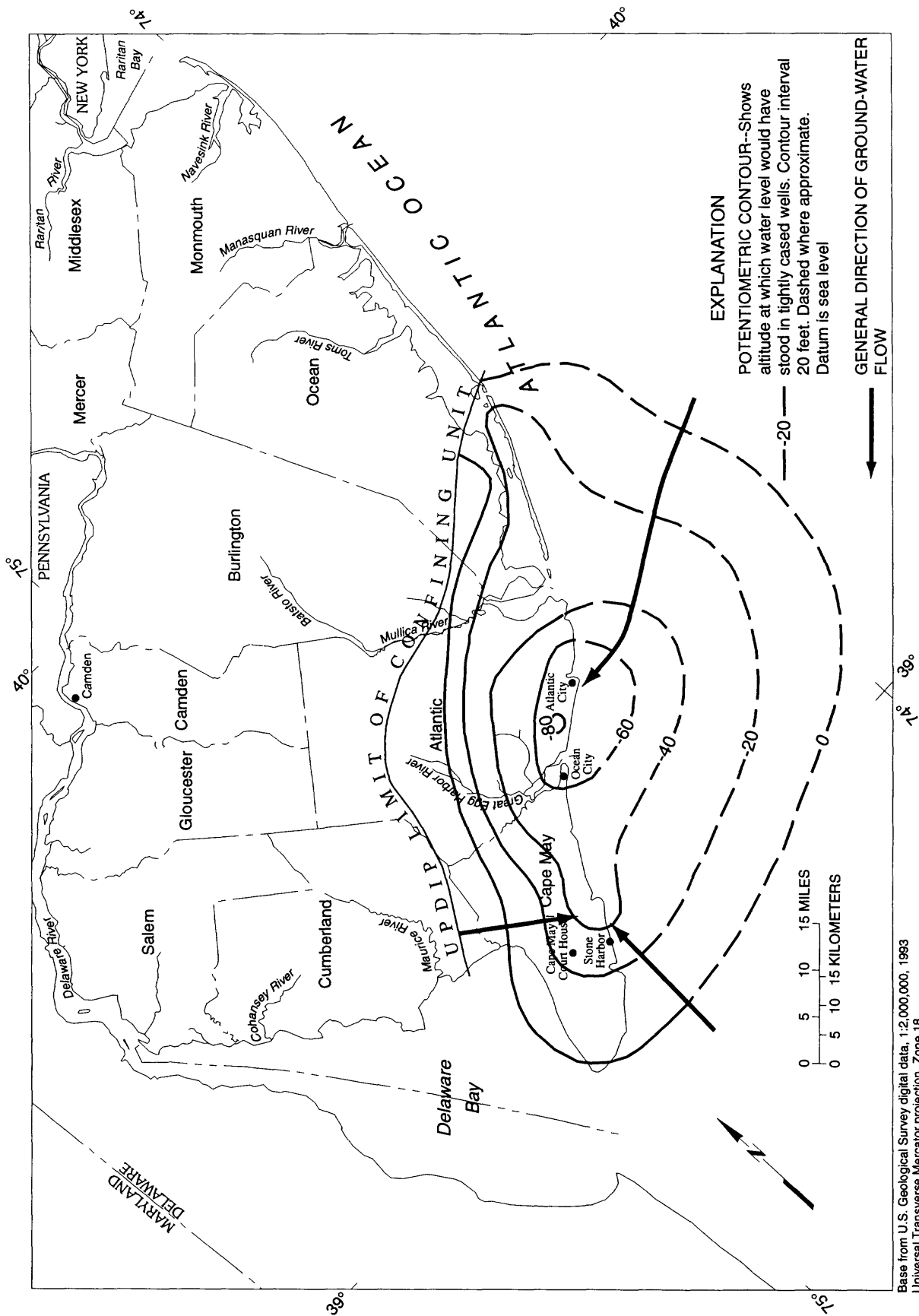
Figure 4. Potentiometric surface in the Atlantic City 800-foot sand in the New Jersey Coastal Plain, 1988. (Modified from Rosman and others, 1996, pl. 1)

EXPLANATION

POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 20 feet. Dashed where approximate. Datum is sea level

GENERAL DIRECTION OF GROUND-WATER FLOW

Base from U.S. Geological Survey digital data, 1:2,000,000, 1993
Universal Transverse Mercator projection, Zone 18

Previous Investigations

Several studies of the ground-water resources of Cape May County, New Jersey, have been conducted. These studies also evaluated the hydrogeology of, aquifer and confining-unit properties of, and water levels and chloride concentrations in Cape May County's aquifer system. Studies that include the Atlantic City 800-foot sand are summarized in table 1, where they are divided into three categories: (1) countywide studies, (2) Coastal Plain studies, and (3) simulation studies.

COUPLED MODEL

The subregional model was used to simulate ground-water flow in the two aquifer layers and the intervening confining unit of the Atlantic City 800- foot sand. The model consists of a finite-difference grid with 100 rows and 140 columns. Each cell is 1,320 ft on a side.

Model Boundaries

The boundaries of the subregional model are shown in figure 5. The top and bottom boundaries were represented as specified fluxes across confining units. The lateral boundaries were assigned specified ground-water fluxes, except at the limit of the confining unit overlying the Atlantic City 800- foot sand under the Delaware Bay, where the sediments are unconfined (fig. 2). At this location, a head-dependent boundary was used (fig. 5). All specified fluxes were applied as ground water that flows from the regional model into or out of the Cape May County subregional model area. At the lateral boundaries of the subregion, the specified flows from the regional model were apportioned according to the relative thickness of the two aquifer layers in the subregional model.

For the head-dependent boundary under the Delaware Bay, the water level and vertical conductance were specified. A water level of zero, which represents the water level in the Delaware Bay, and a vertical conductance of 0.001 ft /d, which represents the product of the hydraulic conductivity of the sediments and the area of the model cell divided by the thickness of the sediments, were assigned to model nodes.

Hydraulic Characteristics of Aquifer Layers and Confining Unit

Few values of hydraulic conductivity have been reported for the Atlantic City 800-foot sand in Cape May County. Gill (1962, p. 47) reports a horizontal hydraulic conductivity for the Atlantic City 800-foot sand of 38 to 41 ft/d in the Stone Harbor area. Horizontal hydraulic conductivities used in the model were 35 ft/d for the upper layer of the Atlantic City 800- foot sand and 55 ft/d for the lower layer. A vertical hydraulic

Table 1. Previous investigations of the Atlantic City 800-foot sand, Cape May County, New Jersey (Modified from Spitz and Barringer, 1992, table 1.)

Reference	Area or subject
COUNTYWIDE STUDIES	
Geraghty and Miler, 1971	Gound-water resources
Gill, 1962a	Ground-water resources, saltwater intrusion
Gill, 1962b	Well records and logs, stratigraphy
COASTAL PLAIN STUDIES	
Bauersfeld and others, 1990	Water-resources data
Eckel and Walker, 1986	Aquifer water levels, 1983
Meisler, 1980	Delineation of salty ground water
Rosman and others, 1996	Aquifer water levels, 1988
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 and others, 1987	Predevelopment aquifer water levels, withdrawals
SIMULATION STUDIES	
Martin, in press	Ground-water flow, Coastal Plain
Meisler and others, 1985	Sea-level effects on saltwater-freshwater relations, Coastal Plain
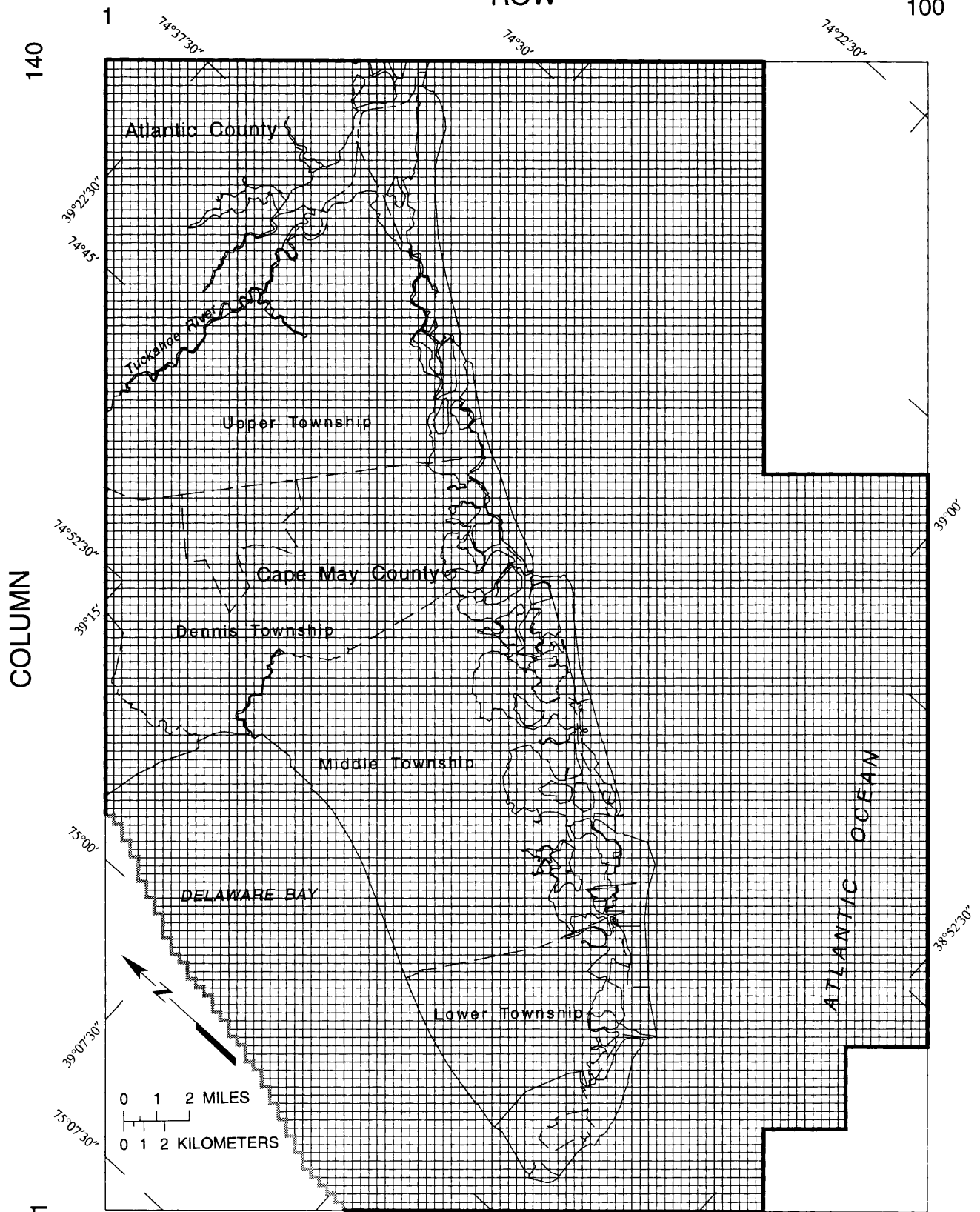
Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 18

EXPLANATION

LATERAL SPECIFIED-FLUX BOUNDARY

HEAD-DEPENDENT
BOUNDARY

VERTICAL SPECIFIED-FLUX BOUNDARY

Figure 5. Subregional model grid and location of model boundaries, Cape May County, New Jersey.

conductivity of 0.001 ft/d was assigned to the confining unit between the two layers. Leakance between the two aquifer layers was simulated by dividing this value by the thickness of the confining unit, which ranged from 10 to 60 ft.

Model Calibration

The subregional model was calibrated to water levels measured during April 1991 in 33 wells (6 observation wells and 27 public and industrial supply wells) screened in the Atlantic City 800-foot sand in Cape May and Atlantic Counties (fig. 6). Although the model was used to simulate steady-state conditions and water levels in April 1991 were higher than average, this was the most recent and complete data set available.

The model was calibrated by using average annual ground-water withdrawals during 1983-88. Well-construction data and average ground-water withdrawals during 1983-88 for the public supply and observation wells are listed in table 2.

The long-term hydrograph for well 1-578, shown in figure 7 along with annual rates of ground-water withdrawals from public supply wells in Cape May County, indicates that water levels declined during 1960-91 as a result of increasing ground-water withdrawals. As ground-water- withdrawal rates increased during 1960-87, water levels declined. After 1987, water levels in well 1-578 began to level off, probably because ground-water-withdrawal rates did not increase. The ground-water system may have reached equilibrium with 1987-90 withdrawal rates. Ground-water withdrawals throughout much of the Atlantic City 800-foot sand are near coastal areas and are seasonal. Water use in the coastal areas of southern New Jersey is greatly affected by the summer resort industry; ground-water withdrawals are much greater during May through September than during October through April. The highest water levels of the year consistently are measured in April. The annual average water levels during 1983-90 are about 10 ft lower than the water level measured in April 1991. The model, therefore, was considered to most closely approximate steady-state conditions when simulated water levels were about 10 ft lower than April 1991 water levels.

Simulated Hydraulic Heads

The simulated potentiometric surface and water levels measured in April 1991 in the two layers of the Atlantic City 800-foot sand are shown in figures 8 and 9. In general, the simulated water levels are slightly less than 10 ft lower than the water levels measured in April 1991. The simulated water level in observation well 9-185 (April 1991 water level 29 ft below sea level), screened in the lower layer in the northwestern part of the subregional model area, was 15 ft higher than the measured water level, apparently indicating effects of processes not accounted for in the simulation. Simulation results in all other modeled areas, including Stone Harbor, were acceptable.
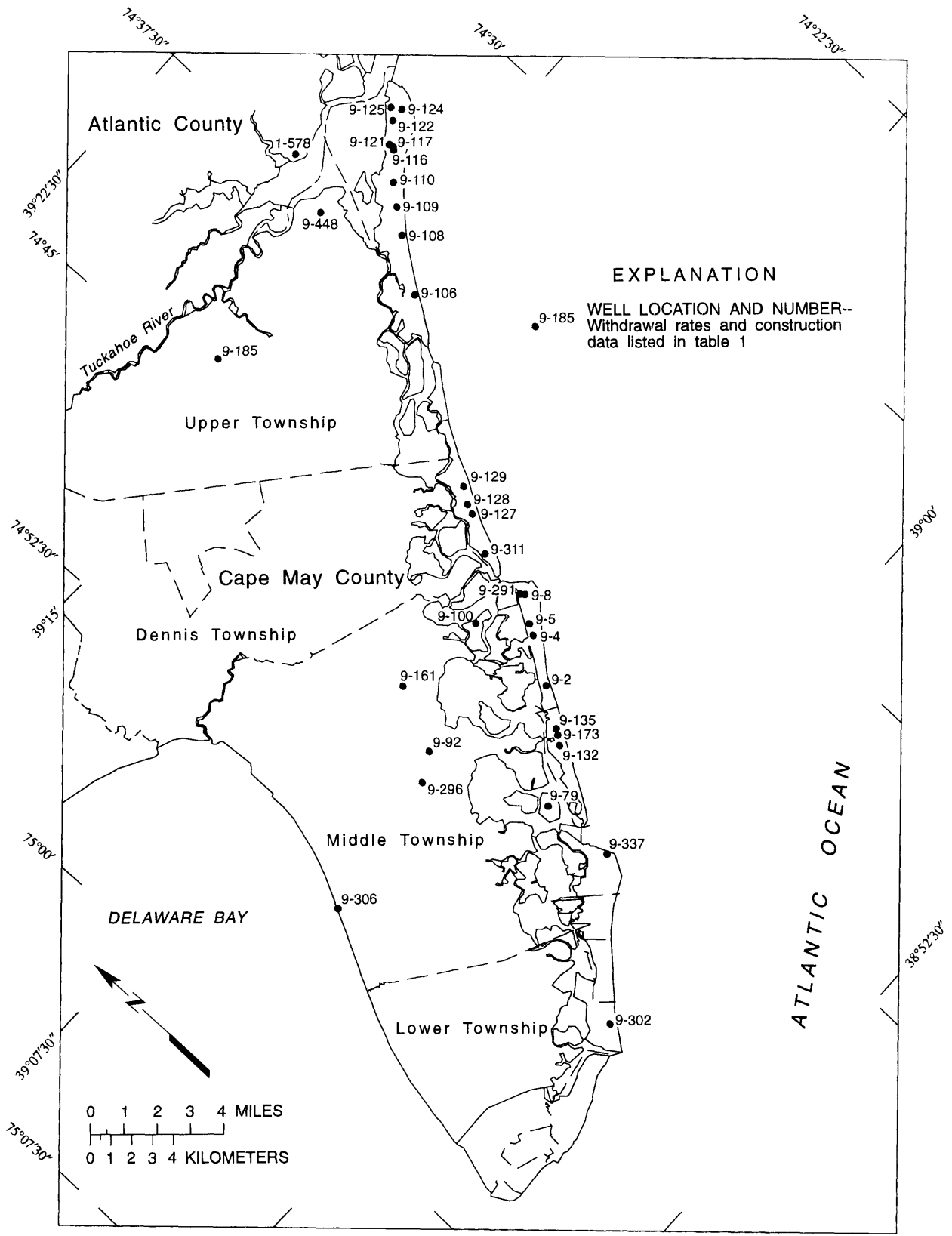
Figure 6. Location of selected industrial, public supply, and observation wells screened in the Atlantic City 800-foot sand in Cape May and Atlantic Counties, New Jersey.

Table 2. Well-construction data and average annual withdrawals during 1983-88 for selected wells in Cape May and Atlantic Counties, New Jersey
[Withdrawals in million gallons per year; NJDEP, New Jersey Department of Environmental Protection; N/A, not available; USGS, U.S.Geological Survey]

| USGS well number	NJDEP well-permit number	Local well name	Depth of well (feet below land surface)	Screened interval (feet below land surface)	Average annual ground-water withdrawals, 1983-88
1-578	N/A	JOBS POINT OBS	680	670 - 680	0
9-2	37-00280	AVALON WD 7-71	861	821 - 861	81.7
9-4	37-00265	AVALON WD 6	920	880 - 920	106.1
9-5	37-00313	AVALON WD 8-76	839	784 - 839	105.4
9-8	N/A	AVALON WD 3	925	845 - 925	31.6
9- 79	N/A	TEST HOLE 2	876	833 - 876	0
9- 92	37-00240	NEPTUNUS 7	791	681 - 791	117.9
9-100	37-00224	AVALON M WW 1	827	763 - 815	7.3
9-106	56-00006	SHORE DIV 7	810	760 - 810	113.5
9-108	36-00413	SHORE DIV 14	840	774 - 840	113.5
9-109	56-00008	SHORE DIV 9	809	749 - 809	113.5
9-110	36-00373	SHORE DIV 12	814	N/A	113.5
9-116	56-00007	SHORE DIV 8	810	N/A	113.5
9-117	36-00117	SHORE DIV 10	798	746 - 798	113.5
9-121	N/A	SHORE DIV 4	825	N/A	0
9-122	56-00005	SHORE DIV 5	825	N/A	113.5
9-123	N/A	2	795	745 - 795	113.5
9-124	36-00412	SHORE DIV 13	846	757 - 840	113.5
9-125	36-00314	SHORE DIV 11	800	N/A	113.5
9-126	37-00162	SICWD 5	802	731 - 802	122.4
9-127	37-00064	SICWD 4	830	742 - 830	97.9
9-128	57-00010	SICWD 3	870	800 - 870	87.1
9-129	57-00009	SICWD 2	861	744 - 861	116.2
9-132	37-00079	SHWD 4	880	830 - 880	51.5
9-135	37-00009	SHWD 3	878	837 - 877	51.5
9-136	N/A	CIWC 1	834	802 - 834	49.7
9-148	36-00364	ACEC 3 Layne 4	675	645 - 680	66.8
9-161	N/A	1	654	639 - 654	N/A
9-166	37-00312	SHWD 5	860	820 - 860	51.5
9-173	37-00579	SHWD 6	862	822 - 862	51.8
9-185	N/A	MACNAMARA W A	650	640 - 650	N/A
9-291	36-09846	AVALON WD 9	946	764 - 941	37.0
9-296	35-06073	HAND AVE 8	817	682 - 812	N/A
9-302	37-03628-9	COAST GUARD 800	903	883 - 893	N/A
9-306	N/A	OYSTER 800	709	656 - 666	N/A
9-311	36-10378	SICWD 6-1989	901	732 - 896	N/A
9-337	37-04660	M-1 N WILDWOOD 800	965	910 - 960	N/A
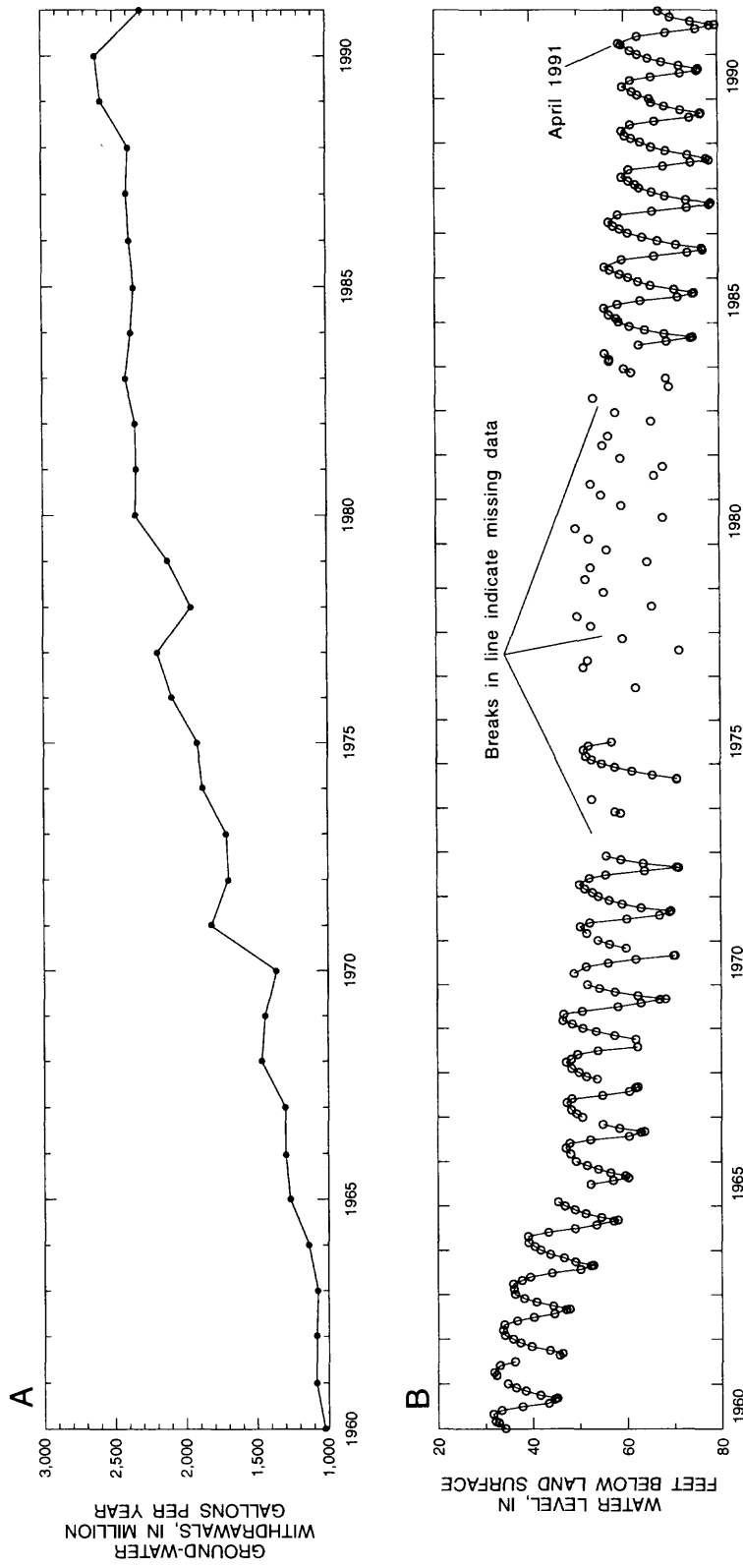
Figure 7. (A) Total annual ground-water withdrawals from the Atlantic City 800-foot sand, Cape May County, New Jersey, 1960-91, and (B) water-level hydrograph for well 1-578 (location of well shown in fig. 6).

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Figure 8. Simulated potentiometric surface and measured water levels
in the upper layer of the Atlantic City 800-foot sand, Cape May County,
New Jersey, 1991.
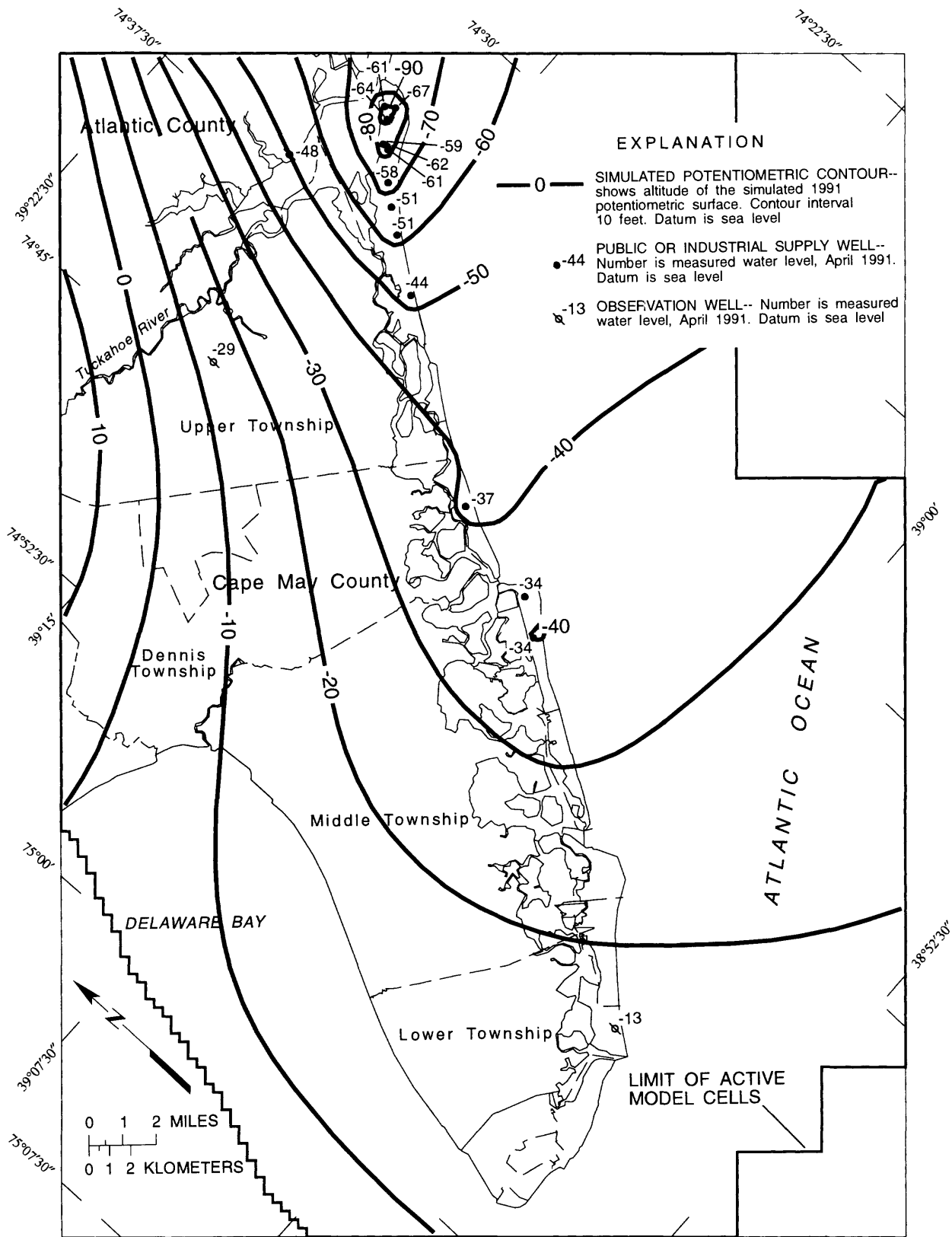
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EXPLANATION

——— 0 ——— SIMULATED POTENTIOMETRIC CONTOUR--
shows altitude of the simulated 1991
potentiometric surface. Contour interval
10 feet. Datum is sea level

•-44 PUBLIC OR INDUSTRIAL SUPPLY WELL--
Number is measured water level, April 1991.
Datum is sea level

ⵁ-13 OBSERVATION WELL-- Number is measured
water level, April 1991. Datum is sea level

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

Figure 9. Simulated potentiometric surface and measured water levels
in the lower layer of the Atlantic City 800-foot sand, Cape May County,
New Jersey, 1991.

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The previously defined limit of the confining unit overlying the Atlantic City 800-foot sand in the Delaware Bay (D.A. Pope, U.S. Geological Survey, written commun., 1991) was refined to achieve a good match between measured and simulated water levels for the well at the Rutgers oyster research laboratory (9-306, fig. 8). Therefore, the limit of the overlying confining unit in this area in the subregional model was slightly west of the limit used in the regional model (fig. 1).

SALTWATER INTRUSION AND TRAVEL TIME

Saltwater Intrusion

The inferred location of the 250-mg/L line of equal chloride concentration in ground water in the Atlantic City 800-foot sand in 1992 (P.J. Lacombe and G.B. Carleton, U.S. Geological Survey, written commun., 1992) is shown in figure 10. The location is based on results of laboratory analyses of water samples collected from observation wells drilled in 1988 and 1992 and the most recent (dates given in fig. 10) chemical analyses of samples from public and industrial supply wells that are abandoned or in use in Cape May County. The line bends toward the mainland as it crosses the peninsula and bends toward the edge of the overlying confining unit to account for the likelihood that saltwater flows from the Delaware Bay toward the supply wells in Cape May County. This orientation is supported, in part, by the concentration of chloride in a sample collected from the observation well at the Rutgers research oyster laboratory (fig. 10). The chloride concentration, 49 mg/L, was higher than background concentrations, which ranged from 10 to 36 mg/L in water samples from wells on or near the barrier islands in Cape May County. The location of the 250-mg/L line of equal chloride concentration in the offshore area is based on data from four wells--two offshore near Atlantic City, one at North Wildwood, and one at the U.S. Coast Guard base electronic station (fig. 10).

Flows at model boundaries under average 1983-88 ground-water withdrawal conditions provide an indication of the relative importance of sources of water to the Atlantic City 800-foot sand (table 3; fig. 10). The most significant flow into the study area (7.52 ft /s) is freshwater recharge from the area where the confining unit that overlies the Atlantic City 800- foot sand is absent (boundary 2). This flow represents 59 percent of the total ground-water flow into the subregional model area. About 22 percent (2.74 ft /s) of the total ground-water flow into the area is saltwater that flows across boundary 4. Vertical flow from the aquifers above and below the Atlantic City 800-foot sand accounts for 14 percent (1.78 ft /s) of ground-water flow into the model area. Flow from the Delaware Bay (boundary 1) is saltwater that accounts for about 5 percent (0.60 ft /s) of the ground water entering the model area.
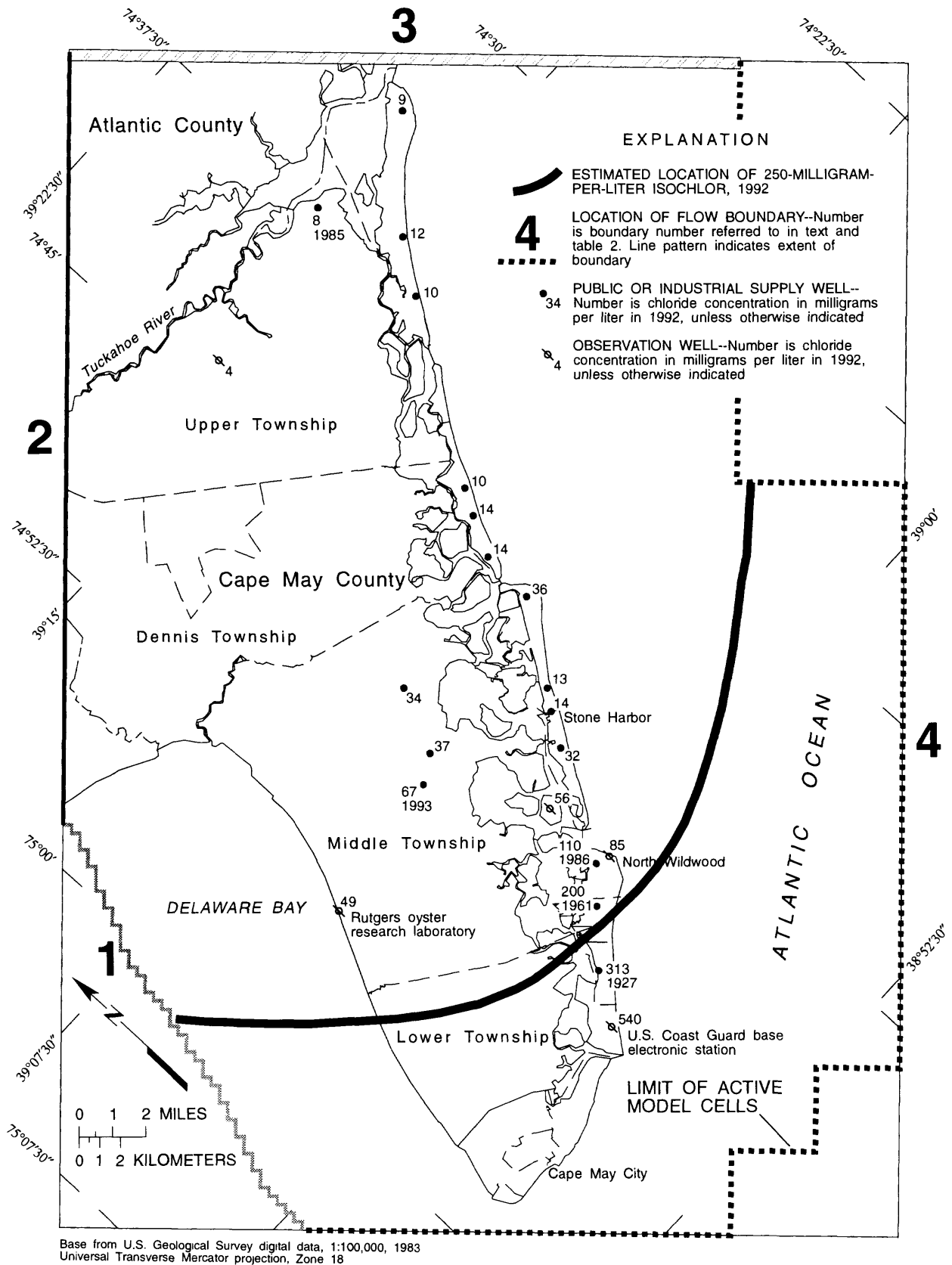
Figure 10. Estimated location of areas where chloride concentrations exceed 250 milligrams per liter in the Atlantic City 800-foot sand, Cape May County, New Jersey, 1992. (From P.J. Lacombe and G.B. Carleton, U.S. Geological Survey, written commun., 1992)

Table 3. Simulated 1983-88 steady-state ground-water budget of the Atlantic City 800-foot sand, Cape May County, New Jersey

[Rates in cubic feet per second; boundary locations are shown in figure 10]

	Inflow	Outflow
Boundary		
Lateral flow		
Boundary 1	0.60	0.00
Boundary 2	7.52	.00
Boundary 3	.00	2.55
Boundary 4	2.74	.00
Vertical flow through upper confining unit	1.46	.05
Vertical flow through lower confining unit	.32	.01
Pumpage	.00	10.03
Total	12.64	12.64

Beneath the barrier islands, chloride concentrations in ground water in the Kirkwood-Cohansey aquifer system, which overlies the Rio Grande water- bearing zone and Atlantic City 800-foot sand, exceed 250 mg/L (Spitz and Barringer, 1992). Ground water in the underlying Piney Point aquifer contains chloride in concentrations that exceed 250 mg/L throughout most of Cape May County. These aquifers could be a minor source of saltwater to the Atlantic City 800-foot sand in the model area. Predevelopment water levels (Zapecza and others, 1987) in the Atlantic City 800-foot sand in the Stone Harbor area were higher than those in the overlying Kirkwood-Cohansey aquifer system and the underlying Piney Point aquifer; therefore, fresh ground water from the Atlantic City 800-foot sand would have flowed vertically into these aquifers. The overlying and underlying confining units probably contain freshwater rather than saltwater because of these flows from the Atlantic City 800-foot sand. Results of the simulation in which vertical specified fluxes were 0.0001258 ft /s (calculated from the regional model in the Stone Harbor area), estimated porosity was 0.35, and confining-unit thickness was 150 ft indicate that thousands of years would be required for saltwater to flow through the thick confining units to the Atlantic City 800-foot sand if withdrawals are maintained at 1991 levels.

Travel Time

A particle-tracking post-processor was used to compute three-dimensional flow paths from areas where chloride concentrations exceed 250 mg/L to public supply wells at Stone Harbor, New Jersey. The positions of these flow paths, which were determined on the basis of 1991 ground-water withdrawals, are shown in figure 11. All travel times shown are for lateral flow. Actual travel times may differ from predicted travel times as a result of the uncertainty in estimating the location of the 250-mg/L line of equal chloride concentration.

Results of particle-tracking analysis indicate that the time required for saltwater to reach the public supply wells at Stone Harbor if ground-water withdrawals are maintained at 1991 rates is on the order of hundreds of years. However, these results are based on the assumptions that the aquifer is homogeneous and that the horizontal hydraulic conductivities of both layers of the Atlantic City 800-foot sand in Cape May County are identical. The presence of zones of high permeability in the aquifer could reduce the predicted travel time of the saltwater from its present location to the wells at Stone Harbor. In addition, the accuracy of predicted travel times is limited by the uncertainties inherent in the representation of the natural hydrologic conditions and the possibility that the rate of ground- water withdrawals will increase. Therefore, travel times could be shorter than those predicted.
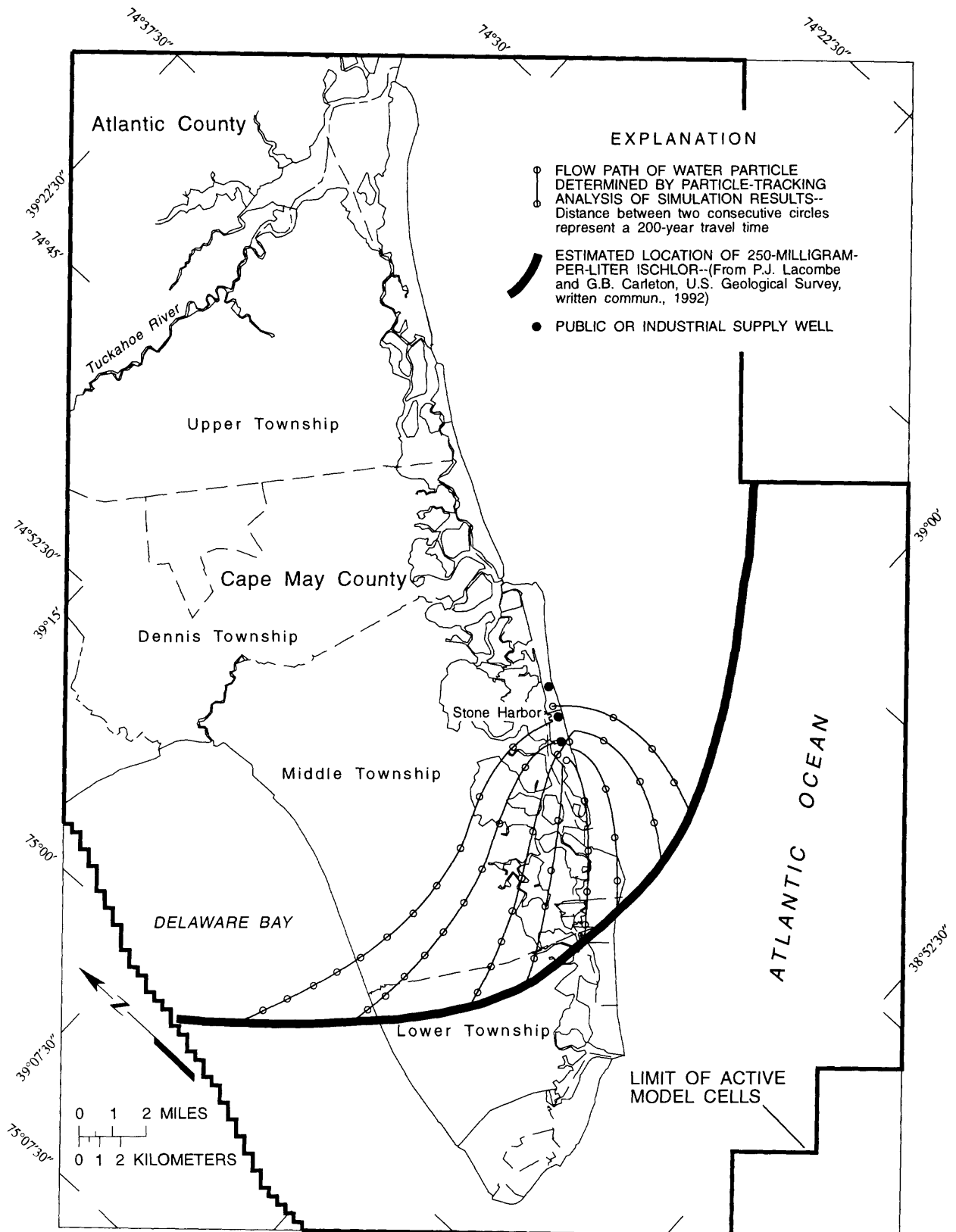
Figure 11. Flow paths of water particles in the upper layer of the Atlantic City 800-foot sand, Cape May County, New Jersey, determined by particle-tracking analysis of simulation results, 1991.

SUMMARY AND CONCLUSIONS

Ground water is the most important source of public water supply in Cape May County, New Jersey. In the barrier-island communities, ground water is withdrawn from the regionally confined aquifer system, the Atlantic City 800-foot sand. The presence of saline ground water (ground water in which the chloride concentration exceeds 250 mg/L) in Cape May County was documented in 1926 when water samples from a well screened in the Atlantic City 800-foot sand in Wildwood were found to contain chloride in a concentration of 352 mg/L. Increasing evidence of the landward movement of saltwater in other aquifers led to concern about the future adequacy of freshwater supplies from the Atlantic City 800-foot sand in Cape May County. Therefore, the U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, undertook a study of saltwater intrusion in this aquifer in order to estimate the travel time of the saltwater from its present location to the county's nearest public supply wells.

A regional and a subregional ground-water-flow model were coupled to assess the effects of ground-water withdrawals on the movement of saltwater in the Atlantic City 800-foot sand. First, a regional model of ground- water flow through the sediments of the New Jersey Coastal Plain was used to estimate the quantity and distribution of flow across the natural and artificial boundaries of the Cape May subregional model area. Next, the results of this simulation were input to the subregional model to refine the estimates of flow in the Atlantic City 800-foot sand in the smaller area of interest. Finally, a particle-tracking method was used to determine ground-water-flow paths and travel time from parts of the aquifer that contain saltwater to the public supply wells at Stone Harbor, New Jersey.

Results of the analysis indicate that the time required for saltwater to reach the public supply wells is on the order of hundreds of years. These results, however, are based on the assumptions that the aquifer is homogeneous, and that ground-water withdrawals are maintained at 1991 rates. The presence of zones of high permeability in the aquifer or an increase in ground-water withdrawals could reduce the predicted travel times of the saltwater from its present location to the supply wells.

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