Hydrogeology and Analysis of the Ground-Water-Flow System of the Eastern Shore, Virginia

United States Geological Survey Water-Supply Paper 2401

Prepared in cooperation wit
Accomack County,
Northampton County, and
the Virginia Water Control
Board

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By DONNA L. RICHARDSON

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CONTENTS

PLATE

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FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow	
million gallons per day (Mgal/d)	.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	.09290	meter squared per day (m^2/d)

Water-quality units: Water-quality units are expressed in this report as milligrams per liter (mg/L).

Hydraulic conductivity and transmissivity: In this report, hydraulic conductivity is reported in feet per day (ft/d), a mathematical reduction of the unit cubic foot per day per square foot $[(ft^3/d)/ft^2]$. Transmissivity is reported in feet squared per day (ft^2/d), a mathematical reduction of the unit cubic feet per day per square foot times feet of aquifer thickness ($[(ft^3/d)/ft^2]ft$).

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.

Hydrogeology and Analysis of the Ground-Water-Flow System of the Eastern Shore, Virginia

By Donna L. Richardson

Abstract

This report presents the results of a study of the hydrogeology and ground-water-flow system of the Eastern Shore in Virginia by the U.S. Geological Survey in cooperation with Accomack County, Northampton County, and the Virginia Water Control Board. The Eastern Shore of Virginia is a peninsula that includes Accomack and Northampton Counties and is the easternmost part of Virginia's Coastal Plain physiographic province. Ground water provides the sole freshwater supply to the Eastern Shore. Water demands from increased industrial, commercial, municipal, and agricultural growth have caused water-level declines and concern about the future of the ground-water resource.

Detailed hydrogeologic information was collected and incorporated into the ground-water-flow model. The data were used to develop an understanding of the way ground water enters, moves through, and leaves the multiaquifer system. A hydrogeologic framework of the aquifers and confining units containing potable ground water was developed from geophysical and lithologic information. The hydrogeologic framework consists of an unconfined aquifer (Columbia aquifer) and three confined aquifers (upper, middle, and lower Yorktown-Eastover aquifers) separated by intervening confining units (upper, middle, and lower Yorktown-Eastover confining units). The ability of the aquifer and confining-unit sediments to transmit, store, and release water was defined by estimating values for transmissivity, vertical leakance, and storage. Transmissivities estimated from specific-capacity data range from 61 to 4,530 feet squared per day (ft^2/d). Transmissivities generally are greater in the upper Yorktown-Eastover aquifer and decrease with depth in the middle and lower Yorktown-Eastover aquifers. Annual ground-water withdrawals were compiled by aquifer for commercial, industrial, and municipal uses. Major pumping centers are located near the towns of Accomac, Cape Charles, Cheriton, Chincoteague, Exmore, Hallwood, and Oyster, Va. Total ground-water use was estimated to be about 5 million gallons per day in 1988. The upper, middle, and lower Yorktown-Eastover aquifers supplied 36, 42, and 22 percent of the total withdrawal in 1988, respectively. Data on chloride concentrations were compiled by aquifer to provide information on the distribution of chlorides in the study area. Chloride concentrations generally increase with depth; chloride concentrations are greater in the lower Yorktown-Eastover aquifer than are found in the overlying middle and upper Yorktown-Eastover aquifers.

A digital flow model was developed to aid in the analysis of the ground-water-flow system. The model incorporates the hydrogeologic characteristics of the aquifers and confining units, simulates freshwater and saltwater flow, and simulates the movement of the saltwater-freshwater interface. The effects of historical ground-water development were examined by comparing simulations of prepumping with past pumping conditions. Model results indicate that most of the ground water

withdrawn from the system comes from an increase in the amount of water recharging the confined-aquifer system from the unconfined aquifer and a decrease in the amount of discharge from the confined-aquifer system to the unconfined aquifer. The simulation of prepumping conditions indicates that about 11 million gallons per day enter and exit the confined-aquifer system. Given 1988 withdrawal conditions, simulated flow into the confined-aquifer system is increased to about 13 million gallons per day, and simulated flow out of the confined-aquifer system is reduced to 8.64 million gallons per day. The position of the simulated saltwater-freshwater interface does not change in response to historical pumpage.

Three model scenarios of hypothetical increases in withdrawals provide information on the regional response of the ground-water system to additional pumping. Results indicate that (1) water levels continue to decline as withdrawals increase and could result in well interference among major ground-water users, (2) increases in withdrawals result in a decrease in the amount of offshore freshwater discharge, (3) water-level declines associated with increased withdrawals cause slight movement of the saltwater-freshwater interface over a 50-year simulation period, (4) increased withdrawals near the shoreline cause offshore water-level declines and a reversal in the direction of ground-water flow that could induce vertical leakage of saltwater into the freshwater parts of the uppermost confined aquifer, and (5) withdrawals near the center of the peninsula cause less landward movement of the saltwater-freshwater interface than withdrawals near the shoreline.

INTRODUCTION

The Eastern Shore of Virginia includes Accomack and Northampton Counties and is the easternmost part of Virginia's Coastal Plain physiographic province. The Eastern Shore is a peninsula surrounded on three sides by salty water and has no major fresh surface-water sources; therefore, ground water provides the sole freshwater supply. Fresh ground water is present in a layered system of aquifers consisting of sand, gravel, and shell material separated by confining units of silt and clay. The fresh ground water is limited to approximately the first 300 ft below land surface; the water at depths greater than 300 ft is salty (greater than 250 milligrams per liter (mg/L) chloride concentration).

Beginning about 1965, increases in withdrawals for agricultural, commercial, and industrial uses have caused water-level declines and created cone-like depressions in the water-level surface around major pumping centers. In November 1976 the Eastern Shore was declared a Ground-Water Management Area by the Virginia Water Control Board[1] (VWCB). Under the management-area designation, a permit is required for ground-water users that withdraw more than 300,000 gallons per month (gal/month).

Increased water needs due to intensifying agricultural, industrial, commercial, and urban development could adversely affect the supply of fresh ground-water on the Eastern Shore. Potential problems are (1) declining water levels, (2) decreased freshwater discharge to nearshore estuaries, (3) intrusion of salty water into freshwater parts of aquifers, and (4) contamination of potable water by the migration of pesticides and nitrates. A thorough knowledge of the ground-water-flow system is needed to enable planners to minimize the detrimental effects that would result from increased use of the resource. In 1986 the U.S. Geological Survey (USGS), in cooperation with the VWCB and the counties of Accomack and Northampton, began a comprehensive study of the ground-water resources of the Eastern Shore of Virginia.

Purpose and Scope

The purpose of this report is to describe the hydrogeology and ground-water-flow system of the Eastern Shore of Virginia. The report includes discussions of (1) the hydrogeologic framework of aquifers and confining units, (2) the flow of water through the multiaquifer system, (3) the hydraulic characteristics of aquifers and confining units, (4) the distribution of chloride concentrations in the aquifers, (5) the digital model used to simulate ground-water flow, and (6) the simulated effects of increased ground-water withdrawals.

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[1]Predecessor of the Virginia Department of Environmental Quality—Water Division.

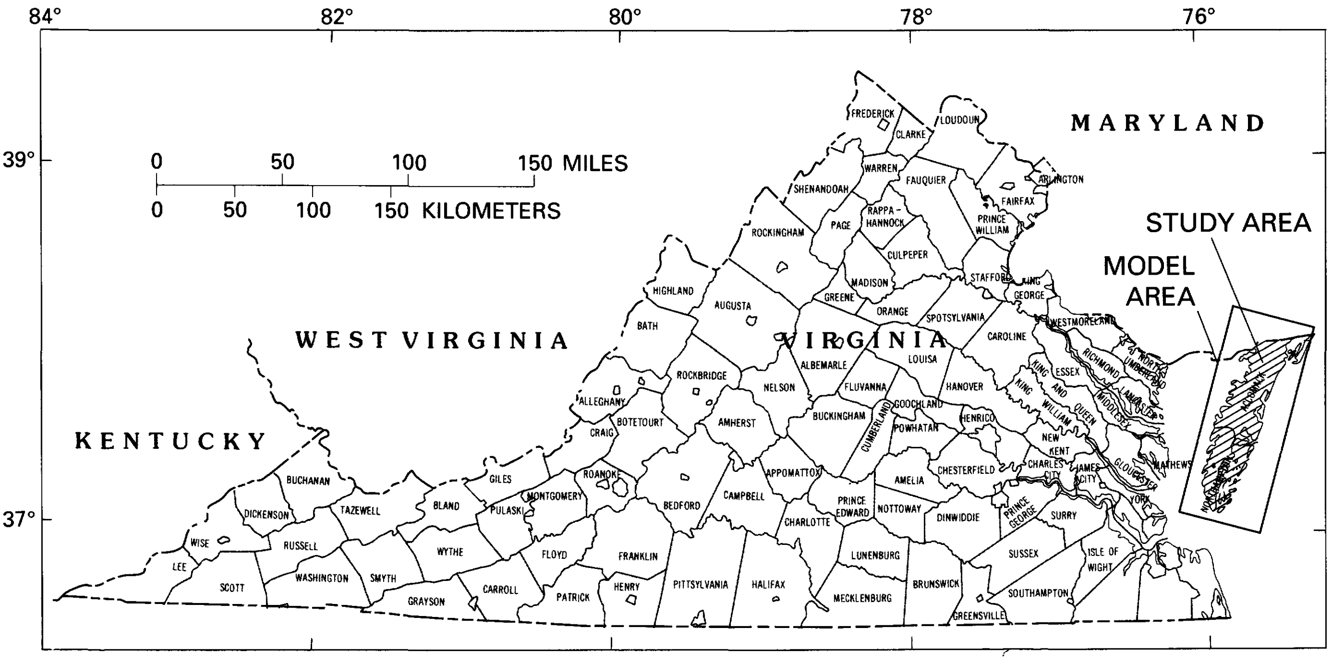


Figure 1. Location of study and model area.

This study is primarily an evaluation of the fresh ground-water-flow system of the Eastern Shore; therefore, the hydrogeologic data compiled for the study focus on the uppermost 300 feet (ft) of the system. Hydrogeologic data for aquifers and confining units of the Eastern Shore were collected, compiled, and analyzed. Hydraulic characteristics of the aquifers and confining units were estimated from hydrologic data. Water samples were collected and analyzed to determine the distribution of chloride concentrations in each aquifer. These data were used to develop a digital model of three-dimensional flow that simulates ground-water movement and tracks the lateral movement of the saltwater-freshwater interface.

Location of Study and Model Area

The study area includes Accomack and Northampton Counties in the easternmost part of Virginia's Coastal Plain physiographic province (fig. 1). The two counties are collectively referred to as the Eastern Shore of Virginia. The Eastern Shore is a peninsula that is about 70 mi long and covers approximately 695 square miles (mi^2) of land area. It is bounded on the east by the Atlantic Ocean, on the west and south by the Chesapeake Bay, and on the north by the State of Maryland. The model area extends into Maryland and includes offshore areas in the Atlantic Ocean and Chesapeake Bay, so that the effects of offshore saltwater flow could be incorporated into the model of the ground-water-flow system.

Previous Studies

Previous studies provide information about the ground-water resources of the Eastern Shore of Virginia. Sanford (1913) was the first to document the geology and ground water throughout the Virginia Coastal Plain. Sinnot and Tibbitts (1954, 1957, 1968) describe the ground-water resources of Northampton and Accomack Counties. Cushing and others (1973) provide a comprehensive study of the ground water of the Delmarva Peninsula. Siudyla (1975) and Siudyla and others (1977, 1981) present ground-water information for the Eastern Shore from a planner's perspective. Fennema and Newton (1982) present a summary of ground-water information for the Eastern Shore, and Bal (1977) developed the first digital ground-water-flow model for the area. Mixon (1985) describes the stratigraphy and geomorphic framework of the uppermost Cenozoic deposits in the southern Delmarva Peninsula. Knobel (1985) provides ground-water-quality data for the northern Atlantic Coastal Plain including the

Eastern Shore. Harsh and Laczniak (1986) and Meng and Harsh (1988) contribute to the understanding of the ground-water resource by describing the hydrogeologic framework and conceptualization of ground-water flow for the Virginia Coastal Plain. Kull and Laczniak (1987) compiled ground-water-withdrawal data for the Virginia Coastal Plain.

Several reports examine the distribution of saltwater in areas that include the Eastern Shore of Virginia. Cederstrom (1945) and Larson (1981) describe the distribution of chloride concentrations in the ground water of the Virginia Coastal Plain. Back (1966) describes the patterns of ground-water flow and the interface between freshwater and saltwater in the northern Atlantic Coastal Plain. Meisler and others (1985) document the distribution of salty ground water beneath the Atlantic Ocean in the northern Atlantic Coastal Plain aquifer system.

Methods of Investigation

The report by Meng and Harsh (1988) provided data that were used to develop the hydrogeologic framework described in this study. Additional hydrogeologic data were obtained from local well drillers and the VWCB to refine the framework for the fresh ground-water system of the Eastern Shore. Two clusters of observation wells were drilled by the VWCB to provide additional hydrologic information and further define the ground-water-flow system.

Water levels were measured to provide information on ground-water flow through the multiaquifer system. An established water-level network was expanded to a total of 58 wells, and water levels were measured every 6 weeks by the VWCB. Historic water-level data were compiled for use in model development. A transect of wells in the unconfined aquifer was constructed across the peninsula in southern Northampton County to improve the understanding of ground-water flow in the unconfined aquifer. Aquifer-test and specific-capacity data were reviewed to define the hydraulic characteristics of the aquifers.

Data obtained from the USGS water-use data base and the VWCB were reviewed for errors and compiled by aquifer through 1988. Water-use data for the Eastern Shore consist of pumpage for major industrial, municipal, commercial, and public-supply systems. Pumpage for agricultural use is not accurately reported; therefore, withdrawals for irrigation are not included in the pumpage estimates.

Data on chloride concentrations and distributions throughout the study area were compiled from previous investigations. Additional water samples were collected and analyzed for chlorides during this study.

SHARP, a quasi-three-dimensional, digital, ground-water-flow model, was used to simulate past and present ground-water-flow conditions. The SHARP model simulates freshwater and saltwater flow and tracks the lateral movement of the saltwater-freshwater interface (Essaid, 1990a). Simulations of hypothetical withdrawal scenarios were used to assess potential changes in water levels, ground-water flow, and saltwater-interface position. These scenarios are intended to identify the general nature of the response of the hydrologic system to various stresses. The scenarios are not intended to predict specific future problems.

Acknowledgments

The author would like to thank Keith Bull, former Northampton County administrator, for his support of this study. Terry Wagner, Virginia Newton, Scott Bruce, and Eugene Powell of the Virginia Water Control Board provided data and support. Special thanks also are extended to local drillers for providing well-construction data and other pertinent hydrogeologic information.

HYDROGEOLOGY

The Eastern Shore of Virginia is the easternmost part of Virginia's Coastal Plain physiographic province. The Coastal Plain consists of layered, unconsolidated, sedimentary deposits that thicken and slope seaward. These deposits consist of interbedded clay, silt, sand, and gravel and variable amounts of shell material that form a system of layered aquifers and confining units.

General Geology

The sedimentary deposits composing the Eastern Shore generally thicken and dip northeastward and range in thickness from about 3,000 ft west of the peninsula to about 7,500 ft east of the peninsula (Meng and Harsh, 1988). These Coastal Plain deposits overlie a hard-rock surface, commonly referred to as "basement," that also dips northeastward. The geologic age of these unconsolidated sediments ranges from Early Cretaceous to Holocene. The sediments have a varied depositional history. The lower 70 percent of the sediments are of Early to Late Cretaceous age and were deposited in fluvial environments (Robbins and others, 1975). The remaining 30 percent of the sediments are mostly of Tertiary age and were deposited in marine environments (Cushing and others, 1973). The Tertiary sediments are overlain by a thin veneer of sediments of Quaternary age that were deposited in various environments (Mixon, 1985). Figure 2 shows the location of control wells used in the development of the hydrogeologic framework of aquifers and confining units for the Eastern Shore.

Cretaceous Sediments

Most of the Cretaceous sediment underlying the Eastern Shore is commonly referred to as the Potomac Formation (Meng and Harsh, 1988) or the Potomac Group (Robbins and others, 1975). Information is limited concerning the composition and lithology of these Cretaceous sediments beneath the Eastern Shore. The most complete source of geologic data available is a deep oil-test hole in Temperanceville, Va. (66M1, fig. 2). The Potomac Formation beneath Virginia's Eastern Shore is probably similar in composition and lithology to that of surrounding areas (Meng and Harsh, 1988; Glaser, 1969; Hansen, 1969; Robbins and others, 1975). These deposits in the Virginia Coastal Plain range in age from Early to early Late Cretaceous (Robbins and others, 1975) and are characteristically heterogeneous in composition, consisting of interlayered and intermixed clay, silt, sand, and gravel deposits that mainly are a result of fluvial deposition. Current interpretations suggest that the sediments in the eastern part of the Virginia Coastal Plain (including the Eastern Shore) probably were deposited in a marginal-marine environment. The thickness of the Cretaceous sediments beneath the Eastern Shore ranges from about 2,000 to 5,600 ft.

The Early and early Late Cretaceous sediments are overlain by late Late Cretaceous sediments deposited in marginal-marine to marine environments. Information is limited concerning the composition and lithology of these uppermost Cretaceous deposits; however, in addition to data available from well 66M1, data are also provided by the VWCB research stations at Jenkins Bridge (well 66M23, fig. 2), Accomack County, Va. These Late Cretaceous deposits vary in composition from clayey, shelly, glauconitic sands to chalky marl and range in thickness from 50 to 60 ft in the northeastern part of Accomack County.

Tertiary Sediments

The Late Cretaceous sediments are overlain by a sequence of marine sediments of Tertiary age. The Tertiary sediments underlying the Eastern Shore are divided into a series of formations by depositional environment, texture, grain size, and lithology. As is true for the underlying Cretaceous sediments, information is limited concerning the composition, lithology, and nature of most Tertiary deposits beneath the Eastern Shore. If the Tertiary sediments are similar to those beneath the Virginia mainland, they are really extensive and homogeneous in character, forming layered sequences of clay, silt, and sand and varying amounts of shell material. The probable Tertiary formations, from oldest to youngest, are the Brightseat, Aquia, Nanjemoy, Piney Point, Chickahominy, Old Church, Calvert, Choptank, St. Marys, Eastover, and Yorktown Formations. Geologic data for these Tertiary units on the Eastern Shore are from the deep wells 66M1 and 66M23. An additional source of information for the deep Tertiary sediments is a stratigraphic core hole (well 64J14, fig. 2) that was drilled by the USGS at the Virginia Truck Experimental Station north of Exmore, Va. (R.B. Mixon, U.S. Geological Survey, oral commun., 1986). Preliminary analyses of these cores indicate an extremely thick Eocene section, overlain by a sequence of Oligocene, Miocene, and Quaternary deposits. In the Miocene sediments, the Calvert Formation contains a sand facies overlain by a clay-silt facies. The thickness of the Tertiary sediments ranges from 1,000 to 1,500 ft.

Quaternary Sediments

As sea levels fluctuated with the advance and retreat of continental ice sheets during the Pleistocene Epoch, the drainage patterns of the major river systems in the Chesapeake Bay area were altered, eroding channels into previously deposited sediments. As sea levels declined with the advance of the glaciers, streams flowed eastward across the Eastern Shore, deeply dissecting (more than 200 ft

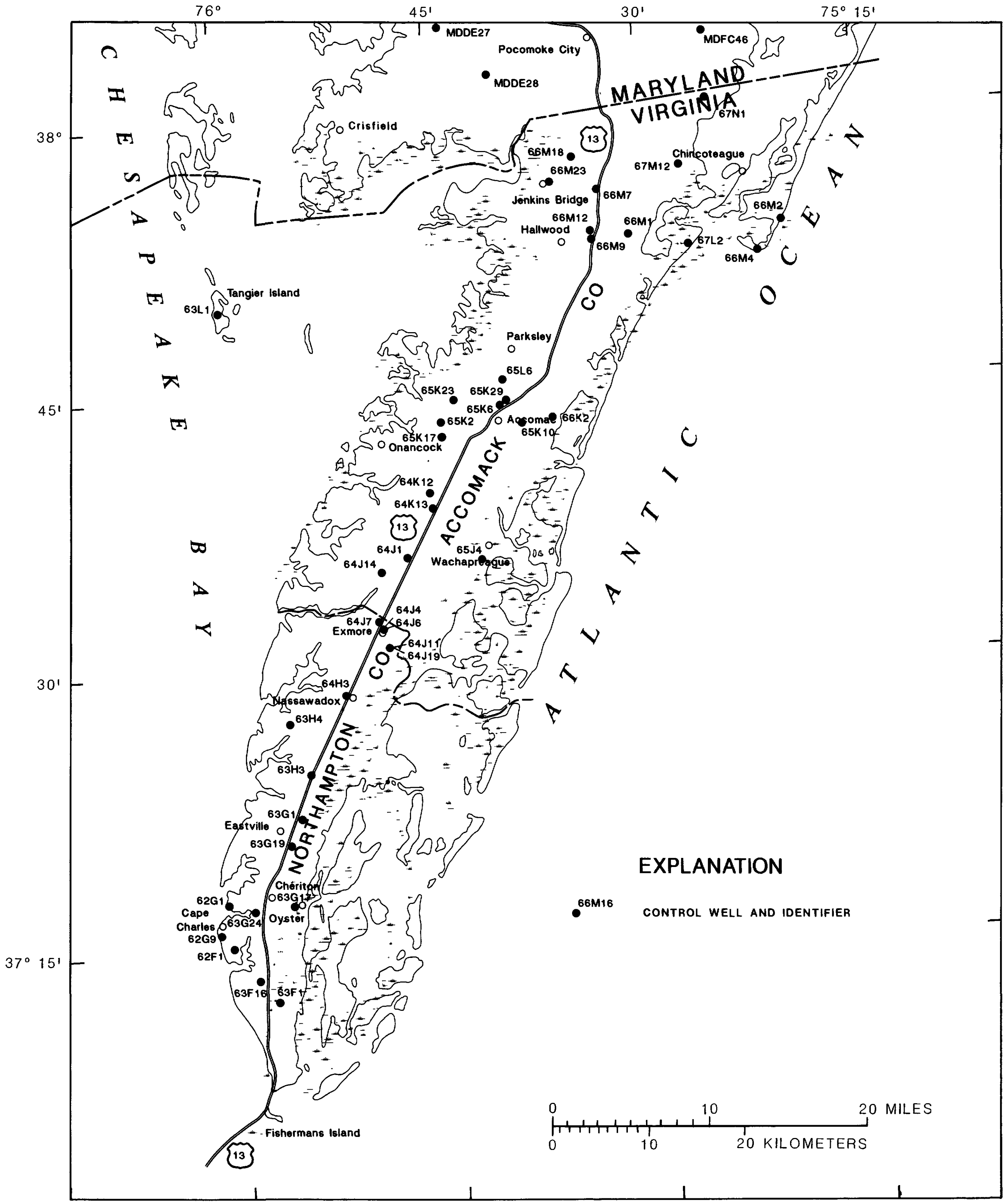


Figure 2. Location of control wells used in hydrogeologic framework analysis.

below present sea level) or removing the Yorktown Formation. As sea levels rose with the retreat of the glaciers, the incised stream channels were infilled with estuarine and marginal-marine deposits generally of a composition different from the eroded sediments. Mixon (1985) and Colman and Mixon (1988) describe such paleochannels that cut eastward across the peninsula at Cape Charles, Eastville, and Exmore, Va.

The remaining Quaternary sediments were deposited in marginal-marine and estuarine environments. The central uplands of the Eastern Shore are flanked by broad, flat terraces and bordered by linear scarps. Mixon (1985) provides the stratigraphic nomenclature and describes the depositional history of Quaternary sediments on the Eastern Shore. Since the Pleistocene Epoch, sea levels have continued to rise along the margins of the Eastern Shore, and Holocene-age deposits make up the salt-marsh, back-bay, and barrier-island sediments around the peninsula. The thickness of the Quaternary sediments ranges from 40 to 150 ft.

Aquifers and Confining Units

Sediments beneath the Eastern Shore have been divided on the basis of hydrologic properties into a layered sequence of aquifers and intervening confining units. Aquifers consist of sand, gravel, and shell material of sufficient saturated thickness to yield significant quantities of water. Confining units consist of clay and silt that are continuous and of low permeability; confining units yield little water and retard the movement of water. Aquifers commonly contain interbedded clay and silt, whereas confining units commonly contain interbedded sand, gravel, and shell material. An aquifer or confining unit can comprise part of a geologic formation, all of a formation, or a combination of all or parts of adjacent formations.

The hydrogeologic framework of aquifers and confining units on the Eastern Shore has been delineated by correlating lithologic and geophysical logs and by analyzing water-quality and water-level data. The locations and depths of the wells used in this analysis and the altitudes of the tops of aquifers and confining units are given in table 1. The relative positions of the hydrogeologic units throughout the peninsula are illustrated in the hydrogeologic sections shown in plate 1. The altitudes of the tops of the aquifers and confining units in the freshwater part of the ground-water-flow system are shown in figures 3–9.

Aquifers beneath the Eastern Shore consist of an unconfined aquifer underlain by a series of confined aquifers and intervening confining units (fig. 10). The Columbia aquifer is the uppermost aquifer and is unconfined. The confined aquifers shallower than approximately 300 ft contain freshwater and are named the upper Yorktown-Eastover, middle Yorktown-Eastover, and lower Yorktown-Eastover aquifers. These freshwater aquifers are the focus of this report. The previously defined Yorktown-Eastover aquifer (Meng and Harsh, 1988) has been refined for this report and divided into the upper, middle, and lower Yorktown-Eastover aquifers. The Yorktown-Eastover aquifers are underlain by aquifers and confining units that contain salty water (water with chloride concentrations greater than 250 mg/L).

Columbia Aquifer

The Columbia aquifer is unconfined throughout the Eastern Shore. It is defined as the saturated, chiefly sandy, surficial sediments that overlie the uppermost continuous clay-silt unit (Meng and Harsh, 1988). The Columbia aquifer primarily consists of Pleistocene sediments of the Columbia Group. Holocene sediments, which overlie the Pleistocene deposits around the margin of the Eastern Shore, are not used as a ground-water source and, therefore, are not discussed further in this report. Lithologically, the Columbia aquifer has a large range in composition, depending on the depositional environment of its lithic units. The composition of the Columbia aquifer ranges from very fine silty sands to very coarse and gravelly clean sands, commonly consisting of thin, discontinuous, interbedded clay and silt. Sinnott and Tibbitts (1968) characterize the deposits that compose the Columbia aquifer as chiefly yellow sand and sandy clay, with minor lenses and beds of gravel. The thickness of the Columbia aquifer and the depth to the water table generally vary with topography. Usually, land-surface elevation is proportional to the thickness of the Columbia aquifer and the depth to the water table. Surface expressions of the water table in this aquifer are the ponds and streams throughout the Eastern Shore.

The Columbia aquifer generally supplies sufficient quantities of ground water for domestic

Table 1. Locations and depths of wells used to define the hydrogeologic framework and altitude of structural tops of hydrologic units for the Eastern Shore

[Datum is sea level; (-) indicates below; --, well does not penetrate contact; latitude and longitude are reported in degrees, arc minutes, and arc seconds; UYCU, upper Yorktown-Eastover confining unit; UYAQ, upper Yorktown-Eastover aquifer; MYCU, middle Yorktown-Eastover confining unit; MYAQ, middle Yorktown-Eastover aquifer; LYCU, lower Yorktown-Eastover confining unit; LYAQ, lower Yorktown-Eastover aquifer; STCU, St. Marys confining unit; STAQ, St. Marys–Choptank aquifer]

Well number	Station number	Latitude	Longitude	Land surface altitude (feet)	Well depth (feet)	Altitude of structural top of hydrogeologic unit (feet)							
						UYCU	UYAQ	MYCU	MYAQ	LYCU	LYAQ	STCU	STAQ
62F 1	371457076002801	37 14 57	76 00 28	12	-248	-22	-60	-136	-164	-220	-230	-328	-499
62G 1	371721076004301	37 17 21	76 00 43	4	-251	-24	-80	-116	-130	-202	-238	--	--
62G 9	371539076011401	37 15 39	76 01 14	12	-213	-33	-84	-124	-142	-182	--	--	--
63F 1	371159075573201	37 11 59	75 57 32	30	-430	-26	-56	-86	-110	-180	-220	-324	--
63F 16	371307075583502	37 13 07	75 58 35	28	-267	-32	-58	-92	-120	-162	-204	--	--
63G 1	372152075522101	37 21 52	75 55 21	41	-267	-65	-95	-163	-199	-235	-251	--	--
63G 17	371709075560803	37 17 09	75 56 07	28	-372	-24	-88	-116	-162	-224	-256	-338	--
63G 19	372022075561201	37 20 22	75 56 12	35	-200	-20	-75	-12	-189	--	--	--	--
63G 24	371653075584803	37 16 53	75 58 48	15	-356	-51	-113	-17	-165	-223	-247	-325	--
63H 3	372414075543301	37 24 14	75 54 33	37	-64	-39	--	--	--	--	--	--	--
63H 4	372705075555901	37 27 06	75 55 59	17	-321	-15	-71	-127	-177	-227	-253	-315	--
63L 1	374948075594701	37 49 48	75 59 47	2	-985	--	--	-38	-82	-122	-136	-158	-280
64H 3	372830075515501	37 28 30	75 51 55	35	-315	-15	-91	-135	-183	-205	-239	-291	--
64J 1	373600075463801	37 36 00	75 46 38	45	-405	-41	-89	-131	-163	-185	-199	-267	--
64J 4	373201075491301	37 32 01	75 49 13	37	-243	-33	-83	-123	-149	-181	-227	--	--
64J 7	372245075533501	37 32 30	75 49 17	35	-185	-40	-115	-135	--	--	--	--	--
64J 8	373201075491601	37 32 01	75 49 16	35	-245	-49	-85	-135	-150	-195	-229	--	--
64J 11	373059075484503	37 30 59	75 48 45	30	-378	-32	-96	-148	-162	-206	-248	-286	--
64J 14	373508076490901	37 35 08	75 49 09	30	-1,366	-36	-100	-150	-158	-182	-204	-286	-506
64J 19	370939075570401	37 30 59	75 48 45	37	-203	-42	-83	-123	-148	-187	--	--	--
64K 12	373932075452703	37 39 32	75 45 27	47	-293	-15	-91	-129	-147	-183	-209	-269	--
64K 13	373830075422001	37 38 83	75 45 20	45	-276	-33	-95	-133	-163	-191	-219	-257	--
65J 4	373528075420801	37 35 28	75 42 08	10	-290	-40	-100	-135	-164	-216	-242	-283	--
65K 2	374324075443201	37 43 24	75 44 32	15	-325	-19	-67	-129	-145	-175	-215	-265	--
65K 8	373740075400001	37 44 03	75 39 37	50	-290	-14	-78	-144	-180	-200	-212	-280	--

Table 1. Locations and depths of wells used to define the hydrogeologic framework and altitude of structural tops of hydrologic units for the Eastern Shore—Continued

Well number	Station number	Latitude	Longitude	Land surface altitude (feet)	Well depth (feet)	Altitude of structural top of hydrogeologic unit (feet)							
						UYCU	UYAQ	MYCU	MYAQ	LYCU	LYAQ	STCU	STAQ
65K 10	374309075385801	37 43 09	75 38 58	37	-293	-23	-81	-143	-165	-195	-218	-279	--
65K 17	373735075400001	37 42 33	75 44 29	17	-263	-13	-85	-135	-145	-191	-225	--	--
65K 23	374442075432501	37 44 28	75 43 28	13	-277	-33	-65	-115	-125	-163	-199	-275	--
65K 29	374425075400003	37 44 27	75 40 00	35	-355	-7	-75	-145	-170	-195	-215	-295	--
65L 6	374530075401001	37 45 30	75 40 10	35	-250	-31	-105	-120	-135	-180	-202	--	--
66K 2	374320075380501	37 43 19	75 36 54	10	-378	-24	-94	-152	-168	-210	-234	-318	--
66M 1	375303075310101	37 53 03	75 31 01	42	-6,220	-36	-106	-172	-210	-248	-286	-366	-588
66M 7	375538075330201	37 55 38	75 33 02	27	-424	-37	-91	-141	-171	-198	-227	-295	--
66M 9	375256075332301	37 52 56	75 33 23	44	-251	-36	-90	-130	-162	-204	-230	--	--
66M 12	375321075334401	37 53 21	75 33 44	42	-278	-38	-88	-128	-162	-193	-230	--	--
66M 18	375723075344403	37 57 23	75 34 45	11	-338	-25	-99	-127	-141	-165	-209	-259	--
66M 23	375610075361801	37 56 10	75 36 18	6	-1,202	-42	-72	-106	-130	-174	-202	-342	-494
67L 2	375220075265401	37 52 20	75 26 54	10	-172	-42	-120	--	--	--	--	--	--
67M 12	375635075271503	37 56 35	75 27 15	13	-267	-21	-95	-161	-189	--	--	--	--
67N 1	380010075253401	38 00 10	75 25 34	25	-387	-47	-109	-195	-230	-303	-347	-382	--
68M 2	375324075202501	37 53 24	75 20 25	10	-790	-35	-144	-226	-258	-304	-378	-430	-748
68M 4	375153075221001	37 51 53	75 22 10	5	-284	-39	-135	-245	-277	--	--	--	--
MDCE42	380930075415601	38 09 30	75 41 56	105	-206	-10	--	--	-48	-60	-116	-166	-218
MDDE28	380209075401801	38 02 09	75 40 18	5	-1,045	--	-35	-57	-73	-145	-185	-265	-395
MDFC46	380359075251501	38 03 59	75 25 15	39	-521	-54	-86	-152	-228	-280	-312	-370	--
MDDE27	380455075433201	38 04 55	75 43 32	5	-1,008	--	--	--	--	--	--	-171	-345
MDDG20	381427075081101	38 14 27	75 08 11	6	-593	-10	-54	-156	-266	-390	-414	-524	--

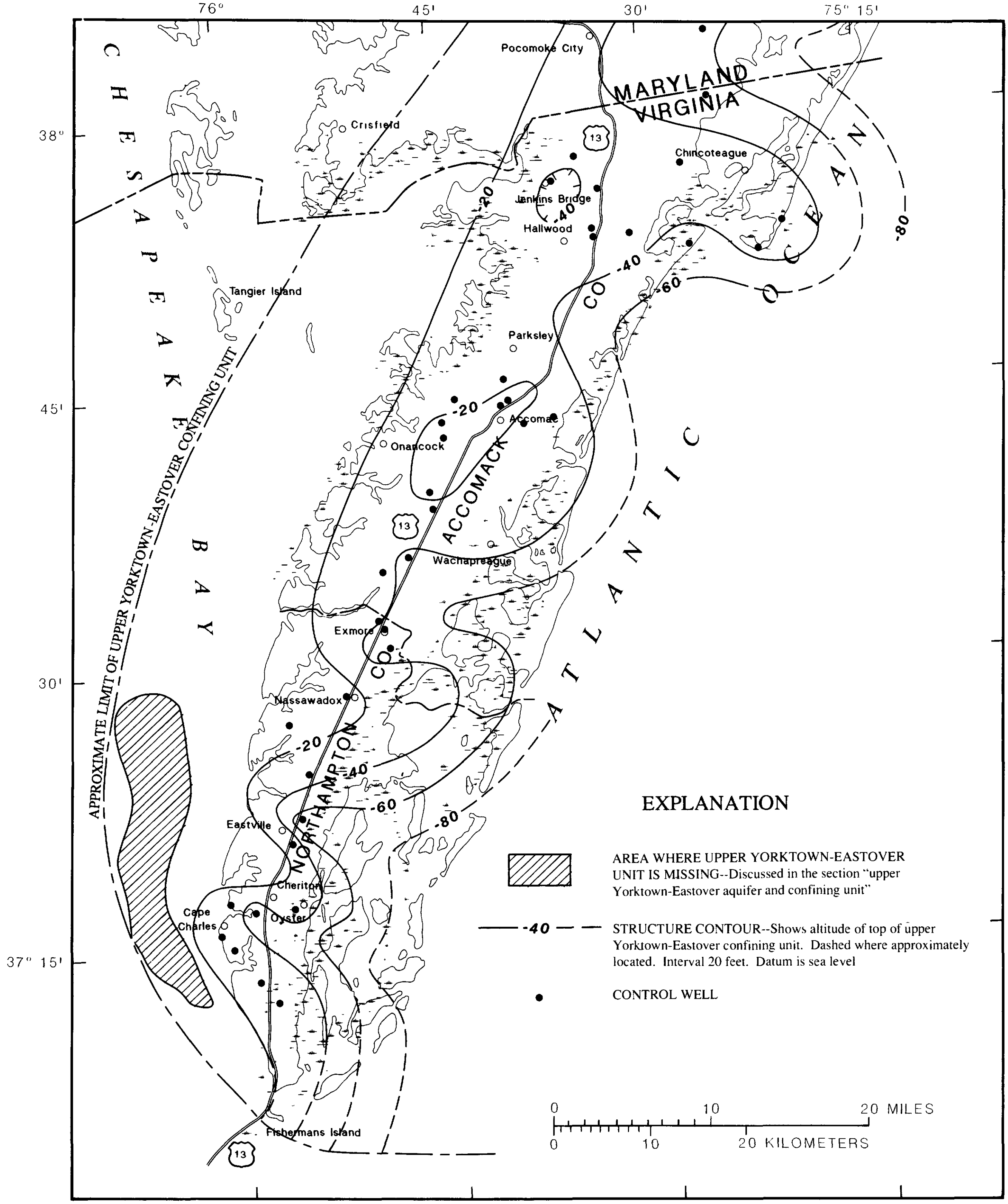


Figure 3. Altitude of top of upper Yorktown-Eastover confining unit.

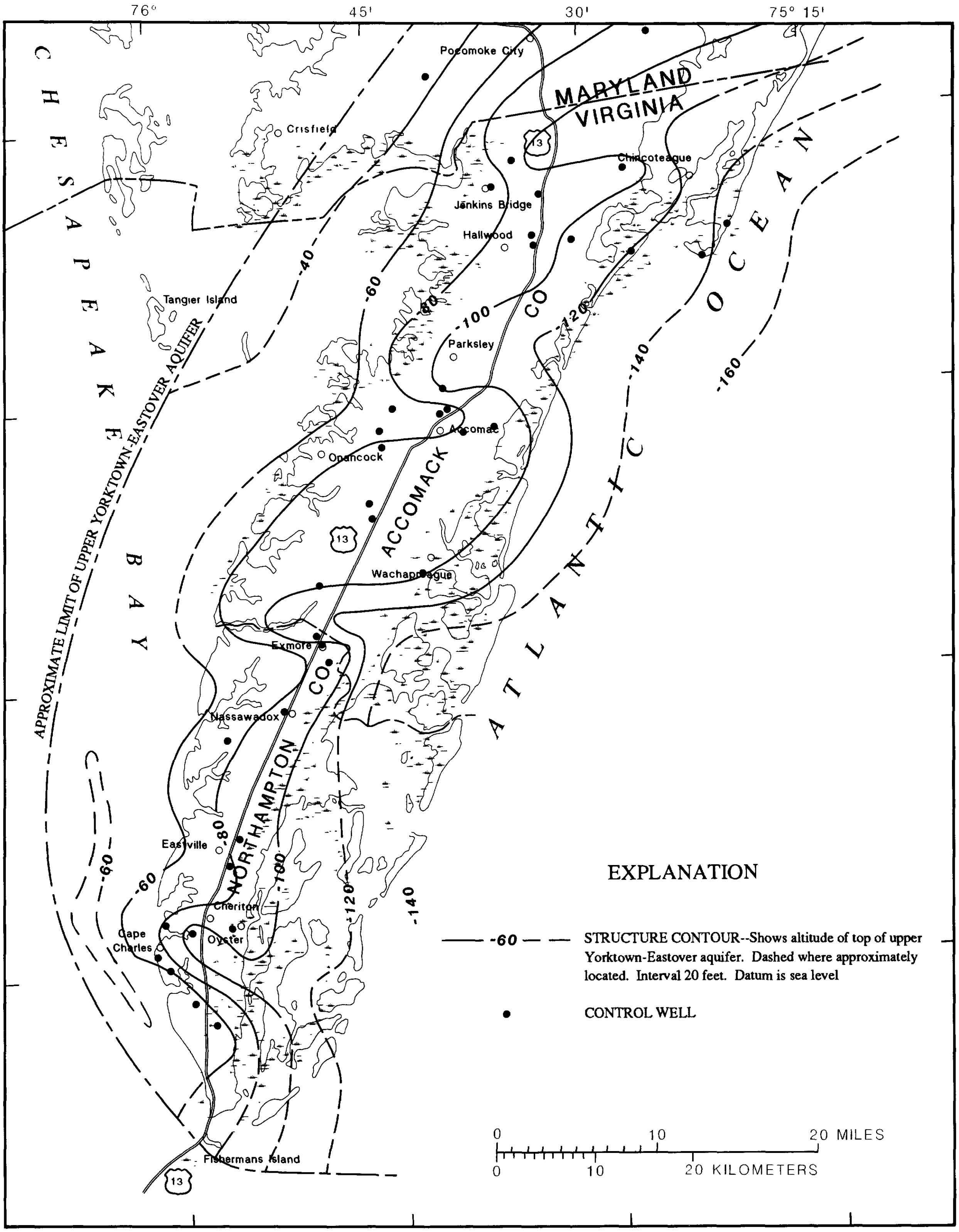


Figure 4. Altitude of top of upper Yorktown-Eastover aquifer.

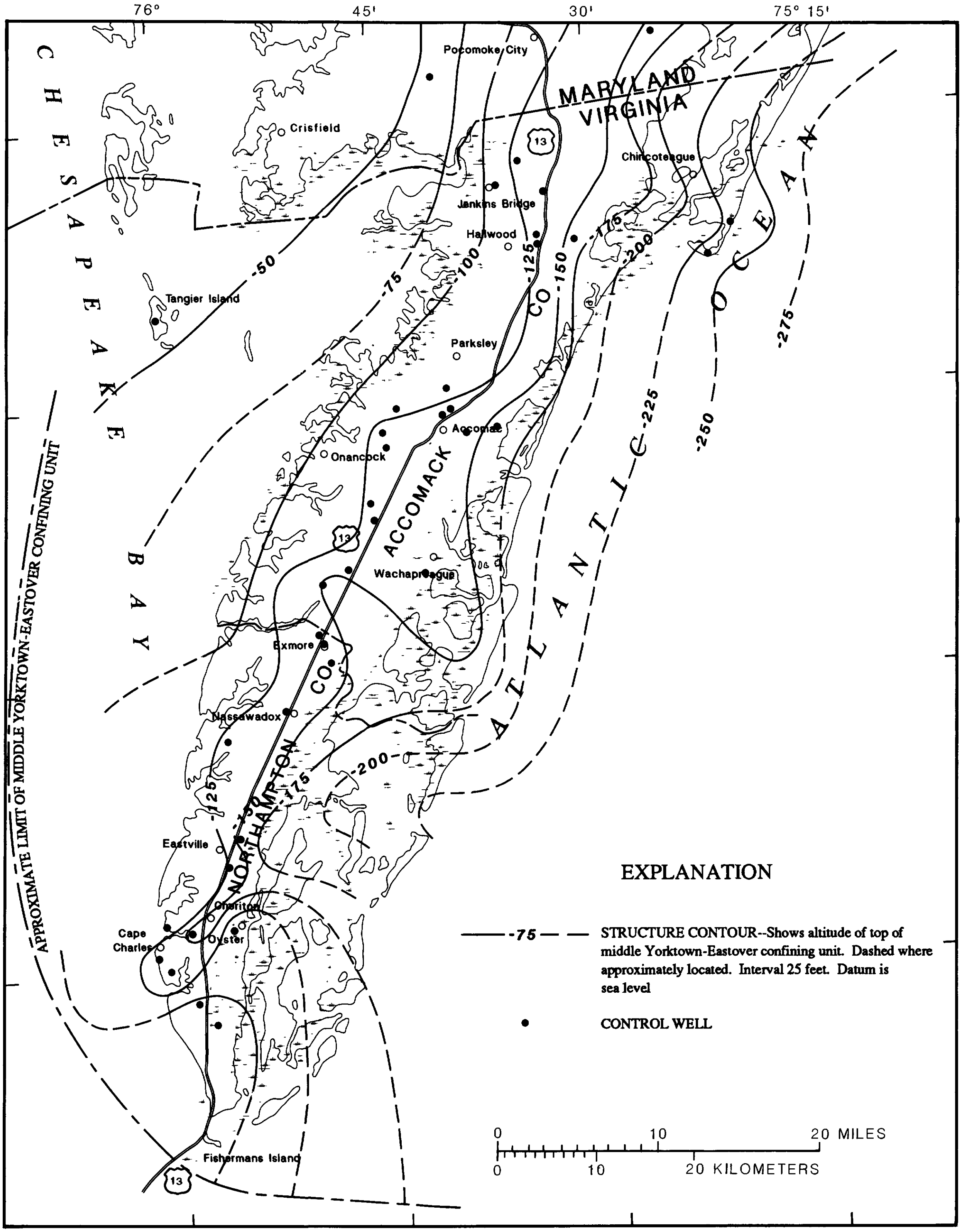


Figure 5. Altitude of top of middle Yorktown-Eastover confining unit.

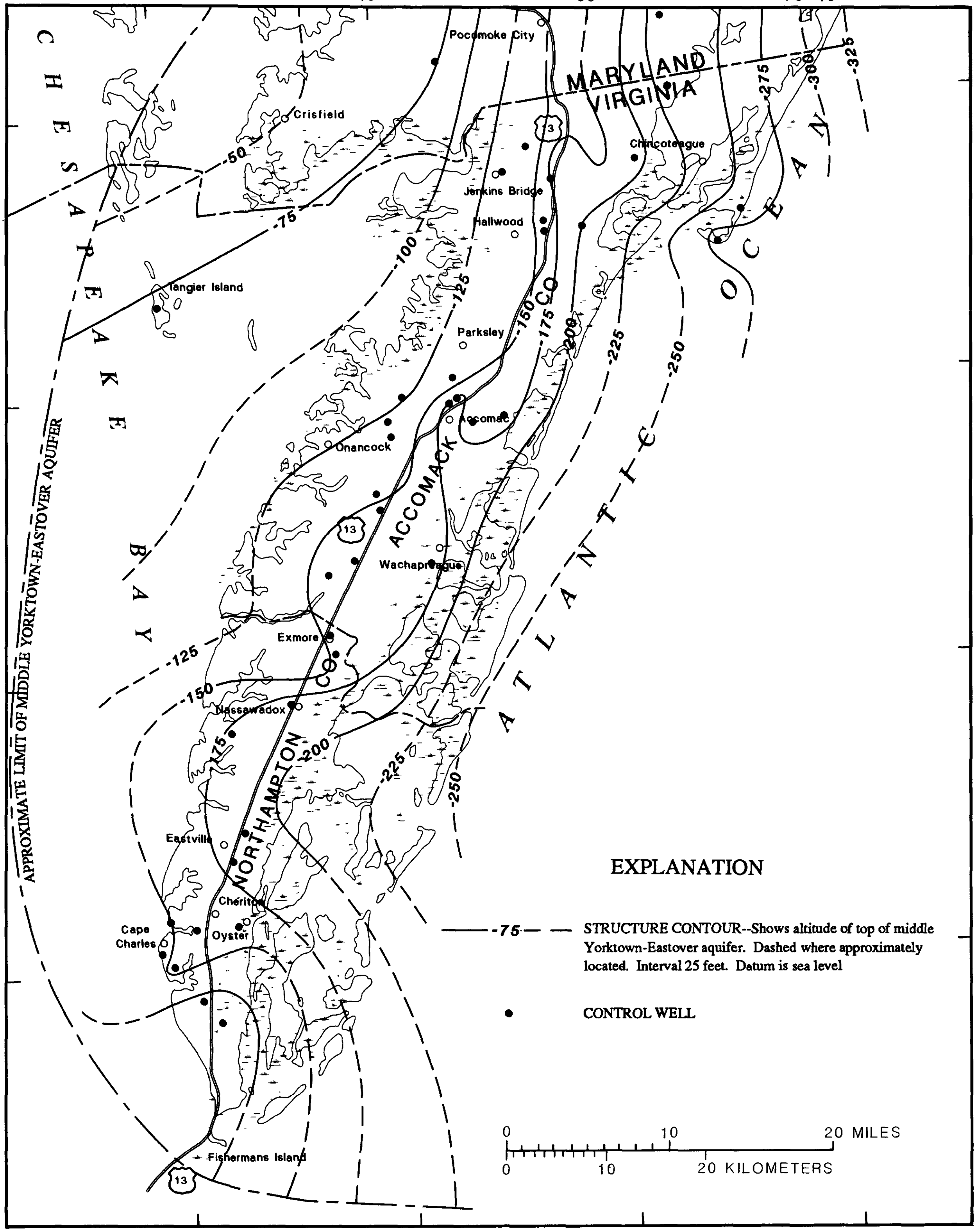


Figure 6. Altitude of top of middle Yorktown-Eastover aquifer.

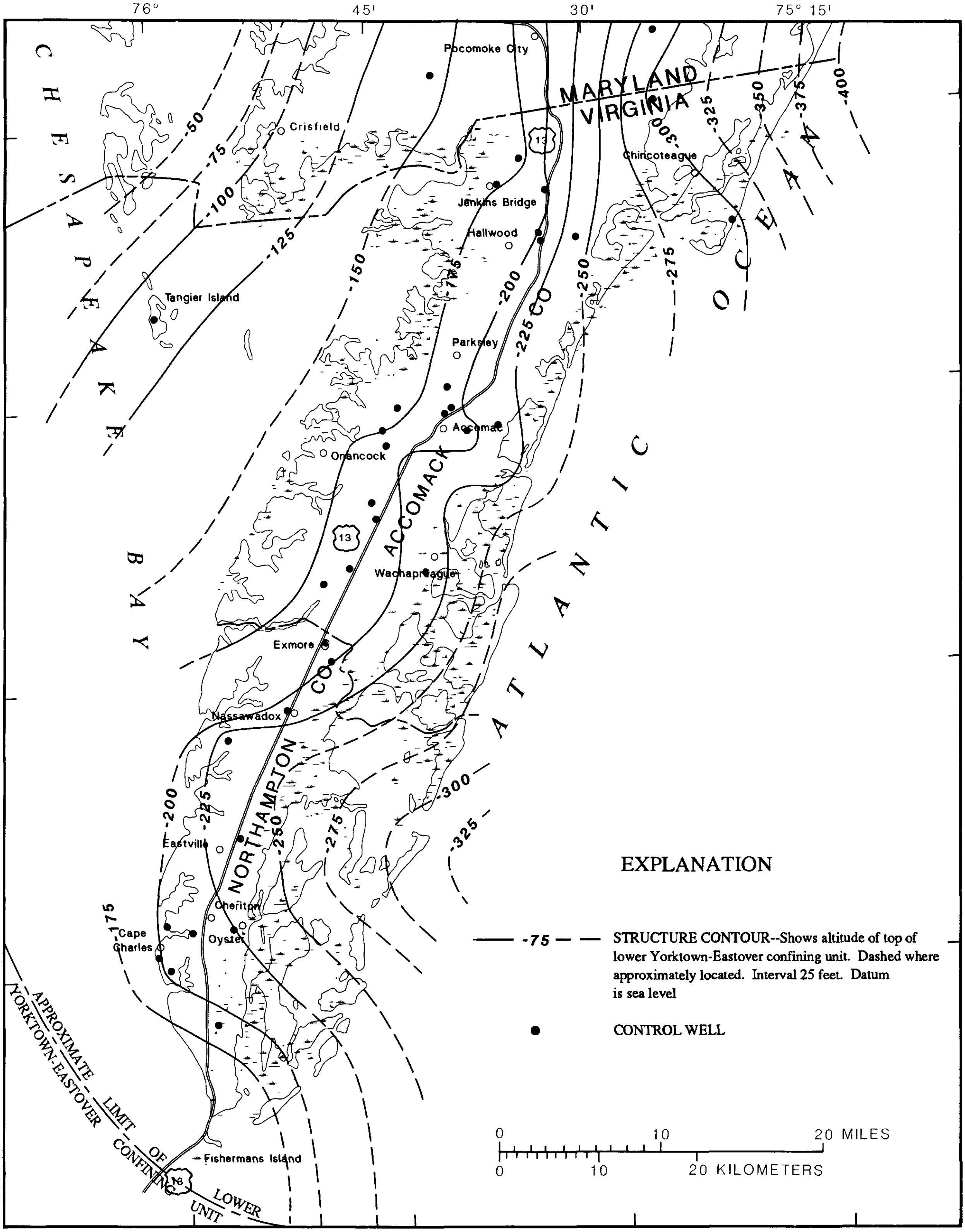


Figure 7. Altitude of top of lower Yorktown-Eastover confining unit.

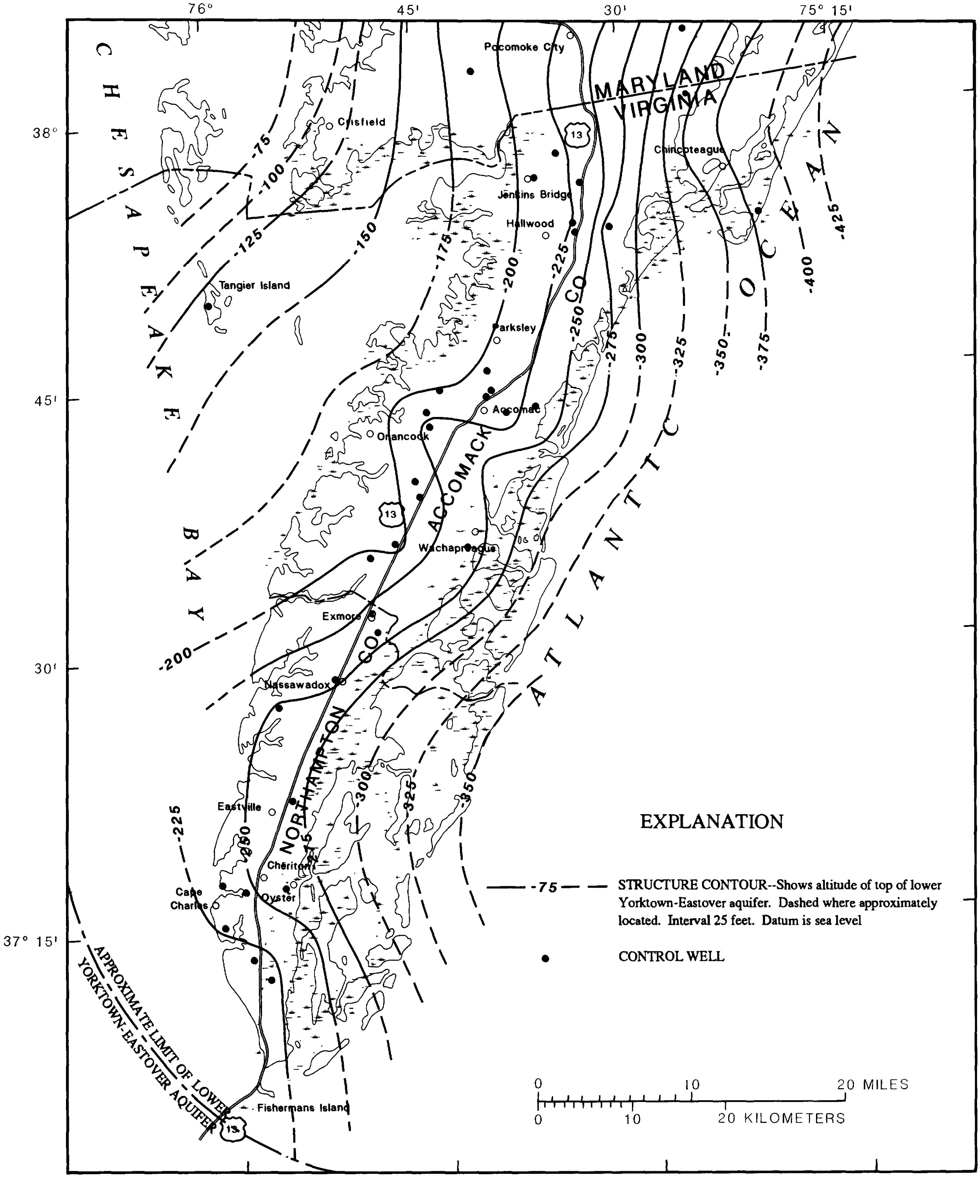


Figure 8. Altitude of top of lower Yorktown-Eastover aquifer.

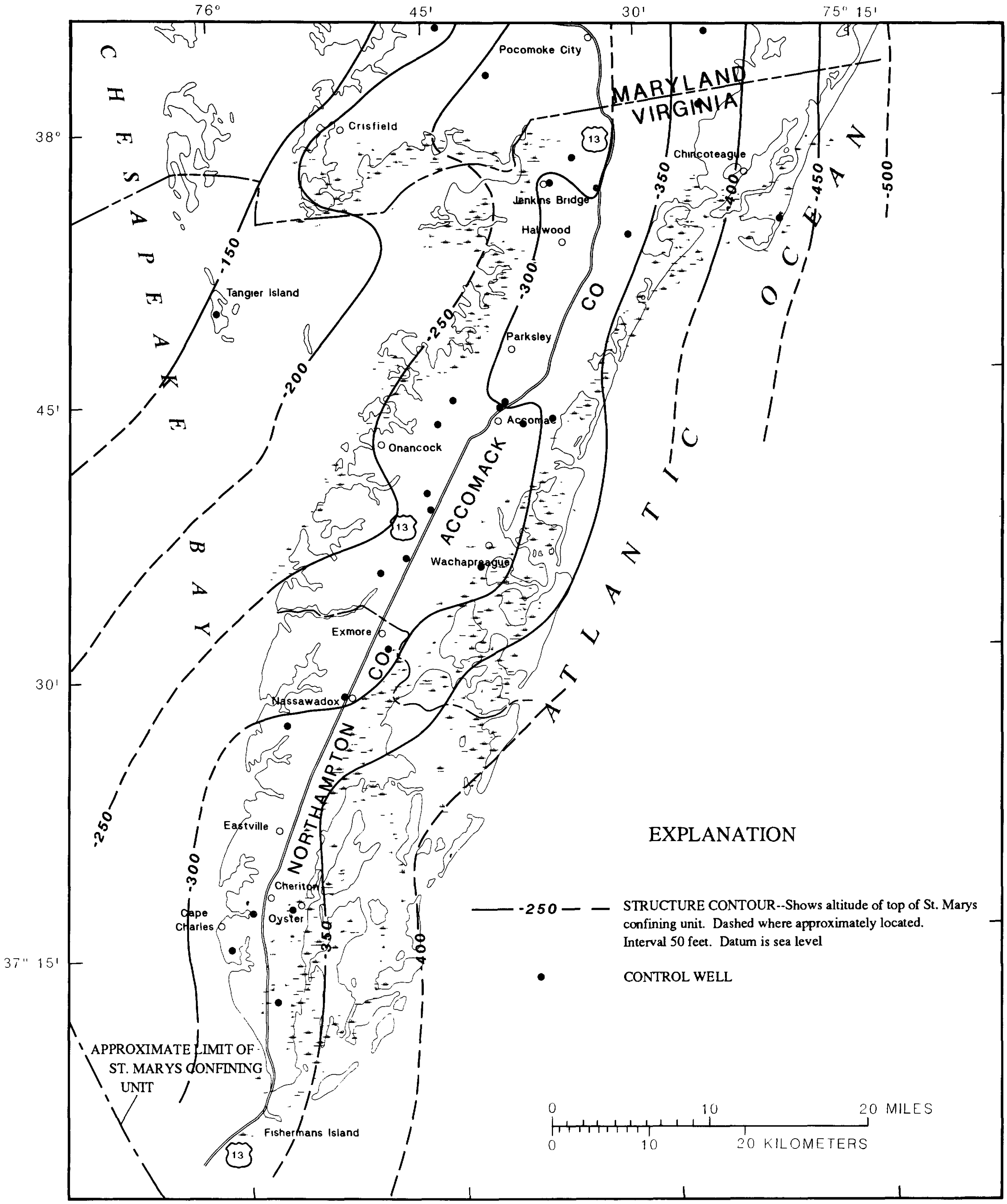


Figure 9. Altitude of top of St. Marys confining unit.

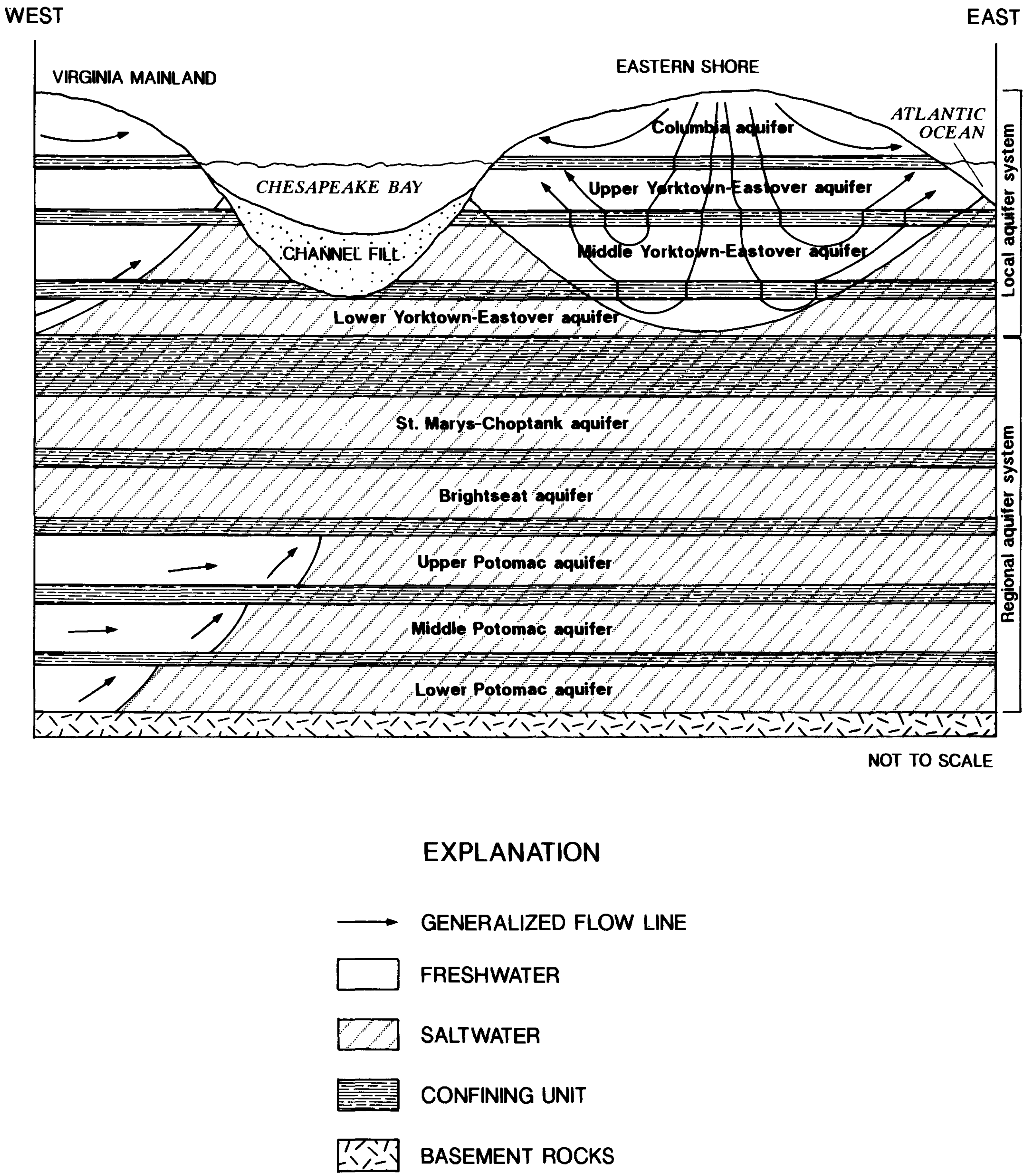


Figure 10. Schematic diagram of aquifers and confining units and generalized flow lines.

Table 2. Statistical summary of transmissivity and storage coefficients derived from aquifer-test results
[ft^2/d, foot squared per day; --, no values reported]

Yorktown-Eastover aquifer		Nonleaky analysis of Theis (1935) Transmissivity (ft^2/d)	Nonleaky analysis of Theis (1935) Storage coefficient (dimensionless)	Nonleaky analysis of Cooper and Jacob (1946) Transmissivity (ft^2/d)	Nonleaky analysis of Cooper and Jacob (1946) Storage coefficient (dimensionless)
Upper	Maximum	3,960	1.3×10^{-3}	670	9.5×10^{-4}
	Minimum	470	2.0×10^{-4}	620	4.6×10^{-4}
	Median	1,670	9.7×10^{-4}	--	--
	Mean	1,940	8.6×10^{-4}	--	--
	Number of tests	4	4	2	2
Middle	Maximum	2,650	8.5×10^{-4}	--	--
	Minimum	230	9.5×10^{-5}	--	--
	Median	1,130	5.2×10^{-4}	--	--
	Mean	1,290	4.9×10^{-4}	350	3.8×10^{-4}
	Number of tests	4	4	1	1
Lower	Maximum	1,360	9.4×10^{-4}	--	--
	Minimum	120	2.6×10^{-4}	--	--
	Median	--	--	--	--
	Mean	--	--	--	--
	Number of tests	2	2		

purposes. Irrigation ponds in the Columbia aquifer provide much of the water needed for agricultural purposes. In upland areas, the quality of water in this aquifer is generally within drinking-water standards if wells are not located downgradient of potential sources of contamination. In low-lying and poorly drained areas, the water quality is worse than in upland areas, reflecting the nearness of saltwater bodies and contamination from land uses.

Pleistocene Paleochannel Aquifers

Evidence indicates the presence of subsurface erosional channels where all or part of the Yorktown Formation sediments have been removed and replaced by marginal-marine deposits of Pleistocene age. The sediments in these paleochannel areas are, therefore, quite different from the Yorktown sediments that are typical of the rest of the Eastern Shore. The two major paleochannels that have been identified in the study area cut eastward across the peninsula near Exmore and Eastville, Va. Mixon (1985) describes the lithology of a type cross section in the vicinity of the Eastville paleochannel in southern Northampton County. The channel is covered with a basal-gravelly sand unit that contains pebbles and small cobbles overlain by muddy sand and clay-silt, marginal-marine deposits. The sands and gravels of the channel deposits are extremely transmissive; however, their extent has not yet been defined, and the gravelly sands are overlain by a poorly sorted mixture of mud, silt, and clay of varying thicknesses. Detailed study of the paleochannels is necessary to define the extents of the different types of sediments and determine the hydraulic properties associated with those sediments. For the purposes of this report, the channel sediments are hydraulically connected to the surrounding Yorktown sediments and have been included as part of the Yorktown-Eastover aquifer system.

Yorktown-Eastover Aquifer System

The Yorktown-Eastover aquifer system is a multiaquifer unit consisting of late Miocene and Pliocene deposits and is composed of the sandy facies of the Yorktown and Eastover Formations (Meng and Harsh, 1988). The Yorktown-Eastover aquifer

Table 3. Statistical summary of well yield, specific capacity, transmissivity, and horizontal hydraulic conductivity derived from specific-capacity tests

[gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot; ft^2/d, foot squared per day; ft/d, foot per day]

Yorktown-Eastover aquifer	Statistic	Well yield (gal/min)	Specific capacity [(gal/min)/ft]	Transmissivity (ft^2/d)		Horizontal hydraulic conductivity (ft/d)	
				Unadjusted	Adjusted[1]	Unadjusted	Adjusted[1]
Upper	Maximum	315	17.5	1,000	4,530	17.2	60.4
	Minimum	5	.2	49	61	.9	3.3
	Median	120	1.7	361	739	10.3	10.6
	Mean	125	2.8	446	1,259	8.9	21.3
	Number of tests	14	14	10	10	10	10
Middle	Maximum	645	9.9	912	3,240	15.6	44.3
	Minimum	20	.7	186	206	3.8	4.2
	Median	95	1.5	427	834	6.2	17.2
	Mean	136	2.3	487	1,375	8.3	22.7
	Number of tests	12	12	7	7	7	7
Lower	Maximum	201	5.7	1,697	2,094	19.6	24.2
	Minimum	1	.1	24	95	.4	1.6
	Median	34	1.0	209	353	5.3	8.8
	Mean	53	1.8	35	724	7.6	10.9
	Number of tests	10	10	4	4	4	4

[1]Adjusted for effects of partial penetration.

Table 4. Vertical hydraulic conductivities derived from laboratory analyses of sediment cores from the Jenkins Bridge Research Station

[ft/d, foot per day]

Depth of sample below land surface (feet)	Confining unit	Vertical hydraulic conductivity (ft/d)
63.7– 64.7	Upper Yorktown-Eastover	1.39×10^{-5}
348.7–349.7	St. Marys	1.63×10^{-5}
368.4–369.4	St. Marys	1.27×10^{-5}

system consists of a series of alternating sand and clay-silt units that form three distinct aquifers that generally are present throughout the Eastern Shore. These aquifers are identified as the upper, middle, and lower Yorktown-Eastover aquifers. Correspondingly, each aquifer is overlain by the upper, middle, and lower Yorktown-Eastover confining units. The entire aquifer system is wedge shaped and thickens and dips eastward. The units extend eastward beneath the Atlantic Ocean to the continental shelf and westward underneath the Chesapeake Bay.

The hydraulic characteristics of the aquifers and confining units determine their ability to store, transmit, and release water. Transmissivity, storage coefficient, and vertical hydraulic conductivity are the principal hydraulic characteristics necessary for an analysis of ground-water flow. Transmissivities and storage coefficients derived from aquifer-test data for the freshwater-confined aquifers are summarized in table 2. Few aquifer tests are available that reflect the characteristics of an individual aquifer because most of the wells used for aquifer tests have screens that are open to more than one aquifer. The aquifer-test data are supplemented by transmissivities estimated from specific-capacity data (table 3). Table 3 provides a statistical summary of well yield, specific capacity, transmissivity, and horizontal hydraulic conductivity estimated from specific-capacity tests. A detailed description of the method and equations used to estimate transmissivities from specific-capacity data is presented by Laczniak and Meng (1988). A few point estimates for vertical hydraulic conductivities are available from laboratory analysis of sediment cores from the Jenkins Bridge Research Station (well 66M23) (table 4). These data need to be interpreted and used with caution because (1) the core samples could be disturbed, (2) the core samples represent 1-ft intervals of thicker confining units, and (3) the values are local point values and cannot be interpreted as regional estimates.

Upper Yorktown-Eastover Aquifer and Confining Unit

The Columbia aquifer is underlain by the upper Yorktown-Eastover confining unit. The confining unit consists of gray, greenish-gray, or brownish-gray clayey silt or silty clay. The confining unit is continuous underneath the peninsula; however, incisement by present-day channels in the Chesapeake Bay has likely removed part or all of the upper Yorktown-Eastover confining-unit sediments (figs. 3 and 11) west of the peninsula. In the model area where control wells exist, the confining unit ranges in thickness from 26 ft at well 63F16 in southern Northampton County to 109 ft at well 68M2 on Chincoteague Island. A laboratory analysis of a sediment core from well 66M23 indicates a vertical hydraulic conductivity of 1.39×10^{-5} ft/d for the upper Yorktown-Eastover confining unit. Analyses of cores from the St. Marys confining unit, at the same site, indicated similar values (table 4). Elsewhere on the mainland part of the Virginia Coastal Plain, laboratory analyses of confining-unit sediments have ranged from 3.93×10^{-3} to 9.2×10^{-1} ft/d (Harsh and Laczniak, 1986).

The upper Yorktown-Eastover confining unit is underlain by the upper Yorktown-Eastover aquifer (figs. 3,4). Geologic data from the Exmore core (well 64J14) and the VWCB Jenkins Bridge Research Station (well 66M23) indicate that the upper Yorktown-Eastover aquifer predominantly consists of Yorktown Formation (Pliocene) sediments. Lithologically, the sediments of the Yorktown are diverse, consisting of varying mixtures of fine-grained to very coarse-grained, white to greenish-gray, shelly, glauconitic, and pebbly quartz sands (Meng and Harsh, 1988). Hydraulic properties of the upper Yorktown-Eastover aquifer are summarized in tables 2 and 3. The range of fine-grained to very coarse-grained sediments in the Yorktown Formation and the variable aquifer thickness result in an order of magnitude range in transmissivity values. The upper Yorktown-Eastover aquifer extends eastward to the continental shelf and westward underneath the Chesapeake Bay. The characteristics and extent of the upper Yorktown-Eastover aquifer are not known in offshore areas beneath the Atlantic Ocean and the Chesapeake Bay. The upper Yorktown-Eastover aquifer is most likely truncated beneath the Chesapeake Bay by erosion from the ancient Susquehanna River channel and incised by the nearshore channels of the present-day Chesapeake Bay (Hack, 1957; Colman and others, 1990). In the model area where control wells exist, the upper Yorktown-Eastover aquifer ranges in thickness from 15 ft at well 65L6 in central Accomack County to 110 ft at well 68M4 on Chincoteague Island.

Middle Yorktown-Eastover Aquifer and Confining Unit

The upper Yorktown-Eastover aquifer is underlain by the middle Yorktown-Eastover confining unit. The confining unit consists of gray, greenish-gray, or brownish-gray clayey silt or silty clay and ranges in thickness from 8 ft at well 63G24 in southern Northampton County to 76 ft at well MDFC46 in Worcester County, Md. The confining unit is present throughout the study area.

The middle Yorktown-Eastover confining unit is underlain by the middle Yorktown-Eastover aquifer. Estimated hydraulic properties are summarized in tables 2 and 3. The middle Yorktown-Eastover aquifer consists of sediments from the Yorktown Formation; therefore, the hydraulic properties of the middle Yorktown-Eastover aquifer are similar to those of the upper Yorktown-Eastover aquifer. The middle Yorktown-Eastover aquifer is present throughout the study area. The characteristics and extents of these units in offshore areas are unknown. It is likely that the western limit of the middle Yorktown-Eastover aquifer (fig. 6) extends beyond the western limit of the upper Yorktown-Eastover aquifer (fig. 4) as a result of erosion by the ancient Susquehanna River channel. In the model area, where control wells exist, the middle Yorktown-Eastover aquifer ranges in thickness from 12 ft at well MDCE42 in Somerset County, Md., to 124 ft at well 67N1 in northeastern Accomack County.

Lower Yorktown-Eastover Aquifer and Confining Unit

The middle Yorktown-Eastover aquifer is underlain by the lower Yorktown-Eastover confining unit. The lithology of the confining unit is similar to that of the middle and upper confining units and consists of gray, greenish-gray, or brownish-gray clayey silt or silty clay. The lower Yorktown-Eastover confining unit ranges in thickness from 10 ft at well 62F1 in southern Northampton County to 74 ft at well 68M2 on Chincoteague Island (fig. 2).

The lower Yorktown-Eastover aquifer underlies the lower Yorktown-Eastover confining unit and primarily consists of sediments from the Miocene

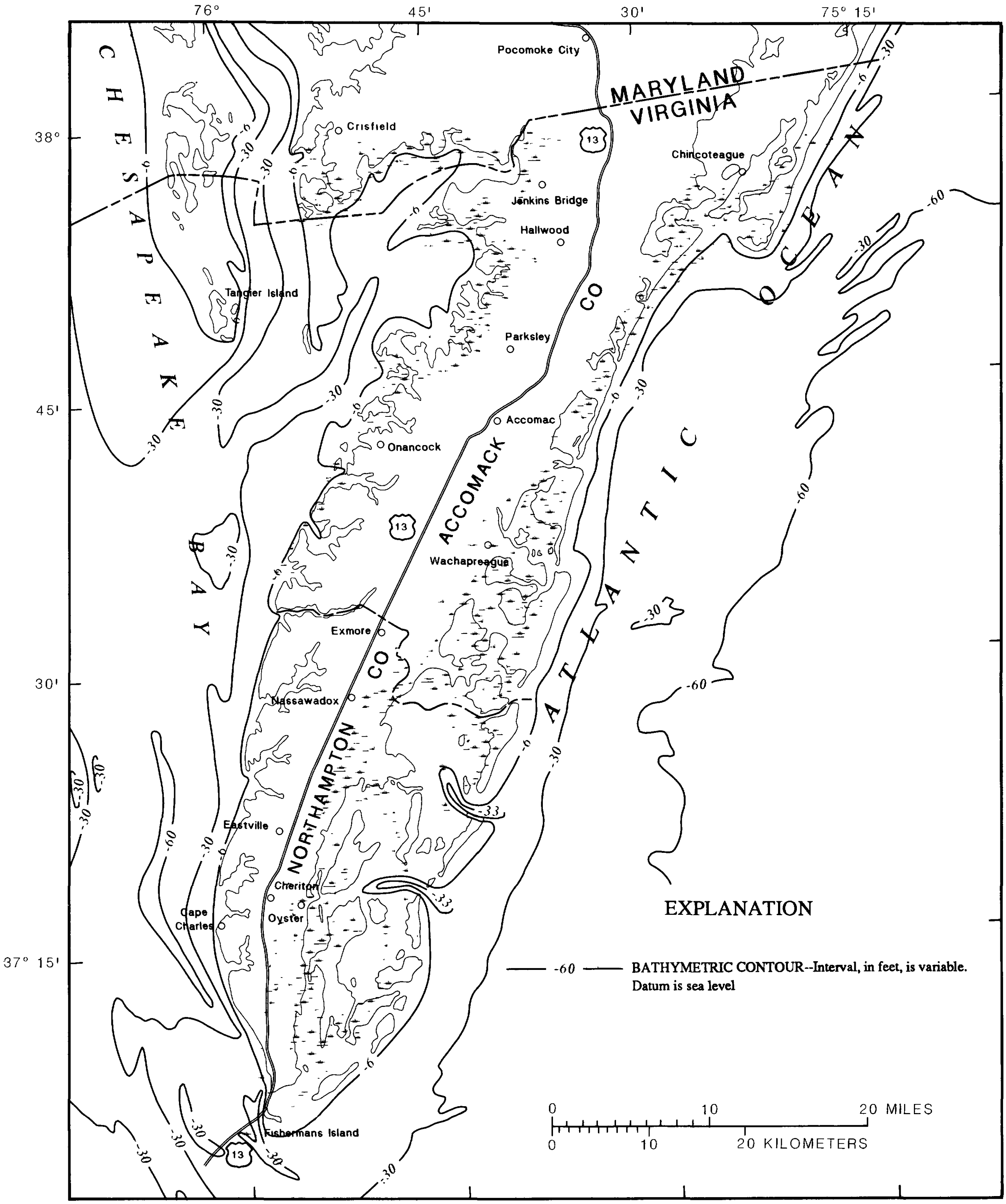


Figure 11. Bathymetry in the vicinity of the Eastern Shore.

Eastover Formation. Mixon (1985) describes the Eastover sediments as chiefly fine-grained to very fine-grained, greenish-gray, clayey, silty, and shelly quartz sands. Estimated hydraulic properties of the lower Yorktown-Eastover aquifer are summarized in tables 2 and 3. The Eastover Formation typically contains finer-grained sediments than the Yorktown Formation; therefore, the lower Yorktown-Eastover aquifer generally is less transmissive than the upper and middle Yorktown-Eastover aquifers. The lower Yorktown-Eastover aquifer is present throughout the study area. Because the lower Yorktown-Eastover aquifer is at a greater depth, its limit probably extends farther west underneath the Chesapeake Bay than the middle and upper Yorktown-Eastover aquifers (figs. 4, 6, and 8). The lower Yorktown-Eastover aquifer ranges in thickness from 22 ft at well 63L1 on Tangier Island (fig. 2) to 140 ft at well 66M23 in Accomack County.

St. Marys Confining Unit

The St. Marys confining unit consists of the predominantly clayey facies of the St. Marys Formation and the lower clayey facies of the Eastover Formation. These sediments are middle to late Miocene in age. The St. Marys confining unit is conformably overlain throughout the study area by the lower Yorktown-Eastover aquifer. The sediments consist of interbedded silty and sandy clay and varying amounts of shells, typically bluish-gray to gray in color (Meng and Harsh, 1988). Laboratory analyses of sediment cores from the St. Marys confining unit at well 66M23 indicate vertical hydraulic conductivities of 1.63×10^{-5} and 1.27×10^{-5} ft/d (table 4). The St. Marys confining unit ranges in thickness from 150 to 350 ft. This massive clay unit is effectively a lower boundary for the fresh ground-water-flow system on the Eastern Shore.

Ground-Water Hydrology

The ground-water-flow system can be divided into a local and a regional ground-water-flow system (fig. 10). The local ground-water-flow system consists of the unconfined aquifer (Columbia) and the confined-freshwater aquifers (upper, middle, and lower Yorktown-Eastover). The aquifers in the local system contain freshwater that is recharged locally by rainfall on the Eastern Shore and discharges locally to estuaries, marshes, the Chesapeake Bay, and the Atlantic Ocean. The regional system of the Eastern Shore consists of the confined aquifers beneath the lower Yorktown-Eastover aquifer. Information for these deep confined aquifers beneath the Eastern Shore is limited; however, it is likely that the lower Yorktown-Eastover aquifer is underlain by the St. Marys–Choptank, Brightseat, upper Potomac, middle Potomac, and lower Potomac aquifers (Meng and Harsh, 1988). These aquifers are hydraulically separated from the overlying freshwater aquifers by the thick St. Marys confining unit. The regional aquifers are continuous underneath the Chesapeake Bay, and deep ground-water-flow beneath the Eastern Shore is affected by the regional Coastal Plain ground-water-flow system.

Local Ground-Water-Flow System

A schematic of ground-water flow in the local ground-water system is presented in figure 10. Freshwater recharges the local ground-water system primarily through precipitation that falls on the peninsula and infiltrates into the sediments, because there are no major surface-water bodies on the peninsula. Cushing and others (1973) estimated that 8.5 to 15 in. of the 43 in. of annual precipitation recharges the unconfined aquifer; the remainder is either surface runoff or evaporation. Using an average recharge of 12 inches per year (in/yr) over a 450 square mile (mi^2) recharge area (total land area minus wetlands) for the Virginia part of the Eastern Shore, the estimated natural recharge to the unconfined aquifer is 257 Mgal/d. Precipitation infiltrates into the ground and percolates to the water table of the Columbia aquifer. Water in the unconfined aquifer flows vertically into the lower parts of the unconfined aquifer and laterally through the unconfined aquifer toward discharge sites such as springs, streams, marshes, estuaries, the Chesapeake Bay, and the Atlantic Ocean. The lateral direction of ground-water flow generally is from the ground-water divide at the center of the peninsula to the Chesapeake Bay and Atlantic Ocean. Eventually, water that is moving vertically encounters the upper Yorktown-Eastover confining unit, and much of the flow is forced to move laterally through the unconfined aquifer. Under natural (prepumping) conditions, a comparatively small amount of water is able to flow through the less permeable confining unit into the confined-aquifer system. The predominant movement of ground water is in a lateral direction through aquifers and in a vertical direction through confining units. Where fresh ground water encounters salty ground water, the less dense freshwater is forced upward. The upward-moving fresh ground water is again inhibited by confining units but eventually discharges into marshes, estuaries, the bay, and ocean.

Water levels in wells in the Columbia aquifer indicate the direction of ground-water flow and the response of the system to recharge and discharge. Well-construction information for wells along a transect from the topographic high (ground-water divide) near U.S. Route 13 near Townsend, Va., to the marsh adjacent to Magothy Bay (ground-water-discharge area) (fig. 12) is presented in table 5. Water levels fluctuate throughout the year in response to the amount of recharge to and discharge from the system (fig. 13). Water-level declines in this agricultural area during the spring and summer indicate the effects of increased evapotranspiration. Water levels are highest at well 63F31 near the center of the peninsula and decline toward the coast (fig. 13). The water-level gradients indicate that ground water flows from the topographic high in the center of the peninsula to the lowlands adjacent to Magothy Bay. Water levels from an irrigation pond (63F38) and a nearby well (63F31) show the response of the unconfined aquifer to pumping (fig. 14). The water level in well 63F31 shows little response to the greater than 4-ft decline in water levels in the pond caused by pumpage during the 1989 growing season. Pumpage from the irrigation pond only has a local effect on ground-water levels because of the high permeability of the coarse-grained sediments in the unconfined aquifer.

Temporal water-level trends and vertical gradients in water levels provide additional information about the response of the ground-water-flow system to recharge, discharge, and pumpage stress. The VWCB has constructed a series of research stations on the Eastern Shore to monitor such responses (fig. 15). Each research station consists of a cluster of wells with individual wells screened in different aquifers. Well identifiers, well location, and well-construction information for wells in selected research stations are summarized in table 6. Water levels from research-station wells provide information about the vertical direction of flow between aquifers. Water levels for two research stations on the Eastern Shore that illustrate the vertical directions of flow in this multiaquifer system are shown in figure 16. The water levels for the research station in a recharge area (fig. 16A) reflect downward vertical flow from the unconfined aquifer (well 64K10), to the upper Yorktown-Eastover aquifer (well 64K11), to the lower Yorktown-Eastover aquifer (well 64K12). In contrast, the water levels presented in figure 16B indicate upward flow in a coastal discharge area. Well 64J11 is screened in the lower Yorktown-Eastover aquifer, whereas wells 64J10 and 64J9 are screened in the middle and upper Yorktown-Eastover aquifers, respectively. Except for the early period of record when water levels appear to be affected by pumping, heads in the wells for this research station reflect vertical flow in an upward direction as ground water flows toward discharge sites in the coastal marshes, estuaries, and ocean.

Table 5. Well-construction data for wells completed in the Columbia aquifer in a transect *A–A′* near Townsend, Va.

[Datum is sea level; well depth is in feet below land surface datum; USGS, U.S. Geological Survey]

USGS well number	Station number	Land-surface elevation (feet)	Well depth (feet)
63F 25	371145075565901	12.38	6.6
63F 26	371143075565801	15.37	8.9
63F 27	371133075570401	22.92	12.7
63F 29	371121075565001	13.40	9.5
63F 30	371128075572101	29.03	15.0
63F 31	371136075580201	31.79	12.0
63F 32	371136075574801	28.95	12.0
63F 38	371144075580201	22.00	pond
63F 49	371125075570205	27.35	16.8

Regional Ground-Water-Flow System

The regional ground-water-flow system consists of the confined aquifers beneath the lower Yorktown-Eastover aquifer (fig. 10). These aquifers are continuous underneath the Chesapeake Bay and are part of the westward-thinning wedge of unconsolidated sediments that make up the Coastal Plain of Virginia. Ground-water flow in these deep confined aquifers beneath the Eastern Shore is affected by the Chesapeake Bay and regional ground-water flow from the Virginia mainland. Freshwater is recharged to the deep confined aquifers from precipitation that falls on the Virginia mainland and infiltrates into the confined system. At the northern end of the peninsula, fresh ground water flows farther beneath the Chesapeake Bay and the Eastern Shore

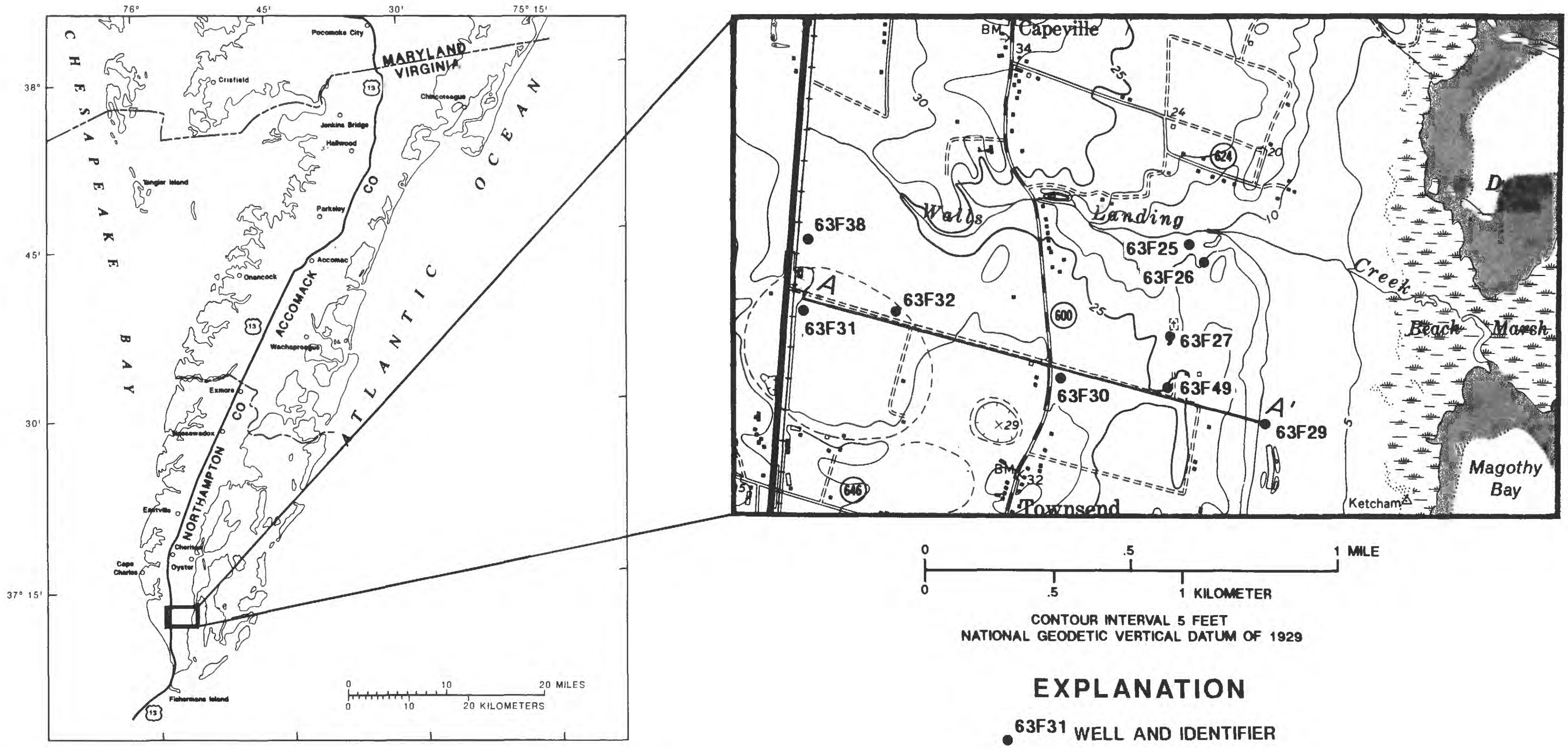


Figure 12. Locations of wells along transect *A–A'* in the Columbia aquifer.

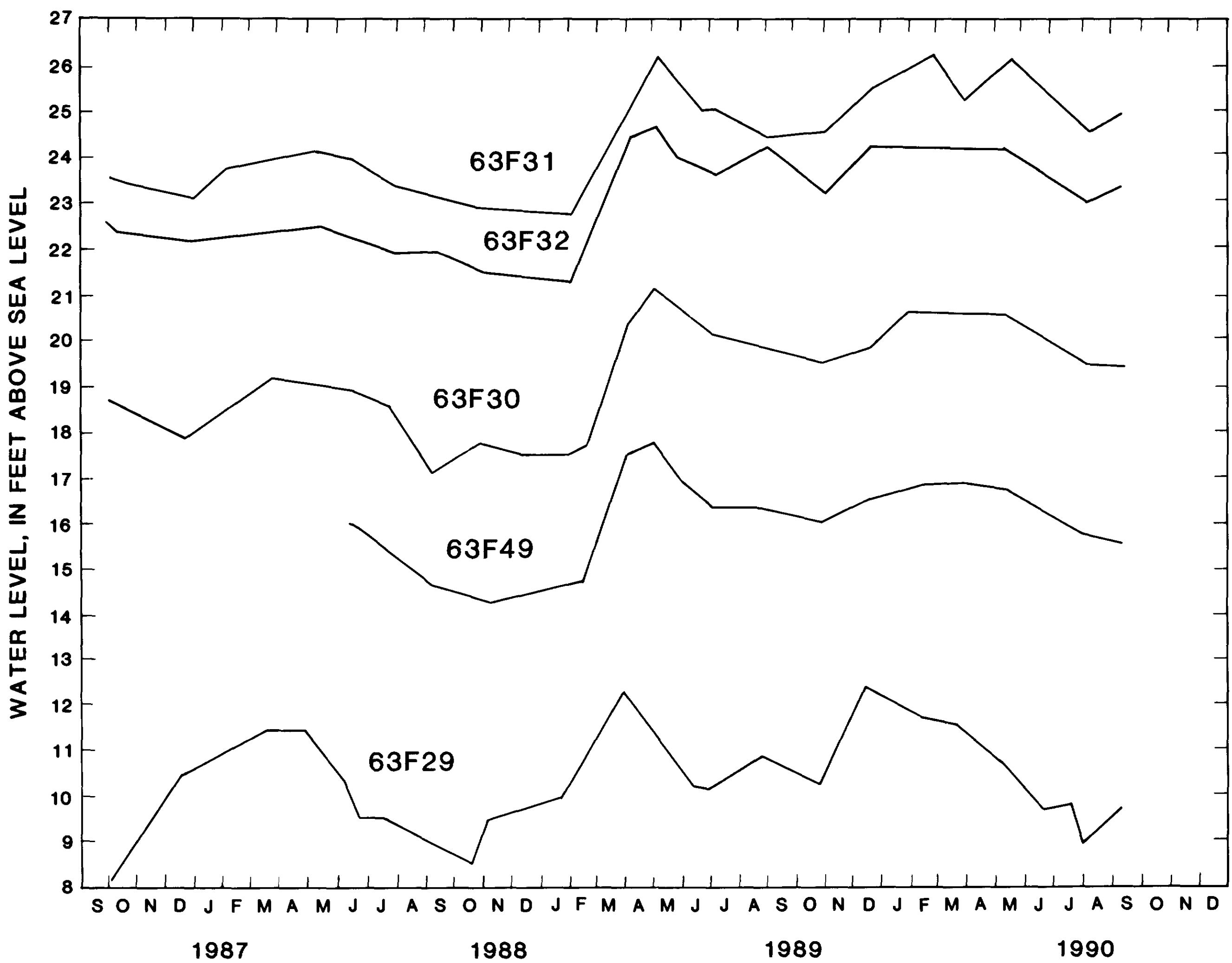


Figure 13. Water levels in selected wells along transect *A–A′* in the Columbia aquifer.

than at the southern end. The northern end of the peninsula is closer to higher landmasses; therefore, it has a nearby freshwater source. The freshwater heads at the southern part of the Virginia Coastal Plain are not high enough to force the saltwater out of the deep sediments beneath the Chesapeake Bay and Eastern Shore.

Chloride concentrations support this conceptualization of ground-water flow. Chloride concentrations in ground water from the upper Potomac aquifer for the Virginia Coastal Plain are lower along the coast in the northeastern part of the Virginia mainland than in the southeastern part (fig. 17). The chloride concentration is 150 mg/L in water from well 63L4 on Tangier Island, which is screened in the upper Potomac aquifer. Chloride concentrations in water from wells at approximately the same longitude in the southeastern part of the Virginia mainland range from 1,360 to 1,900 mg/L in the upper Potomac aquifer. Research-station well clusters on the Eastern Shore also indicate a stronger regional freshwater influence in the northern part of the Eastern Shore than in the southern part. The vertical chloride distribution is shown in table 7 for the two research-station well clusters on the Eastern Shore that have wells located in the upper Potomac aquifer. At the Jenkins Bridge Research Station, chloride concentrations are lower in the upper Potomac aquifer (1,500 mg/L) than in the overlying St. Marys–Choptank (3,800 mg/L) and lower Yorktown-Eastover (2,100 mg/L) aquifers. The vertical profile of chloride concentrations from the

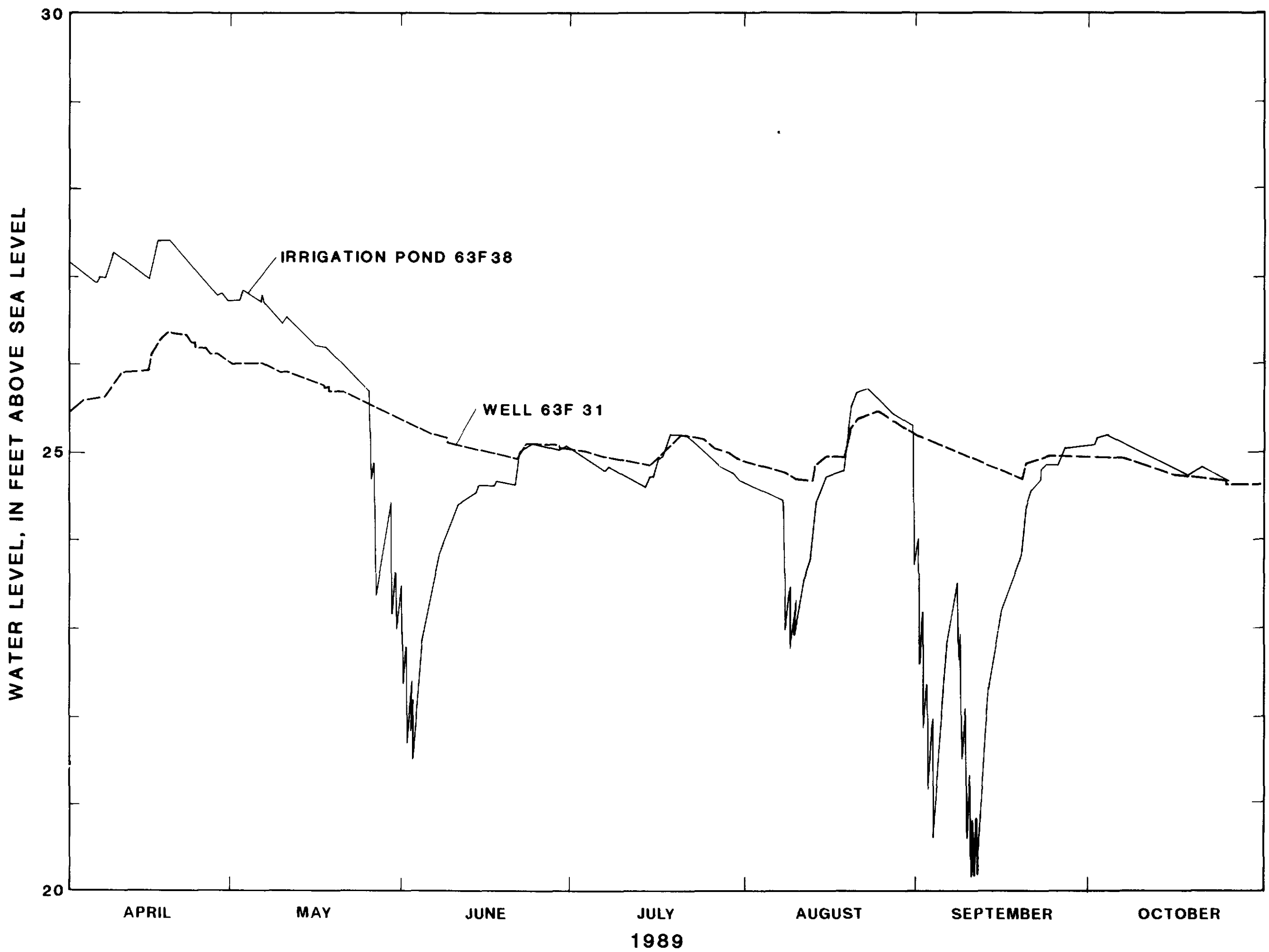


Figure 14. Water levels in an irrigation pond and in a nearby well completed in the Columbia aquifer.

Jenkins Bridge Research Station indicates that the origin of the freshwater in the upper Potomac aquifer is freshwater flowing beneath the Chesapeake Bay from the mainland of Virginia and Maryland (fig. 17, table 7). The vertical profile of chloride concentrations for the Kiptopeke Research Station at the southern tip of the Eastern Shore shows increasing chloride concentrations with depth at this location (table 7). Well 63F52 at the Kiptopeke Research Station is located farther west than well 66M23 at the Jenkins Bridge Research Station (fig. 17); however, the freshwater flow beneath the Chesapeake Bay does not extend as far to the east at the southern tip of the peninsula as it does at the northern part of the peninsula. The chloride concentration in ground water in the upper Potomac aquifer of 24,000 mg/L indicates highly saline water at well 63F52 and no fresh ground-water flow.

Ground-Water Use

Prior to 1965, there were few large users of ground water on the Eastern Shore. By 1970, increased population combined with commercial and industrial growth created a greatly increased demand for the ground-water resource. Major pumping centers on the Eastern Shore are located near the towns of Chincoteague, Hallwood, Accomac, Exmore, Oyster, Cheriton, and Cape Charles, Va.

Annual ground-water withdrawal data for the model area were compiled by confined aquifer for commercial, industrial, and municipal withdrawals

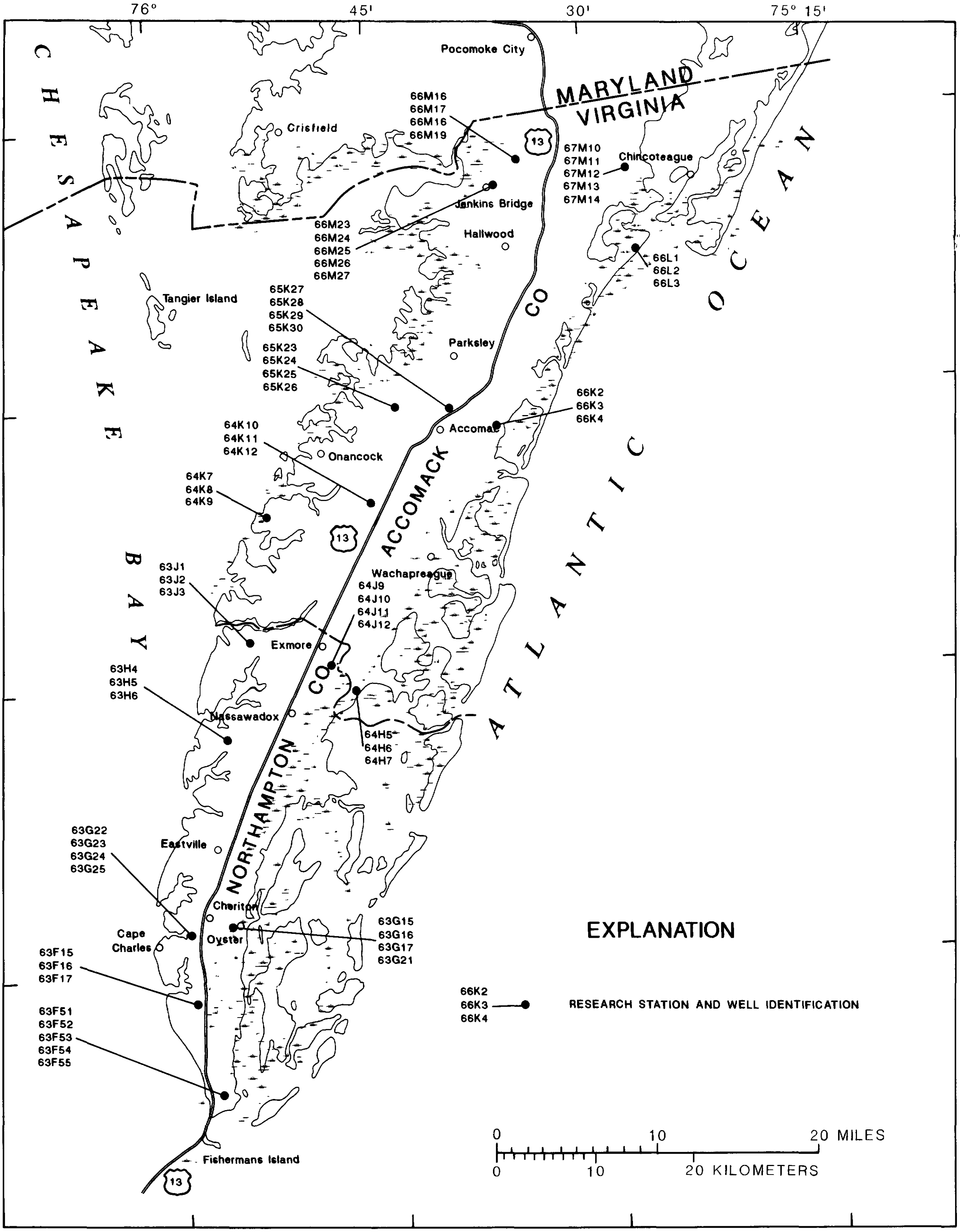


Figure 15. Location of selected Virginia Water Control Board research-station well clusters.

Table 6. Selected Virginia Water Control Board research-station well clusters on the Eastern Shore

[Latitude and longitude are reported in degrees, arc minutes, and arc seconds; USGS, U.S. Geological Survey; VWCB, Virginia Water Control Board]

USGS well number	VWCB well number	Latitude	Longitude	Well depth (feet)	Aquifer penetrated
66K 4	SOW 101A	37 43 20	075 36 56	152	Upper Yorktown-Eastover
66K 3	SOW 101B	37 43 20	075 38 05	220	Middle Yorktown-Eastover
66K 2	SOW 101C	37 43 19	075 36 54	292	Lower Yorktown-Eastover
64H 6	SOW 102A	37 29 25	075 47 04	154	Upper Yorktown-Eastover
64H 7	SOW 102B	37 29 21	075 47 05	220	Middle Yorktown-Eastover
64H 5	SOW 102C	37 29 21	075 47 05	306	Lower Yorktown-Eastover
63H 6	SOW 103A	37 27 05	075 55 59	37	Columbia
63H 5	SOW 103B	37 27 05	075 55 59	132	Upper Yorktown-Eastover
63H 4	SOW 103C	37 27 06	075 55 59	235	Lower Yorktown-Eastover
63G 21	SOW 104S	37 17 09	075 56 08	36	Columbia
63G 17	SOW 104A	37 17 09	075 56 08	140	Upper Yorktown-Eastover
63G 16	SOW 104B	37 17 09	075 56 08	240	Middle Yorktown-Eastover
63G 15	SOW 104C	37 17 09	075 56 07	310	Lower Yorktown-Eastover
63F 15	SOW 105A	37 13 07	075 58 35	130	Upper Yorktown-Eastover
63F 17	SOW 105B	37 13 07	075 58 35	196	Middle Yorktown-Eastover
63F 16	SOW 105C	37 13 07	075 58 35	285	Lower Yorktown-Eastover
64K 9	SOW 106A	37 38 45	075 52 25	37	Columbia
64K 8	SOW 106B	37 38 45	075 52 25	95	Upper Yorktown-Eastover
64K 7	SOW 106C	37 38 45	075 52 25	176	Lower Yorktown-Eastover
66L 2	SOW 107A	37 52 25	075 32 17	140	Upper Yorktown-Eastover
66L 3	SOW 107B	37 52 25	075 32 17	206	Middle Yorktown-Eastover
66L 1	SOW 107C	37 52 25	075 32 17	305	Lower Yorktown-Eastover
64K 10	SOW 108A	37 39 32	075 45 27	50	Columbia
64K 11	SOW 108B	37 39 32	075 45 27	180	Upper Yorktown-Eastover
64K 12	SOW 108C	37 39 32	075 45 27	284	Lower Yorktown-Eastover
65K 26	SOW 109S	37 44 42	075 43 25	25	Columbia
65K 24	SOW 109A	37 44 42	075 43 25	130	Upper Yorktown-Eastover
65K 25	SOW 109B	37 44 42	075 43 25	228	Lower Yorktown-Eastover
65K 23	SOW 109C	37 44 28	075 43 28	290	Lower Yorktown-Eastover
66M 19	SOW 110S	37 57 23	075 34 44	36	Columbia
66M 16	SOW 110A	37 57 23	075 34 44	130	Upper Yorktown-Eastover
66M 17	SOW 110B	37 57 23	075 34 44	178	Middle Yorktown-Eastover
66M 18	SOW 110C	37 57 23	075 34 45	240	Lower Yorktown-Eastover
63G 25	SOW 111S	37 16 53	075 58 48	70	Columbia
63G 22	SOW 111A	37 16 53	075 58 48	150	Upper Yorktown-Eastover
63G 23	SOW 111B	37 16 53	075 58 48	280	Lower Yorktown-Eastover
63G 24	SOW 111C	37 16 53	075 58 48	330	Lower Yorktown-Eastover
64J 12	SOW 112S	37 30 59	075 48 45	47	Columbia
64J 9	SOW 112A	37 30 59	075 48 45	135	Upper Yorktown-Eastover
64J 10	SOW 112B	37 30 59	075 48 45	210	Middle Yorktown-Eastover
64J 11	SOW 112C	37 30 59	075 48 45	313	Lower Yorktown-Eastover
63J 1	SOW 113A	37 32 16	075 54 07	120	Upper Yorktown-Eastover
63J 2	SOW 113B	37 32 16	075 54 07	225	Middle Yorktown-Eastover
63J 3	SOW 113C	37 32 16	075 54 07	290	Lower Yorktown-Eastover
65K 30	SOW 114S	37 44 25	075 40 00	40	Columbia

Table 6. Selected Virginia Water Control Board research-station well clusters on the Eastern Shore—Continued

USGS well number	VWCB well number	Latitude	Longitude	Well depth (feet)	Aquifer penetrated
65K 27	SOW 114A	37 44 25	075 40 00	160	Upper Yorktown-Eastover
65K 28	SOW 114B	37 44 25	075 40 00	230	Middle Yorktown-Eastover
65K 29	SOW 114C	37 44 27	075 40 00	315	Lower Yorktown-Eastover
67M 10	SOW 115A	37 56 35	075 27 15	52	Columbia
67M 11	SOW 115B	37 56 35	075 27 15	138	Upper Yorktown-Eastover
67M 12	SOW 115C	37 56 35	075 27 15	222	Middle Yorktown-Eastover
67M 13	SOW 115D	37 56 35	075 27 15	249	Middle Yorktown-Eastover
67M 14	SOW 115E	37 56 17	075 27 37	280	Middle Yorktown-Eastover
66M 23	SOW 181A	37 56 10	075 36 18	1,300	Upper Potomac
66M 24	SOW 181B	37 56 10	075 36 18	508	St. Marys
66M 25	SOW 181C	37 56 10	075 36 18	340	Lower Yorktown-Eastover
66M 26	SOW 181D	37 56 10	075 36 18	230	Lower Yorktown-Eastover
66M 27	SOW 181E	37 56 10	075 36 18	30	Columbia
63F 51	SOW 182A	37 08 07	075 57 08	1,730	Middle Potomac
63F 52	SOW 182B	37 08 07	075 57 08	1,332	Upper Potomac
63F 53	SOW 182C	37 08 07	075 57 08	220	Lower Yorktown-Eastover
63F 54	SOW 182D	37 08 07	075 57 08	60	Upper Yorktown-Eastover
63F 55	SOW 182E	37 08 07	075 57 08	20	Columbia

Table 7. Vertical distribution of chloride concentrations in ground water at Jenkins Bridge and Kiptopeke Research Station well clusters

[USGS, U.S. Geological Survey; mg/L, milligrams per liter]

USGS well number	Well depth (feet)	Aquifer	Date	Chloride concentration (mg/L)
		Jenkins Bridge Research Station		
66M 27	40	Columbia	10-29-87	31
			08-29-88	23
66M 26	230	Lower Yorktown-Eastover	10-30-87	1,000
			08-29-88	810
66M 25	340	Lower Yorktown-Eastover	10-30-87	2,100
			08-29-88	2,100
66M 24	508	St. Marys – Choptank	10-28-87	3,900
			08-29-88	3,800
66M 25	1,320	Upper Potomac	10-29-87	1,500
			08-29-88	1,500
		Kiptopeke Research Station		
63F 55	20	Columbia	11-16-89	24
63F 54	60	Upper Yorktown-Eastover	11-16-89	32
63F 53	220	Lower Yorktown-Eastover	11-16-89	59
63F 52	1,332	Upper Potomac	11-29-89	24,000

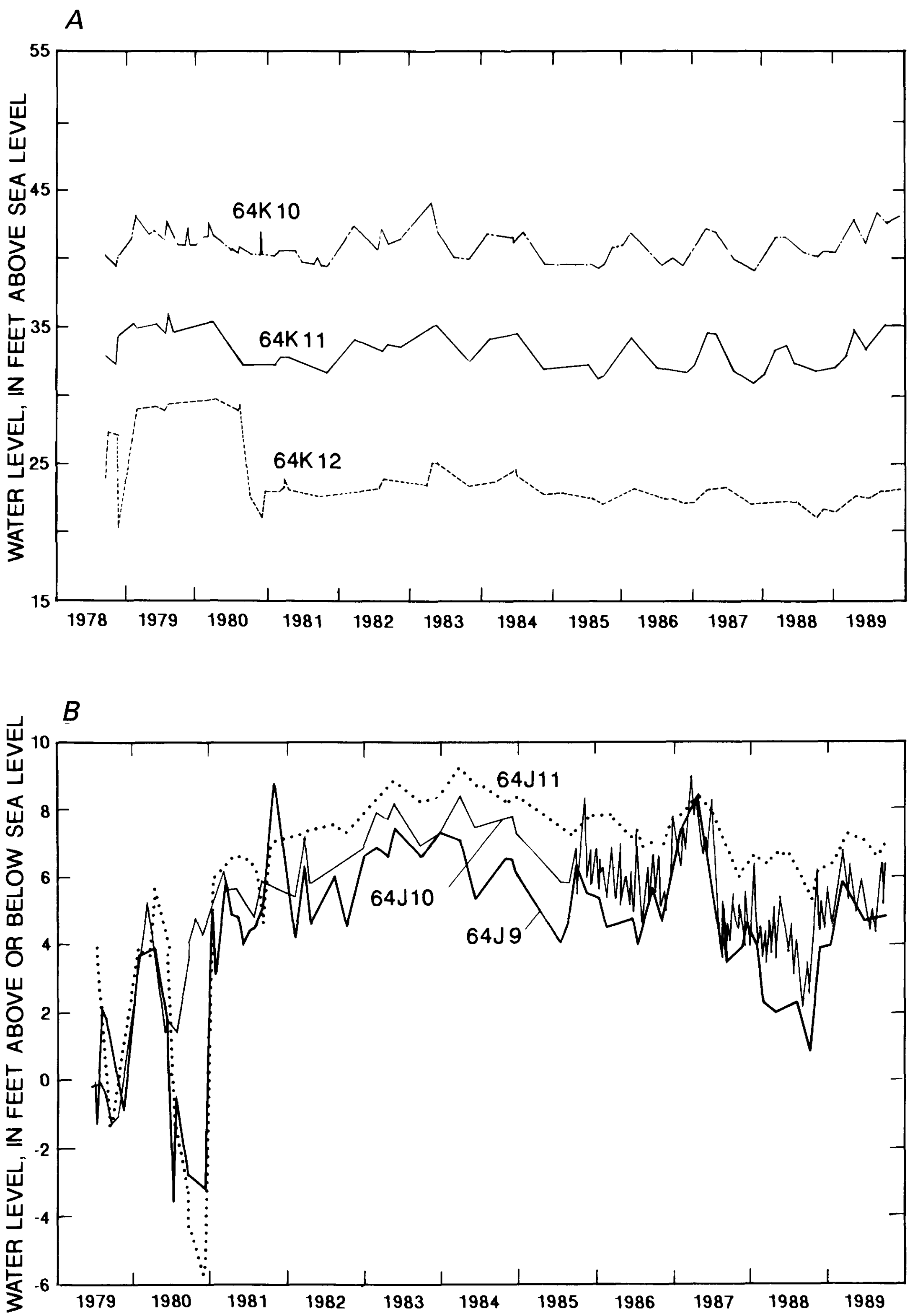


Figure 16. Water levels in research-station well clusters (*A*) in a recharge area and (*B*) in a discharge area.

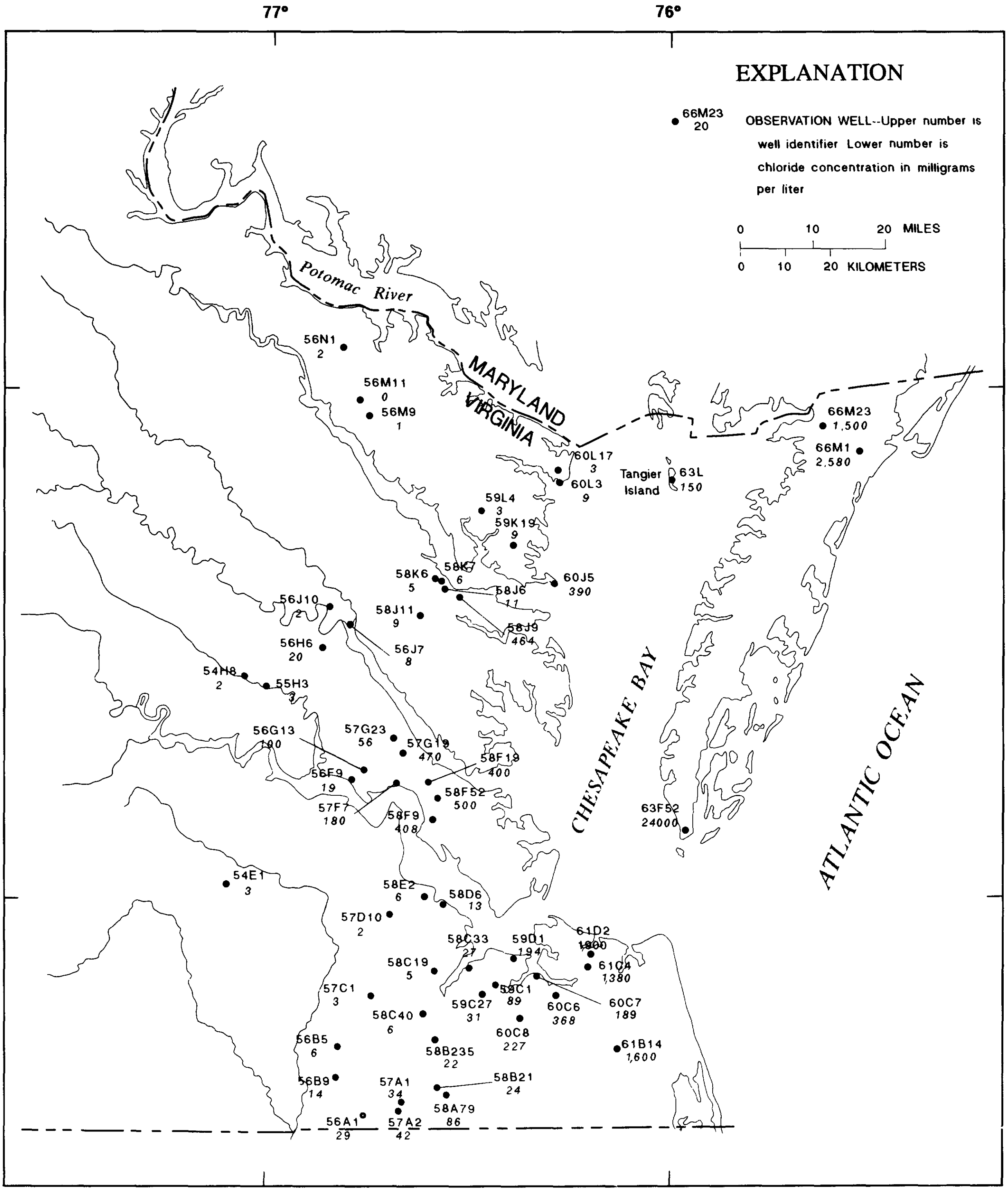


Figure 17. Location of observation wells and chloride concentrations in the upper Potomac aquifer for the Coastal Plain of Virginia.

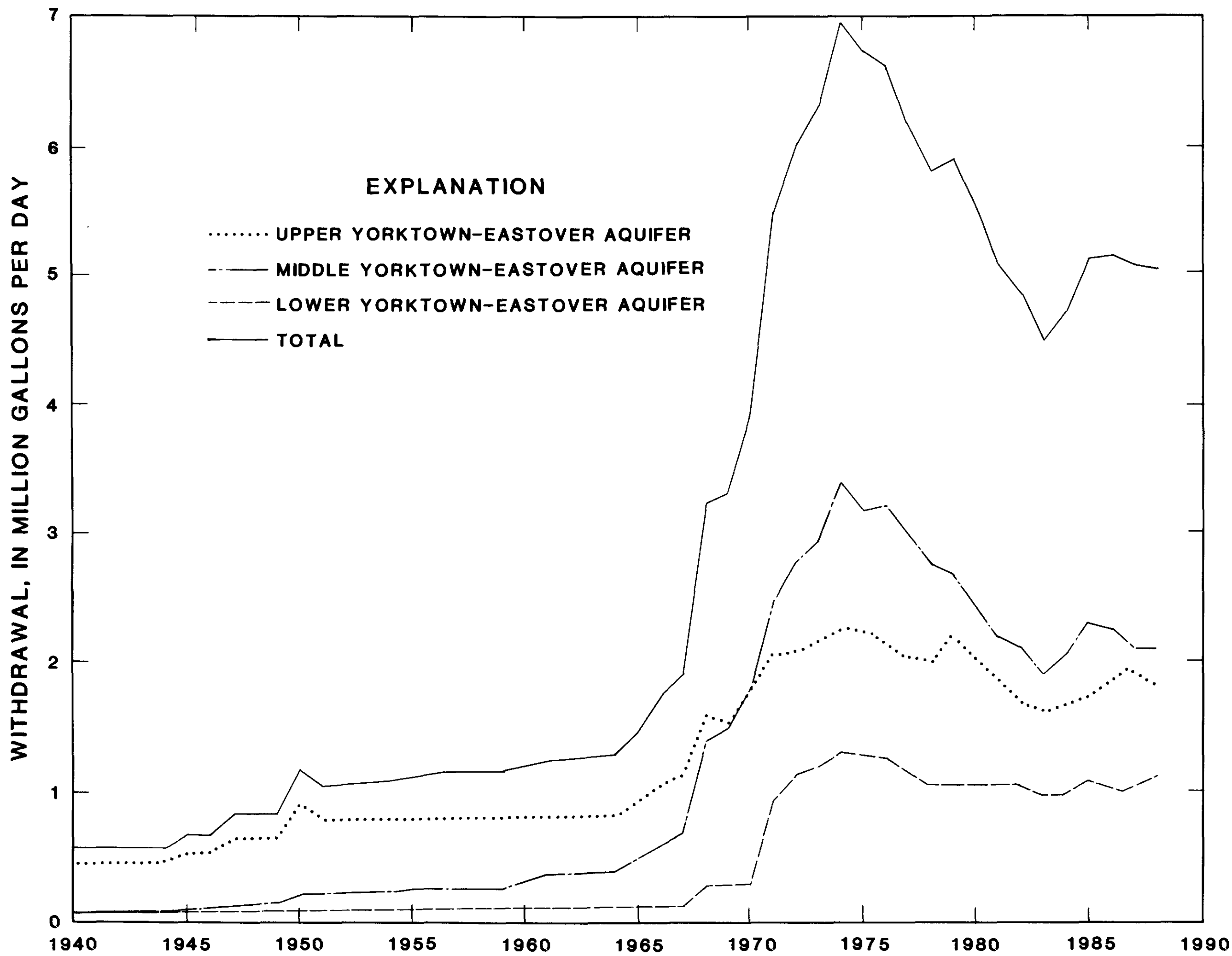


Figure 18. Annual ground-water withdrawal from model area.

(fig. 18). Estimates do not include domestic or agricultural withdrawals. Domestic use is not included because currently there is no practical method of collecting such data by aquifer, and it is assumed to represent only a small percentage of nonreturned water. Agricultural use is significant on the Eastern Shore; however, agricultural users are not required to report withdrawals. As a result, the specific locations and aquifers tapped for agricultural withdrawals are unknown. Most of the ground water used for agricultural purposes is withdrawn from irrigation ponds in the unconfined Columbia aquifer. All other ground-water users in Northampton and Accomack Counties that withdraw over 300,000 gal/month are required to report usage data to the VWCB. The depth of the well screen was used to determine the aquifer from which water was pumped. For wells screened in multiple aquifers, water-withdrawal rates from each aquifer were estimated from the ratio of the length of screen in each aquifer to the total length of well screen.

The middle and upper Yorktown-Eastover aquifers have historically provided most of the freshwater to users on the Eastern Shore. Prior to 1968, the largest withdrawals were from the shallowest confined aquifer, the upper Yorktown-Eastover. By 1970, the middle Yorktown-Eastover aquifer was contributing more water than the upper or lower Yorktown-Eastover aquifers, and pumpage from the lower Yorktown-Eastover aquifer was increasing. Estimated ground-water use peaked in 1974 at 6.96 Mgal/d. The decline in water use for the period 1975–83 represents the loss of several major industrial users. Since 1985, water use has generally been steady. Total ground-water use was estimated to be about 5.04 Mgal/d in 1988. The upper Yorktown-Eastover aquifer supplied 36 percent of the withdrawal in 1988, and the middle and lower Yorktown-Eastover aquifers supplied 42 and 22 percent, respectively.

Chloride Distribution

Chloride concentrations were compiled by aquifer to provide information on the distribution of chlorides in the aquifers that currently are being used as a freshwater supply for the Eastern Shore (figs. 19–22). The chloride concentrations presented on the maps are the most recent chloride analyses for each well. Individual chloride analyses are presented by aquifer in tables 8–11. Chloride concentrations typically are greater along the coast than in the center of the peninsula. Chloride concentrations in water collected from wells in the Columbia aquifer and the upper Yorktown-Eastover aquifer were less than the U.S. Environmental Protection Agency (USEPA) secondary drinking-water regulation of 250 mg/L (U.S. Environmental Protection Agency, 1989). The line delineating the approximate limit of the 250 mg/L chloride concentration in the Columbia aquifer was estimated to be the landward limit of the saltwater marshes and estuaries (fig. 19). All chlorides from the upper Yorktown-Eastover aquifer were well below the 250 mg/L limit; therefore, the limit line was estimated based on the understanding of the ground-water-flow system (fig. 20). Chloride concentrations probably are less than 250 mg/L in the upper Yorktown-Eastover aquifer beneath all major land surfaces on the peninsula. Chloride concentrations generally increase with depth; greater chloride concentrations are found in the lower Yorktown-Eastover aquifer than in the overlying middle Yorktown-Eastover, upper Yorktown-Eastover, and Columbia aquifers. Chloride concentrations in water in the lower Yorktown-Eastover aquifer are stratified; concentrations are less near the top of the aquifer than near the bottom of the aquifer. Data indicate an area of elevated chloride concentrations in water in the middle and lower Yorktown-Eastover aquifer near Exmore, Va. (figs. 21, 22). The elevated concentrations appear to be in the area of an ancient Pleistocene river channel (described in Pleistocene Paleochannel Aquifers section). The erosion of the original aquifer and confining-unit materials combined with the different hydraulic characteristics of the backfilled-channel sediments could result in a better hydraulic connection between the freshwater-flow system and the saltwater-flow system in this area. A detailed study of the extent of the erosion and the hydraulic properties of the channel-fill sediments is needed for a complete understanding of saltwater-freshwater relations in this part of the ground-water-flow system. Elevated chloride concentrations in water in the middle and lower Yorktown-Eastover aquifers also are present near Cape Charles, Va. This area could be affected by the southernmost paleochannel or by incision from a nearshore channel in the present-day Chesapeake Bay.

ANALYSIS OF THE GROUND-WATER-FLOW SYSTEM

The conceptualization of the physical characteristics of the three-dimensional, multiaquifer, flow system can be incorporated into a digital ground-water-flow model. The model is a mathematical representation of the natural system and includes many simplifying assumptions. Model input parameters are based on the measured and estimated characteristics of the aquifers and confining units. The model is calibrated by comparing simulated water levels to water levels measured at observation wells. Once calibrated, the digital model can be used within its limitations to simulate changes in ground-water-flow conditions that result from changes in hydrologic stresses. A digital model can assist in analyzing a ground-water system; however, it is important to realize that the model is only an approximate representation of the actual physical system.

Development of the Flow Model

A ground-water-flow model was developed for the Eastern Shore using SHARP (Essaid, 1990a), a numerical finite-difference model that uses a quasi-three-dimensional approach to simulate freshwater and saltwater flow separated by a sharp interface. The sharp-interface approach assumes that saltwater-between saltwater and freshwater is small relative to the thickness of the aquifer. The approach does not provide information on the physical or chemical

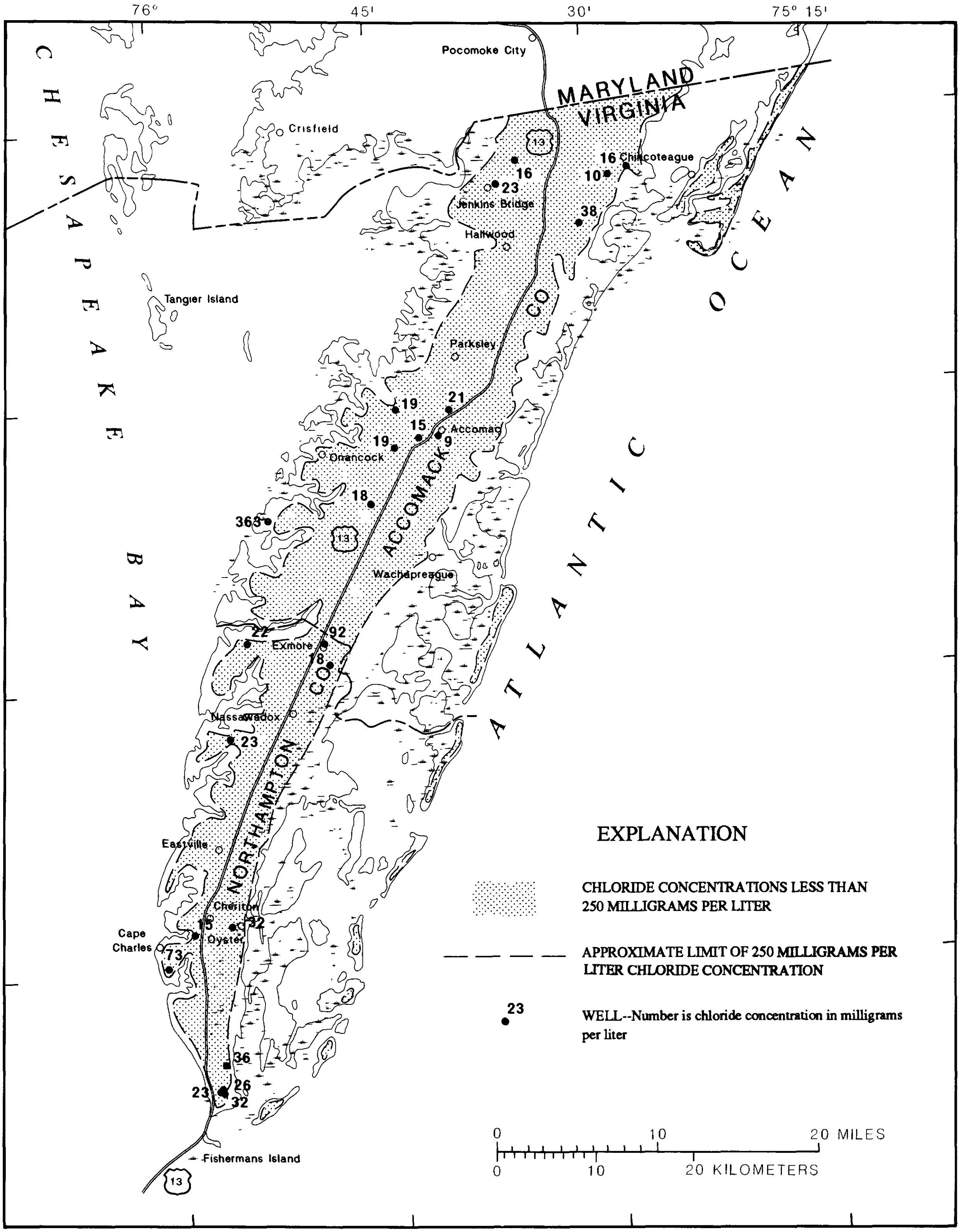


Figure 19. Chloride concentrations in the Columbia aquifer.

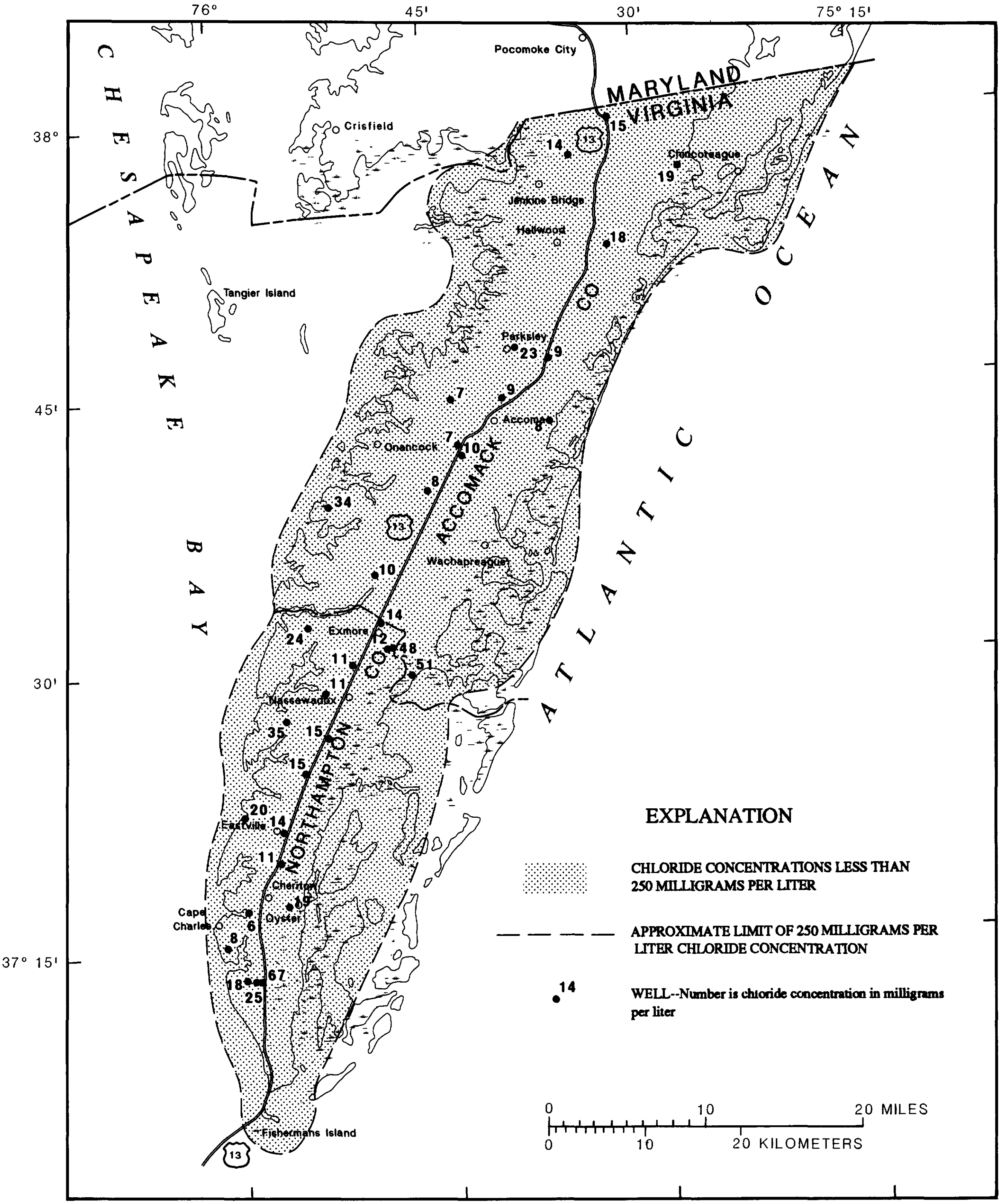


Figure 20. Chloride concentrations in the upper Yorktown-Eastover aquifer.

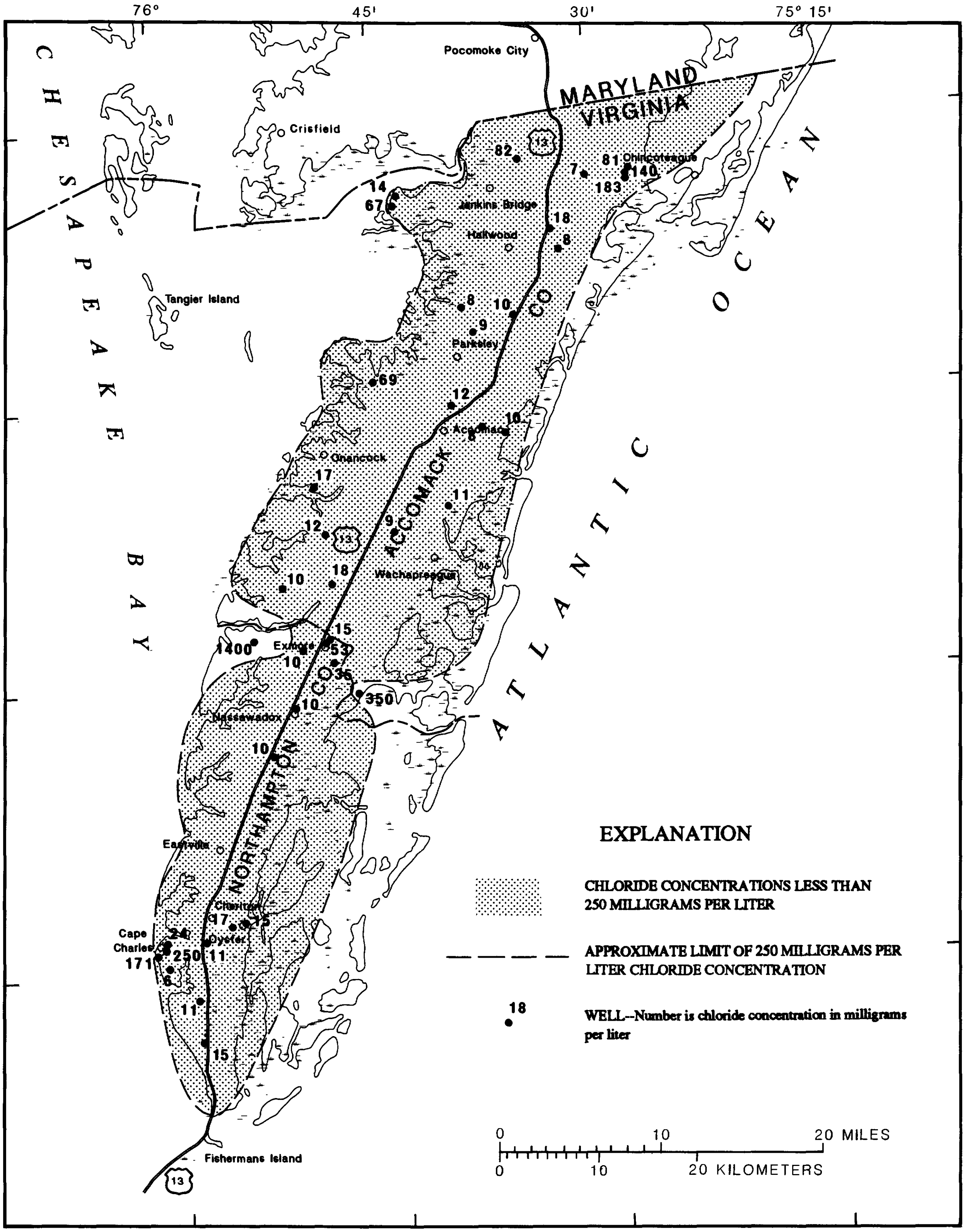


Figure 21. Chloride concentrations in the middle Yorktown-Eastover aquifer.

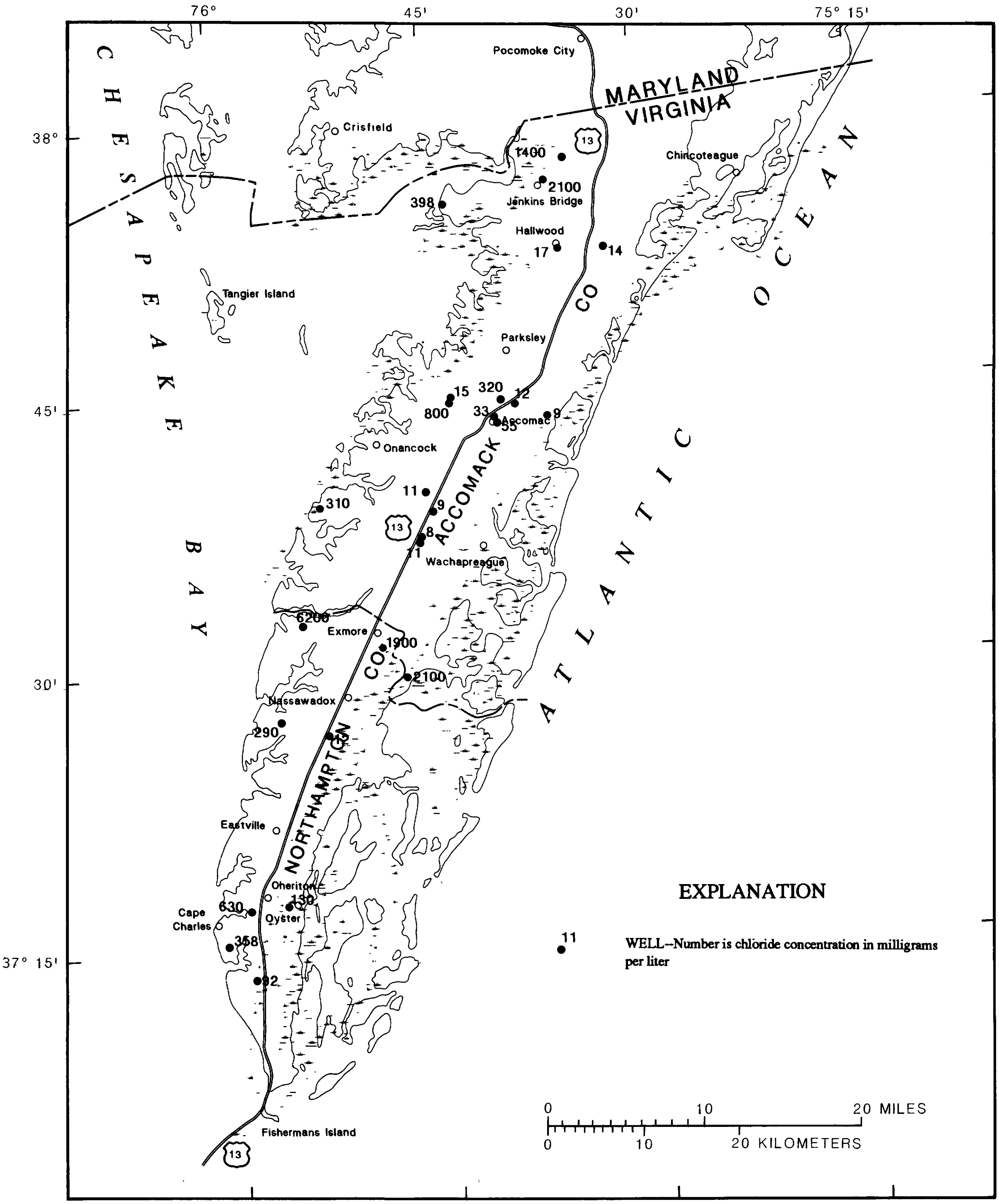


Figure 22. Chloride concentrations in the lower Yorktown-Eastover aquifer.

Table 8. Chloride concentrations in the Columbia aquifer

[USGS, U.S. Geological Survey; VWCB, Virginia Water Control Board; latitude and longitude are reported in degrees, arc minutes, arc seconds; mg/L, milligrams per liter]

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
62F 4	37 14 56	076 00 30	40	10	73	12-01-77	VWCB
63F 6	37 08 06	075 57 18	74	10	54	09-27-55	USGS
63F 19	37 08 06	075 57 09	60	10	23	01-02-75	VWCB
63F 20	37 08 06	075 57 08	62	10	26	01-02-75	VWCB
63F 21	37 08 06	075 57 07	65	10	31	01-02-75	VWCB
					32	02-12-75	VWCB
					32	12-12-75	VWCB
63F 22	37 09 39	075 57 04	46	10	27	01-02-75	VWCB
					36	12-12-75	VWCB
63G 21	37 17 09	075 56 08	36	30	66	10-03-77	VWCB
					43	08-19-80	VWCB
					32	08-04-86	VWCB
63G 25	37 16 53	075 58 48	70	15	13	06-29-79	VWCB
					15	08-19-80	VWCB
63H 6	37 27 05	075 55 59	37	17	43	09-28-77	VWCB
					30	05-11-79	VWCB
					23	06-26-84	VWCB
63J 4	37 32 20	075 54 15	40	25	22	05-11-84	VWCB
64J 12	37 30 59	075 48 45	47	30	23	07-03-79	VWCB
					18	08-21-80	VWCB
64J 26	37 32 00	075 49 17	58	35	41	03-01-67	VWCB
					105	04-01-75	VWCB
					92	09-19-78	VWCB
64K 9	37 38 45	075 52 25	37	2	78	09-21-77	VWCB
					92	08-20-80	VWCB
					363	06-26-84	VWCB
64K 10	37 39 32	075 45 27	50	45	6	08-20-80	VWCB
					18	06-29-84	VWCB
65K 21	37 42 57	075 40 41	45	42	9	09-28-71	VWCB
65K 26	37 44 42	075 43 25	25	10	19	08-20-80	VWCB
65K 30	37 44 25	075 40 00	40	45	12	02-13-80	VWCB
					21	08-26-80	VWCB
65K 32	37 42 32	075 43 42	52	30	19	08-07-81	VWCB
65K 33	37 42 49	075 42 07	55	40	15	08-07-81	VWCB
66M 19	37 57 23	075 34 44	36	10	15	08-26-80	VWCB
					16	07-11-84	VWCB
66M 21	37 54 03	075 30 25	69	35	38	08-04-81	VWCB
66M 27	37 56 10	075 36 18	30	5	31	10-29-87	USGS
					23	08-29-88	USGS
67M 6	37 56 24	075 28 36	45	30	10	08-17-48	VWCB
67M 10	37 56 35	075 27 15	52	15	14	08-13-81	VWCB
					12	05-27-82	VWCB
					16	08-13-84	VWCB

nature of the transition zone; however, it does represent the overall ground-water flow in the system and will reproduce the general response of the interface to applied stresses (Essaid, 1986). The model represents regional-scale ground-water-flow systems as a layered sequence of two-dimensional aquifers separated by confining units that are represented by a vertical leakance term. Vertical gradients within aquifers are not represented; therefore, the modeling approach is not fully three-dimensional. The quasi-three-dimensional solution of the ground-water-flow equation requires several assumptions: (1) flow in the aquifers is in the lateral direction, (2) vertical flow is controlled by confining units, and (3) water released from confining-unit storage is negligible. These assumptions are considered valid when the lateral and vertical hydraulic conductivities of the aquifers are much greater than those of the confining units, and simulation times are long enough to minimize the effects of water released from confining-unit storage.

The Eastern Shore is a peninsula surrounded by saltwater; therefore, the model's inclusion of saltwater-flow dynamics is of particular importance to an analysis of the ground-water system. Any change in offshore freshwater discharge induces movement of the interface between freshwater and saltwater. The rate of interface movement is a function of the flow conditions and aquifer properties of the freshwater and saltwater flow domains.

The model uses two vertically integrated, parabolic, partial-differential flow equations, representing freshwater and saltwater flow, which must be simultaneously solved for freshwater and saltwater head, as follows (Essaid, 1986):

$$S_fB_f\frac{\partial\phi_f}{\partial t}+n\alpha\frac{\partial\phi_f}{\partial t}+\left[n\delta\frac{\partial\phi_f}{\partial t}-n(1+\delta)\frac{\partial\phi_s}{\partial t}\right]$$
$$=\frac{\partial}{\partial x}\left(B_fK_{fx}\frac{\partial\phi_f}{\partial x}\right)+\frac{\partial}{\partial y}\left(B_fK_{fy}\frac{\partial\phi_f}{\partial y}\right)+Q_fQ_{lf}\,, \quad (1)$$

and

$$S_sB_s\frac{\partial\phi_s}{\partial t}+\left[n(1+\delta)\frac{\partial\phi_s}{\partial t}-n\delta\frac{\partial\phi_f}{\partial t}\right]$$
$$=\frac{\partial}{\partial x}\left(B_sK_{sx}\frac{\partial\phi_s}{\partial_x}\right)+\frac{\partial}{\partial y}\left(B_sK_{sy}\frac{\partial\phi_s}{\partial y}\right)+Q_s+Q_{ls}\,, \quad (2)$$

where

K_{fx}, K_{sx} = the freshwater and saltwater hydraulic conductivities in the x direction (LT^{-1});
K_{fy}, K_{sy} = the freshwater and saltwater hydraulic conductivities in the y direction (LT^{-1});
Q_f, Q_s = the freshwater and saltwater source/sink terms (LT^{-1});
Q_{lf}, Q_{ls} = the freshwater and saltwater leakage terms (LT^{-1}), calculated using Darcy's law;
B_f, B_s = the thicknesses of the freshwater and saltwater zones (L);
S_f, S_s = the freshwater and saltwater specific storages (L^{-1});
ϕ_f, ϕ_s = freshwater and saltwater heads (L);
n = effective porosity;
t = time (T); and
α = a parameter equal to 1 for unconfined aquifers and zero for confined aquifers.

The flow equations for the freshwater and saltwater zones are coupled by the interface boundary condition. Continuity of flux and pressure must be maintained at the interface; the fluid pressure of the freshwater must equal the fluid pressure of the saltwater (Bear, 1979).

$$p_f=(\phi_f-\zeta_l)\gamma_f=p_s=(\phi_s-\zeta_l)\gamma_s\,, \quad (3)$$

where

p_f, p_s = the freshwater and saltwater fluid pressures ($ML^{-1}T^{-2}$);
γ_f, γ_s = the freshwater and saltwater specific weights ($ML^{-2}T^{-2}$); and
ζ_l = the interface elevation (L).

Solving for the interface elevation,

$$\zeta_l=(1+\delta)\phi_s-\delta\phi_f\,, \quad (4)$$

where $\delta=\gamma_f/(\gamma_s-\gamma_f)$.

Once the freshwater and saltwater heads have been obtained from equations 1 and 2, the interface elevation can be calculated from equation 4.

The SHARP model calculates and tracks the positions of the interface tip and toe in the finite-difference grid for each aquifer. The interface tip is the intersection of the interface with the top of the aquifer, and the interface toe is the intersection of the interface with the bottom of the aquifer (fig. 23). The interface position will not always coincide with the grid block boundaries. The tip and toe are located by linearly projecting the interface, based on the interface elevations at grid points. On the freshwater side of the interface toe, the entire thickness of the aquifer contains freshwater. Similarly, on the saltwater side of the interface tip, the entire thickness of the aquifer contains saltwater. In the area between the interface tip and toe, the aquifer contains freshwater and saltwater.

The sharp-interface approach assumes that saltwater and freshwater do not mix. Vertical leakage between saltwater and freshwater is restricted. Saltwater is not allowed to leak into the freshwater zone, and freshwater is not allowed to leak downward into the saltwater zone. A node can contain

Table 9. Chloride concentrations in the upper Yorktown-Eastover aquifer

[USGS, U.S. Geological Survey; VWCB, Virginia Water Control Board; latitude and longitude are reported in degrees, arc minutes, arc seconds; mg/L, milligrams per liter]

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
62F 3	37 14 56	076 00 27	130	12	8	02-01-77	VWCB
63F 15	37 13 07	075 58 35	130	31	20	06-07-78	VWCB
					25	08-11-80	VWCB
					25	07-12-84	VWCB
63F 18	37 13 12	075 59 15	112	15	18	04-05-80	VWCB
63F 24	37 13 02	075 58 07	140	37	67	01-08-81	USGS
63G 9	37 21 34	075 59 08	134	2	20	05-26-54	VWCB
63G 17	37 17 09	075 56 08	140	28	16	10-03-77	VWCB
					24	08-18-80	VWCB
					24	08-06-84	VWCB
					19	02-28-89	USGS
63G 22	37 16 53	075 58 48	150	15	8	06-29-79	VWCB
					8	08-19-80	VWCB
					6	07-12-84	VWCB
63G 37	37 21 06	075 56 20	165	38	17	11-01-74	VWCB
					14	11-28-78	VWCB
					13	02-26-79	VWCB
					15	05-02-79	VWCB
					13	08-20-79	VWCB
					12	12-06-79	VWCB
					15	01-28-80	VWCB
					15	08-28-80	VWCB
					14	02-19-81	VWCB
					17	08-24-81	VWCB
					36	07-21-82	VWCB
					16	06-16-83	VWCB
					14	07-23-84	VWCB
63H 5	37 27 05	075 55 59	132	17	24	09-28-77	VWCB
					24	05-11-79	VWCB
					24	06-26-84	VWCB
					28	01-25-88	USGS
					35	03-02-89	USGS
63H 10	37 24 12	075 54 15	152	38	15	12-18-80	VWCB
63H 11	37 26 08	075 53 07	180	30	15	12-18-80	VWCB
63J 1	37 32 30	075 54 10	120	22	27	08-25-80	VWCB
					24	06-28-84	VWCB
64H 6	37 29 05	075 47 40	154	6	52	06-01-77	VWCB
					49	07-11-84	VWCB
					51	03-01-89	USGS
64J 2	37 22 35	075 53 35	190	34	14	10-27-69	USGS
					15	01-29-70	USGS
					14	02-18-75	VWCB
64J 9	37 30 59	075 48 45	135	30	11	07-03-79	VWCB
					12	08-22-80	VWCB
64J 18	37 35 03	075 49 20	167	31	13	02-01-75	VWCB
					10	08-01-78	VWCB
					10	02-19-81	VWCB
64J 24	37 30 45	075 48 29	130	7	48	08-02-79	VWCB

Table 9. Chloride concentrations in the upper Yorktown-Eastover aquifer—Continued

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
64K 8	37 38 45	075 52 25	95	3	33	09-21-77	VWCB
					41	08-20-80	VWCB
					47	06-26-84	VWCB
					34	03-02-89	USGS
64K 11	37 39 32	075 45 27	180	47	10	08-20-80	VWCB
					9	06-29-84	VWCB
					8	01-26-88	USGS
65K 6	37 38 30	075 40 00	190	43	10	10-21-71	USGS
					10	03-04-72	USGS
65K 9	37 42 33	075 44 32	159	17	10	02-26-75	VWCB
					9	09-10-75	USGS
65K 22	37 41 53	075 43 09	180	43	8	09-28-71	USGS
					8	03-06-80	VWCB
					8	02-19-81	VWCB
					5	08-24-81	VWCB
					10	02-11-82	VWCB
					4	09-28-82	VWCB
					9	03-29-84	VWCB
					7	11-19-84	VWCB
65K 24	37 44 42	075 43 25	130	12	7	08-13-80	VWCB
65K 27	37 44 25	075 40 00	160	45	10	02-13-80	VWCB
					9	07-09-84	VWCB
65L 3	37 37 30	075 40 00	160	40	7	04-22-60	VWCB
					24	01-05-72	USGS
					24	03-07-72	USGS
					20	06-01-72	VWCB
					22	06-27-77	VWCB
					22	11-14-77	VWCB
					23	02-23-78	VWCB
66K 4	37 43 20	075 36 56	152	10	8	06-03-77	VWCB
					8	07-10-84	VWCB
66L 2	37 52 25	075 32 17	140	5	6	09-21-77	VWCB
					8	07-10-84	VWCB
66L 4	37 46 25	075 36 46	160	40	9	08-04-81	VWCB
66M 16	37 57 23	075 34 44	130	11	13	08-26-80	VWCB
					14	07-11-84	VWCB
66M 22	37 59 20	075 32 05	132	21	15	03-30-82	VWCB
67M 11	37 56 35	075 27 15	138	14	28	03-29-81	VWCB
					23	05-12-81	VWCB
					19	05-27-82	VWCB
					19	08-07-84	VWCB

freshwater, saltwater, or both freshwater and saltwater. Upward freshwater leakage is distributed between the saltwater and freshwater zones based on the volume of each type of water in the node receiving the leakage. If freshwater is leaking upward into a node that contains 80-percent freshwater and 20-percent saltwater, then 80 percent of the leakage will be incorporated into the freshwater zone and 20 percent of the leakage will be incorporated into the saltwater zone. If freshwater is leaking upward into a node that contains all saltwater, then all the freshwater leakage will be incorporated into the saltwater zone (Essaid, 1990a). Vertical leakage of saltwater into freshwater is not directly simulated; evidence of vertical saltwater intrusion is provided by examination of the hydraulic gradients and areas of reversed ground-water flow.

The sharp-interface modeling approach neglects hydrodynamic dispersion; therefore, the interface position does not represent a particular

Table 10. Chloride concentrations in the middle Yorktown-Eastover aquifer

[USGS, U.S. Geological Survey; VWCB, Virginia Water Control Board; latitude and longitude are reported in degrees, arc minutes, arc seconds; mg/L, milligrams per liter]

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
62F 2	37 14 56	076 00 30	210	12	12	12-01-77	USGS
62G 4	37 22 50	075 53 35	210	12	24	01-04-72	USGS
62G 8	37 15 40	076 01 21	200	12	170	10-17-75	USGS
62G 9	37 15 39	076 01 14	170	12	250	10-17-75	VWCB
62G 15	37 15 43	076 00 34	190	12	175	08-06-84	VWCB
62G 16	37 15 44	076 01 18	221	12	114	05-09-77	VWCB
					130	08-01-77	VWCB
					121	11-28-78	VWCB
					124	01-28-80	VWCB
					144	02-19-81	VWCB
					129	07-22-82	VWCB
					161	02-28-83	VWCB
					147	01-23-84	VWCB
					171	05-15-85	VWCB
63F 10	37 10 57	075 58 14	220	27	14	09-11-75	USGS
					15	02-01-75	VWCB
63F 17	37 13 07	075 58 35	196	31	13	08-01-80	VWCB
					11	07-12-84	VWCB
63G 16	37 17 09	075 56 08	240	28	72	10-03-77	VWCB
					20	08-18-79	VWCB
					31	09-26-79	VWCB
					15	08-06-84	VWCB
					14	01-25-88	USGS
					14	02-28-89	USGS
63G 27	37 17 10	075 55 22	185	5	18	08-25-80	VWCB
63G 34	37 17 15	075 55 21	186	3	19	09-23-81	VWCB
					15	07-22-82	VWCB
					17	03-14-83	VWCB
63G 35	37 17 15	075 55 21	186	5	25	04-07-75	VWCB
					17	10-16-81	VWCB
63G 36	37 17 11	075 55 24	185	6	19	02-12-75	VWCB
					16	04-01-75	VWCB
					15	03-26-80	VWCB
63G 43	37 16 20	075 58 15	215	15	11	03-03-89	VWCB
63J 2	37 32 30	075 54 10	225	22	1,400	08-06-86	VWCB
64H 7	37 29 05	075 47 40	220	6	400	06-01-77	VWCB
					340	07-11-84	VWCB
					400	08-05-86	VWCB
					430	11-12-87	USGS
					350	03-01-89	USGS
64H 9	37 28 30	075 51 32	245	37	10	05-11-84	VWCB
64J 7	37 22 45	075 53 35	228	34	17	06-02-65	VWCB
					15	09-10-70	VWCB
					12	12-19-72	VWCB
					15	11-12-74	VWCB
64J 10	37 30 59	075 48 45	210	30	36	07-03-79	VWCB
					35	08-21-80	VWCB
					35	02-22-88	USGS
64J 17	37 35 07	075 51 55	180	30	10	08-07-81	VWCB
64J 21	37 31 59	075 49 15	229	35	208	03-01-67	VWCB
					41	09-19-78	VWCB
					53	08-01-79	VWCB
64J 23	37 31 46	075 50 47	190	28	10	08-31-81	VWCB
64K 3	37 37 56	075 49 06	210	25	12	12-31-06	USGS

Table 10. Chloride concentrations in the middle Yorktown-Eastover aquifer—Continued

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
64K 21	37 40 29	075 49 25	185	6	17	02-02-89	USGS
64L 1	37 45 59	075 45 15	135	5	69	02-02-89	USGS
65K 28	37 44 25	075 40 00	230	45	15	02-13-80	VWCB
					12	07-09-84	VWCB
65K 34	37 39 04	075 40 34	218	9	11	07-08-75	VWCB
65K 42	37 37 50	075 44 15	225	41	9	02-02-89	USGS
65L 9	37 49 31	075 39 08	155	3	8	02-02-89	USGS
65L 12	37 48 09	075 38 18	220	36	9	02-02-89	USGS
65M 1	37 55 37	075 43 18	115	3	14	08-18-48	USGS
65M 2	37 55 12	075 43 48	115	5	66	02-28-75	VWCB
					65	03-25-75	VWCB
					67	09-08-75	VWCB
66K 3	37 43 20	075 36 56	220	8	16	06-03-77	VWCB
					8	07-10-84	VWCB
66L 3	37 52 25	075 32 17	206	5	5	09-30-77	VWCB
					9	07-10-84	VWCB
					8	02-02-88	VWCB
66L 6	37 49 00	075 35 24	246	53	10	08-09-78	VWCB
					10	10-08-81	VWCB
66M 17	37 57 23	075 34 44	178	11	66	08-26-80	VWCB
					68	07-11-84	VWCB
					82	11-05-86	VWCB
66M 20	37 53 32	075 33 00	240	42	8	08-04-81	VWCB
66M 39	37 56 23	075 30 19	180	25	7	02-02-89	USGS
67M 9	37 56 26	075 27 23	256	19	125	02-27-75	VWCB
					124	04-06-76	VWCB
					107	07-12-76	VWCB
					123	10-12-76	VWCB
					129	04-08-77	VWCB
					141	11-14-77	VWCB
					164	04-21-81	VWCB
					173	12-14-81	VWCB
					167	05-27-82	VWCB
					171	07-22-82	VWCB
					183	01-25-83	VWCB
67M 12	37 56 35	075 27 15	222	13	79	03-29-81	VWCB
					77	05-05-81	VWCB
					73	05-27-82	VWCB
					78	08-07-84	VWCB
					81	11-06-86	VWCB
67M 13	37 56 35	075 27 15	249	16	135	03-29-81	VWCB
					129	05-27-82	VWCB
					135	08-07-84	VWCB
					137	11-06-86	VWCB
67M 14	37 56 17	075 27 37	280	26	134	05-27-82	VWCB
					144	08-07-84	VWCB
					142	11-06-86	VWCB
					140	01-26-88	USGS
67M 24	37 56 39	075 28 59	245	24	62	02-01-65	VWCB
					68	10-27-69	USGS
					64	07-01-70	VWCB
					64	06-01-71	USGS
					65	06-01-72	VWCB
					56	02-27-75	VWCB
					74	04-05-81	VWCB

Table 11. Chloride concentrations in the lower Yorktown-Eastover aquifer

[USGS, U.S. Geological Survey; VWCB, Virginia Water Control Board; latitude and longitude are reported in degrees, arc minutes, arc seconds; mg/L, milligrams per liter]

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
62F 1	37 14 57	076 00 28	260	12	358	01-01-78	VWCB
63F 16	37 13 07	075 58 35	285	31	75	08-11-80	VWCB
					73	07-12-84	VWCB
					77	08-04-86	VWCB
					92	09-27-87	VWCB
63G 15	37 17 09	075 56 08	310	28	148	08-06-84	VWCB
					130	08-04-86	VWCB
					130	02-28-89	USGS
63G 23	37 16 53	075 58 48	280	15	28	06-29-79	VWCB
					9	08-19-80	VWCB
					8	07-12-84	VWCB
					9	01-25-88	USGS
					9	03-01-89	USGS
63G 24	37 16 53	075 58 48	330	15	387	06-29-79	VWCB
					640	08-11-80	VWCB
					630	07-12-84	VWCB
					750	08-04-86	VWCB
					730	11-10-87	USGS
					630	03-01-89	USGS
63H 4	37 27 05	075 55 59	235	17	297	09-28-77	VWCB
					244	05-10-79	VWCB
					246	06-26-84	VWCB
					262	08-04-86	VWCB
					290	03-02-89	USGS
63H 8	37 26 20	075 52 55	295	33	13	05-02-79	VWCB
					10	11-28-79	VWCB
					12	02-19-81	VWCB
					12	07-21-82	VWCB
					14	09-12-83	VWCB
					12	08-23-84	VWCB
					12	02-19-85	VWCB
63J 3	37 32 30	075 54 10	290	22	4,850	06-28-84	VWCB
					6,200	11-18-87	USGS
64H 5	37 29 22	076 47 01	306	6	2,217	06-01-77	VWCB
					2,150	07-11-84	VWCB
					2,350	08-05-86	VWCB
					2,100	11-12-87	USGS
64J 11	37 30 59	075 48 45	313	30	1,598	07-03-79	VWCB
					1,510	08-21-80	VWCB
					1,900	11-10-87	USGS
64J 15	37 36 42	075 46 08	264	39	11	08-07-81	VWCB
64J 16	37 37 05	075 45 50	262	40	8	08-07-81	VWCB
64K 5	37 38 28	075 45 09	290	45	7	02-28-75	VWCB
					9	09-11-75	USGS
64K 7	37 38 45	075 52 25	176	8	320	09-30-77	VWCB
					318	08-20-80	VWCB
					306	06-26-84	VWCB
					300	08-05-86	VWCB
					310	03-02-89	USGS

Table 11. Chloride concentrations in the lower Yorktown-Eastover aquifer—Continued

USGS well number	Latitude	Longitude	Well depth (feet)	Land-surface altitude (feet)	Chloride concentration (mg/L)	Date sampled	Sampling agency
64K 12	37 39 32	075 45 27	284	47	12	08-21-80	VWCB
					12	06-29-84	VWCB
					11	01-26-88	USGS
65K 7	37 38 05	075 40 00	295	36	43	09-21-71	USGS
					12	02-20-75	VWCB
65K 18	37 38 00	075 40 00	283	40	37	09-20-71	USGS
					33	02-27-75	VWCB
65K 20	37 38 10	075 40 00	295	43	55	09-21-71	USGS
65K 23	37 44 42	075 43 25	290	13	515	08-13-80	VWCB
					800	02-01-88	USGS
65K 25	37 44 42	075 43 25	228	12	9	08-13-80	VWCB
					15	01-27-88	USGS
65K 29	37 44 25	075 40 00	315	45	10	08-26-80	VWCB
					226	07-09-84	VWCB
					320	11-11-87	USGS
65M 3	37 55 12	075 43 48	195	5	430	02-01-75	VWCB
					330	01-28-80	VWCB
					343	01-20-82	VWCB
					398	04-17-85	VWCB
66K 2	37 43 20	075 38 05	292	10	130	06-03-84	VWCB
					45	08-06-86	VWCB
					9	01-27-88	USGS
66L 1	37 52 25	075 32 17	305	5	16	09-15-77	VWCB
					12	07-10-84	VWCB
					14	02-01-88	USGS
66M 5	37 52 39	075 35 29	246	17	17	04-06-55	USGS
					16	02-26-76	VWCB
					25	03-23-76	VWCB
					15	06-03-76	VWCB
					19	08-31-76	VWCB
					24	12-02-76	VWCB
					18	03-31-77	VWCB
					23	05-31-77	VWCB
					18	09-15-77	VWCB
					19	12-01-77	VWCB
					17	03-06-78	VWCB
66M 18	37 57 23	075 34 44	240	11	790	08-26-80	VWCB
					755	07-11-84	VWCB
					1,675	11-05-86	VWCB
					1,400	10-30-87	USGS
66M 25	37 56 10	075 36 18	340	6	2,100	10-30-87	USGS
					2,100	08-29-88	USGS
66M 26	37 56 10	075 36 18	230	6	1,000	10-30-87	USGS
					810	08-29-88	USGS

chloride concentration. This approach is not intended to provide specific information concerning the physical and chemical nature of the transition zone between freshwater and saltwater. A more detailed examination of the transition zone would require knowledge of the dispersive characteristics of the aquifers. Comparisons between sharp-interface and disperse-interface solutions have shown that the sharp-interface toe tends to be farther inland than the actual transition zone because the effects of dispersion are neglected (Cooper, 1959; Kohout, 1964; Volker and Rushton, 1982; Hill, 1988). The modeled saltwater-freshwater sharp interface is a first attempt at understanding the saltwater-freshwater-flow dynamics; the sharp interface provides information concerning the general

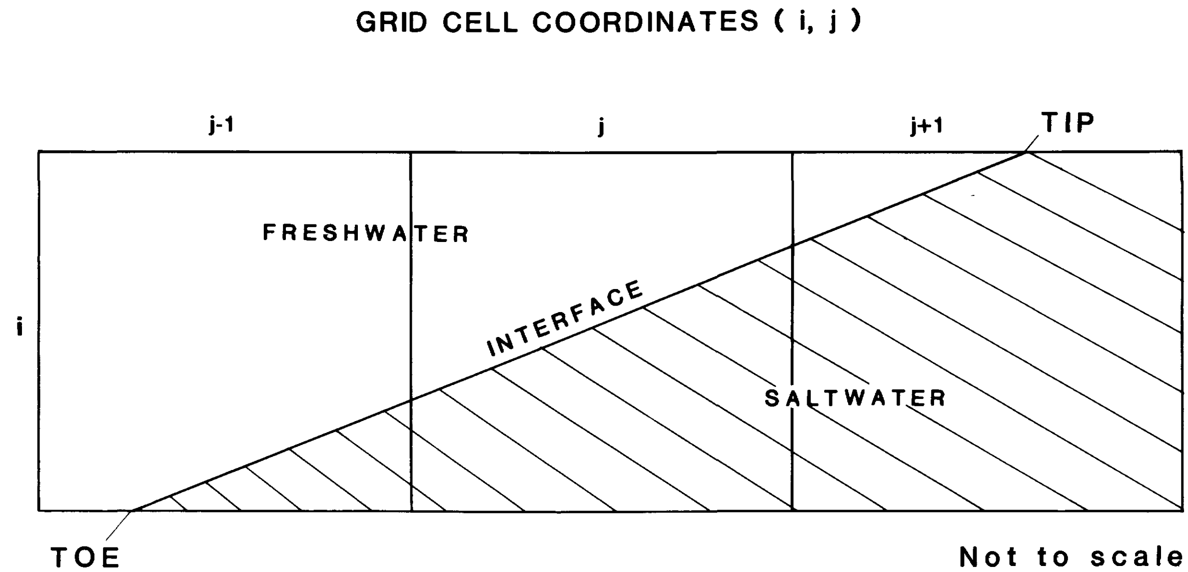


Figure 23. Model representation of the saltwater-freshwater interface tip and toe.

response of the interface to applied stresses. A derivation of the equations and a complete description of the solution algorithm are provided in Essaid (1990a).

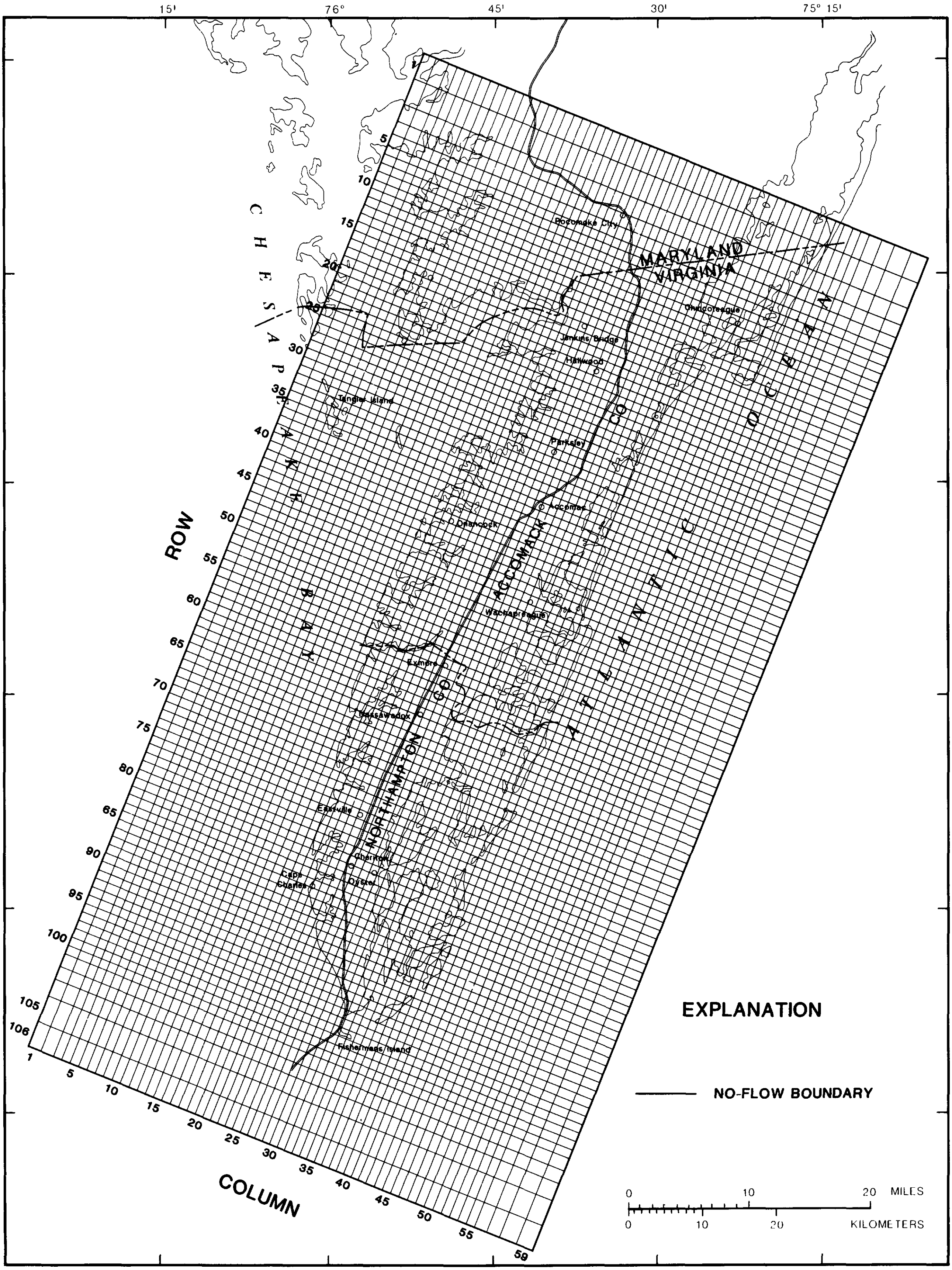
Model Grid and Boundaries

The physical conceptualization of the ground-water-flow system is incorporated into a finite-difference model by dividing the system into a network of rectangular grid blocks (fig. 24). Each grid block is assigned values that represent the average aquifer characteristics and hydrologic stresses for that area. The spatial discretization for the Eastern Shore ground-water-flow model consists of a variable three-dimensional grid of 106 rows and 59 columns. The grid-block dimensions range from a minimum of 0.49 mi to a maximum of 3.29 mi.

The model simulates flow only in the confined aquifers. Each of the three confined aquifers containing freshwater on the Eastern Shore was represented by a separate model layer. The unconfined aquifer was represented as a constant-head boundary overlying the confined-aquifer system. Confining units are not represented by layers but by vertical leakance terms assigned between layers. The physical and model conceptualizations of the ground-water-flow system are shown in figure 25. Model grid blocks can contain all freshwater, all saltwater, or both freshwater and saltwater. When the saltwater-freshwater interface passes through a grid block, the grid block contains both saltwater and freshwater.

The model boundaries are designed to approximate the actual physical system. The western, eastern, and southern boundaries for the Eastern Shore peninsula are the Chesapeake Bay and the Atlantic Ocean and are represented as no-flow boundaries in the digital flow model. The boundaries are located far enough offshore to include the nearshore saltwater-flow regime. The model simulates the position of the saltwater-freshwater interface boundary condition. The location of this boundary changes in response to changes in the saltwater-flow and freshwater-flow regimes. The Ghyben-Herzberg approximation was applied to current water-table head values for an initial estimate of the interface position (Heath, 1983). The lower boundary of the model is simulated as a no-flow boundary and approximates the contact between the lower Yorktown-Eastover aquifer and the 150- to 300-ft-thick St. Marys confining unit. This contact also is the lower limit of the freshwater-flow system. The upper boundary of the model is simulated as a constant-head boundary that represents the long-term

Figure 24. Finite-difference grid and boundaries used ▶ in model analysis.


CHESAPEAKE BAY
ATLANTIC OCEAN
MARYLAND
VIRGINIA
ACCOMACK CO
NORTHAMPTON CO
Pocomoke City
Chincoteague
Jenkins Bridge
Hallwood
Tangier Island
Parksley
Accomac
Onancock
Wachapreague
Exmore
Nassawadox
Eastville
Cheriton
Cape Charles
Oyster
Fishermans Island
ROW
COLUMN
EXPLANATION
NO-FLOW BOUNDARY
MILES
KILOMETERS

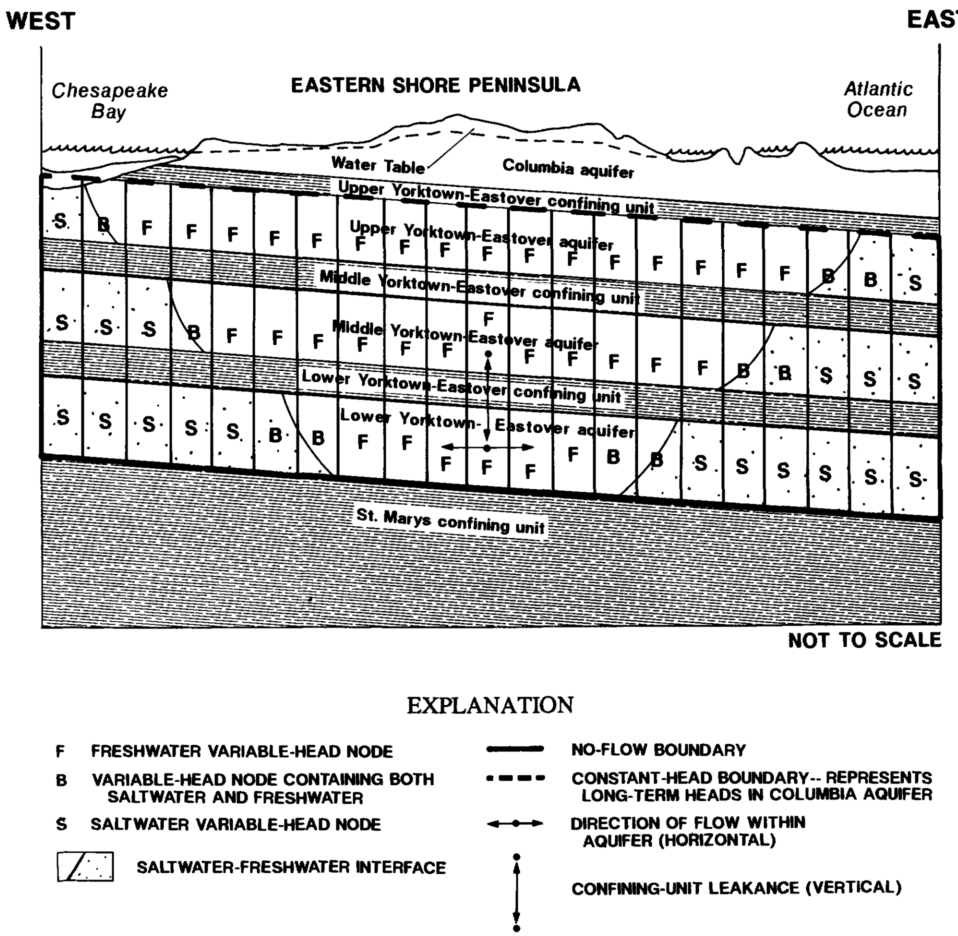


Figure 25. Physical and model conceptualizations of ground-water-flow system.

(quasi-steady-state) water table. This boundary is separated from the uppermost confined aquifer by a confining unit and represents the vertical connection between the unconfined-aquifer and the confined-aquifer system. The relative consistency of water levels in the unconfined aquifer over the time and scale of simulation supports the use of this boundary condition. Constant heads representing the average of the upper boundary in the onshore area were estimated from pond elevations, stream elevations, and water-level measurements in wells in the unconfined aquifer (fig. 26). Average elevations of surface water were estimated from USGS 7.5-min topographic maps. Heads in the offshore part of the upper boundary were calculated as the freshwater equivalent of the saltwater head as indicated from the bathymetry on USGS 1:250,000 scale topographic maps (fig. 11). The northern boundary is the only boundary that could not be delineated on the basis of a physical feature. Therefore, this boundary is extended beyond the study area, and an estimated flow line is represented by a no-flow boundary.

Model Calibration

The hydraulic properties of the aquifers and confining units are not uniform throughout the model area; therefore, the hydraulic characteristics are allowed to vary by assigning average values to each grid block. The hydraulic characteristics that vary spatially in this analysis are transmissivity, storage coefficient, and vertical leakance. Data quantifying these characteristics were not available for each grid block; values were estimated from available measurements of physical and hydrologic properties and laboratory analyses. A constant effective porosity of 0.25 was assigned to each model

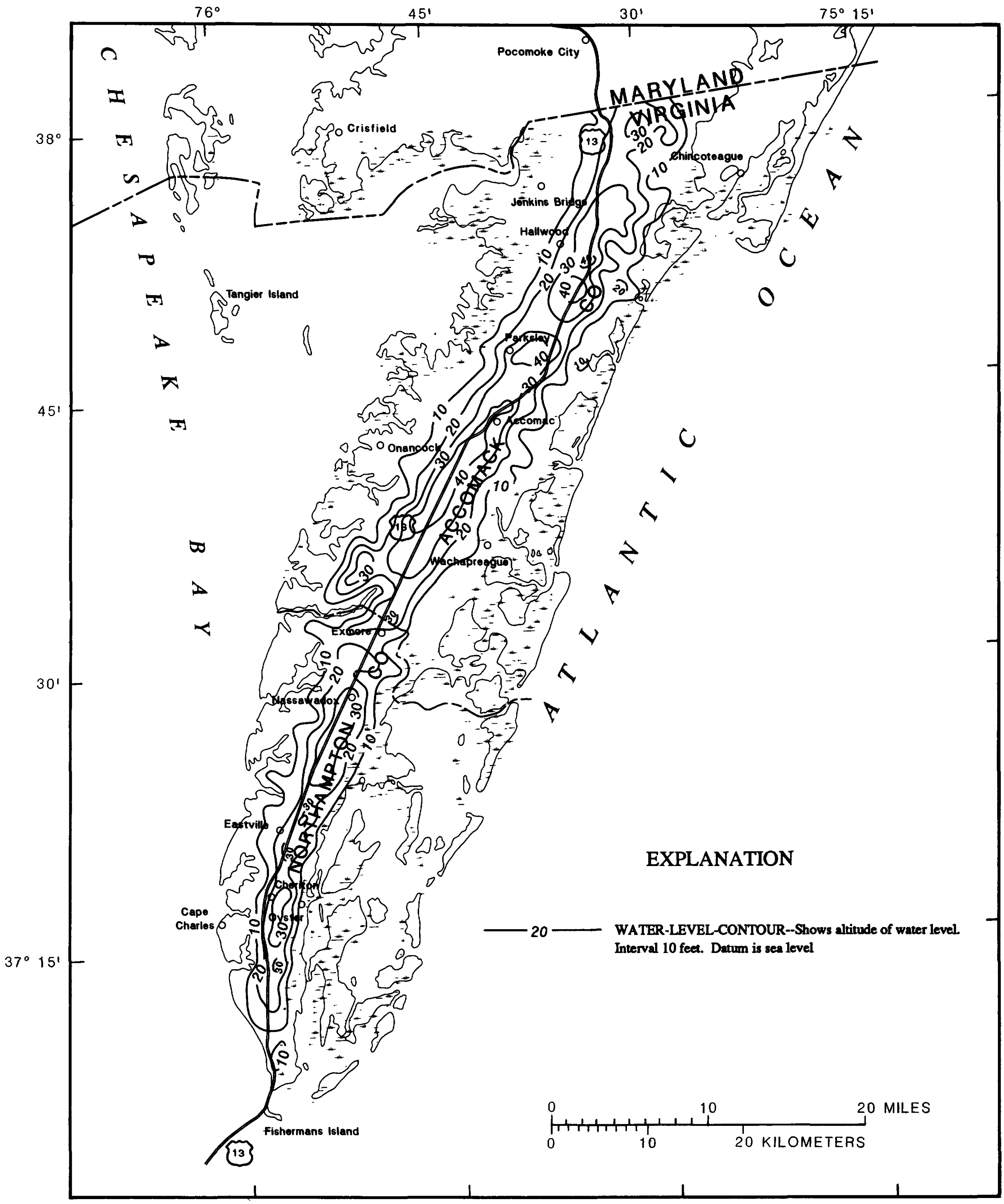


Figure 26. Average water levels for the Columbia aquifer.

layer. Model-sensitivity analyses indicated that results were not sensitive to changes in effective porosity.

An iterative process was used to calibrate the ground-water-flow model. Initial estimates of hydraulic properties were used to run a steady-state simulation for prepumping conditions. The initial steady-state results were used as a starting point for a transient simulation of pumping conditions for the period 1940–88. The initial hydraulic properties were adjusted by comparing the simulated water levels to measured water levels. The process was repeated until simulated and measured water levels were in close agreement at all observation wells. The calibrated values used in the model analysis are stored on computer tapes at the Virginia District Office of the USGS in Richmond, Va.

Transmissivity

The transmissivity for each grid block is calculated by multiplying the average thickness of the aquifer by the average horizontal hydraulic conductivity of the aquifer. The average thickness of the aquifer was calculated for each grid block using maps of the tops of aquifers and confining units (figs. 3–9). Initial average horizontal hydraulic conductivities were estimated from specific-capacity and aquifer-test data. These initial values were adjusted slightly during the transient-model calibration. Actual horizontal hydraulic conductivity data are sparse; therefore, the values were held constant for each layer except in areas where major regional geologic changes could be discerned. The final horizontal hydraulic conductivities used in the model analysis are 51.6, 43.2, and 8.6 ft/d for the upper, middle, and lower Yorktown-Eastover aquifers, respectively (figs. 27–29). The horizontal hydraulic conductivity in the northwestern corner of the model area was reduced to 1.3 ft/d to reflect fine-grained sediments and reduced water-bearing capabilities in the western part of Somerset County, Md. (Werkheiser, 1990). The horizontal hydraulic conductivity was also reduced 1 order of magnitude near Exmore and near Cape Charles in the middle Yorktown-Eastover aquifer (4.3 ft/d) to reflect the presence of Pleistocene paleochannels in which the original aquifer materials in these areas have been eroded and replaced by sediments with different hydraulic properties. A summary of the range of transmissivities estimated from specific-capacity data compared with the range of transmissivities used in the final model analysis is given in table 12.

Storage Coefficient

The storage coefficient for each grid block was calculated by multiplying the estimated specific storage of the aquifer by the average saturated thickness of the aquifer. A constant specific storage of 1×10^{-6}/ft is used in the model analysis; the value for specific storage was not calibrated during model development. This value is commonly used in the literature to represent the specific storage of a confined aquifer and is considered reasonable if all water released from aquifer storage results from the compressibility of water (Lohman, 1979). The range of storage coefficients is listed by aquifer in table 13.

Vertical Leakance

The vertical leakance for each grid block was calculated by dividing the vertical hydraulic conductivity of the confining unit by the average thickness of the confining unit (figs. 3–9). A constant vertical hydraulic conductivity of 1.39×10^{-5}ft/d from laboratory analysis of core samples (table 4) was used to calculate the initial vertical leakance used in the model calibration. Few core samples are available for the Eastern Shore; therefore, initial estimates were adjusted during transient-model development to estimate areal variations in vertical hydraulic conductivity. The range of final calibrated values for vertical leakance is listed by confining unit in table 14.

Steady-State-Model Simulation of Prepumping Conditions

Prior to 1940, ground-water withdrawals on the Eastern Shore were minor. Ground-water use consisted of a relatively small number of users withdrawing small amounts of water. The ground-water-flow system at this time existed in an approximate state of hydraulic equilibrium (steady state). A steady-state-flow condition is reached when recharge to the system equals discharge from the system. This condition implies that the water levels are constant over time and that the change in storage in the ground-water system is negligible. A steady-state simulation was conducted using prepumping conditions for the Eastern Shore. The steady-state

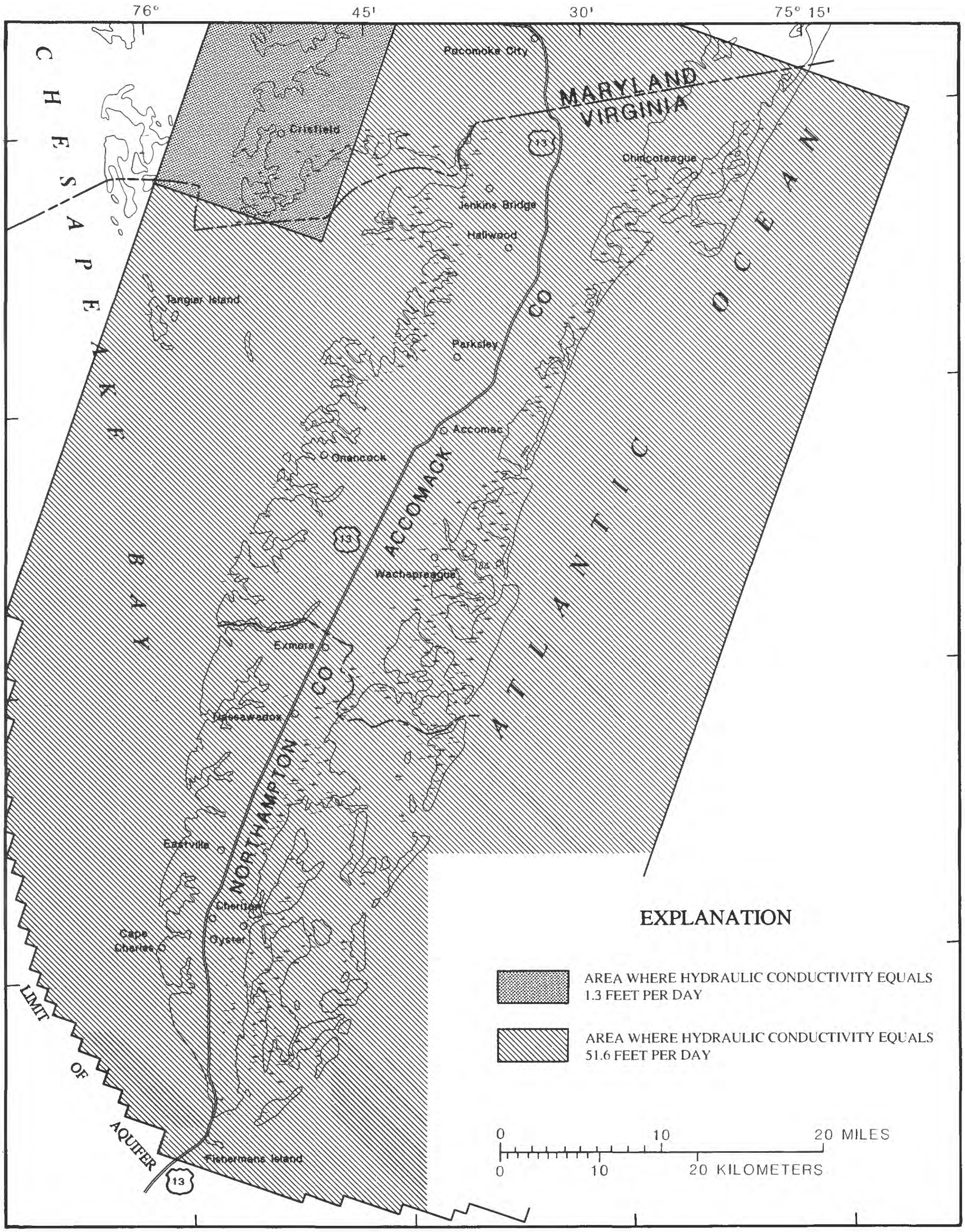


Figure 27. Hydraulic conductivity of the upper Yorktown-Eastover aquifer based on model calibration.

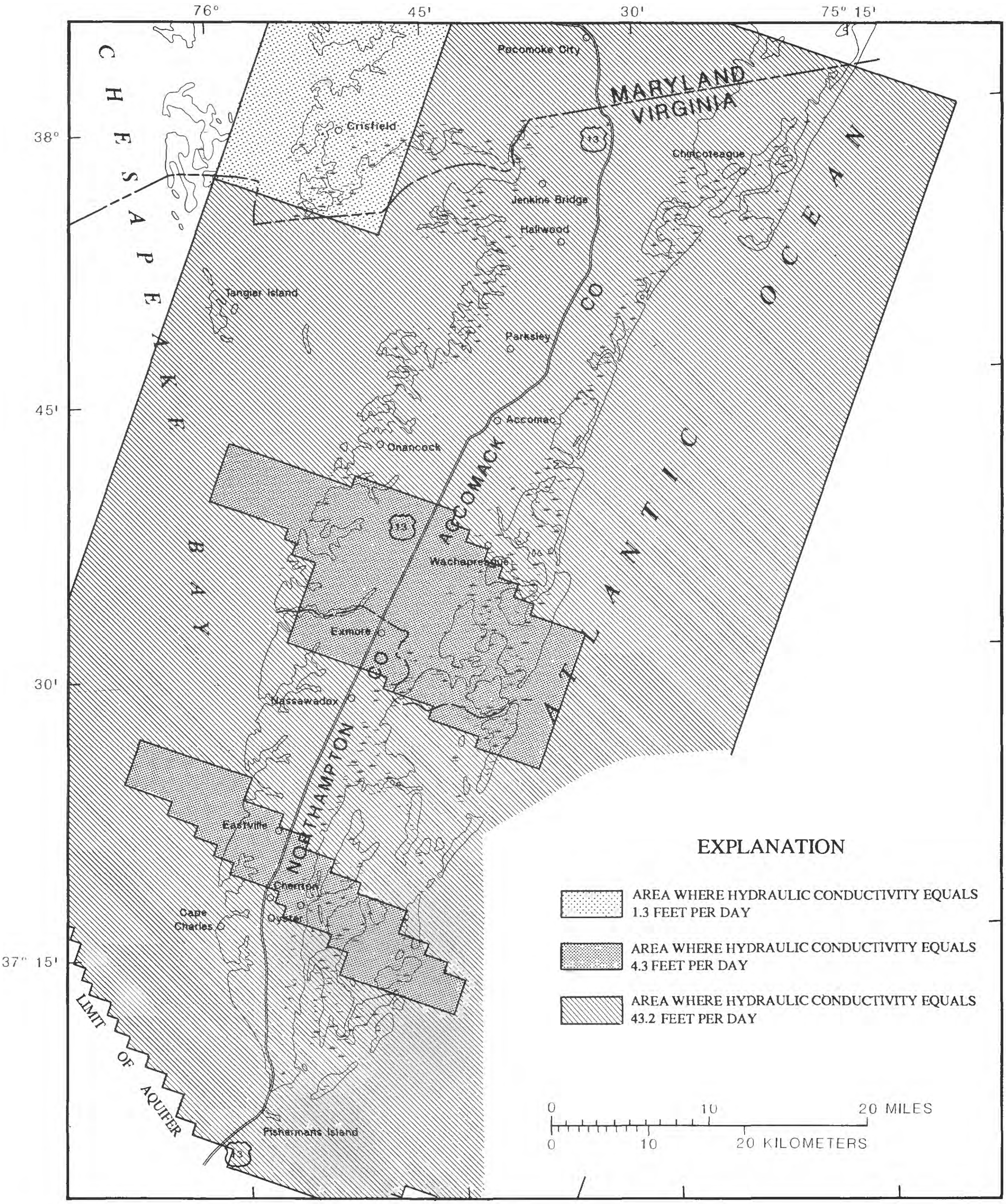


Figure 28. Hydraulic conductivity of the middle Yorktown-Eastover aquifer based on model calibration.

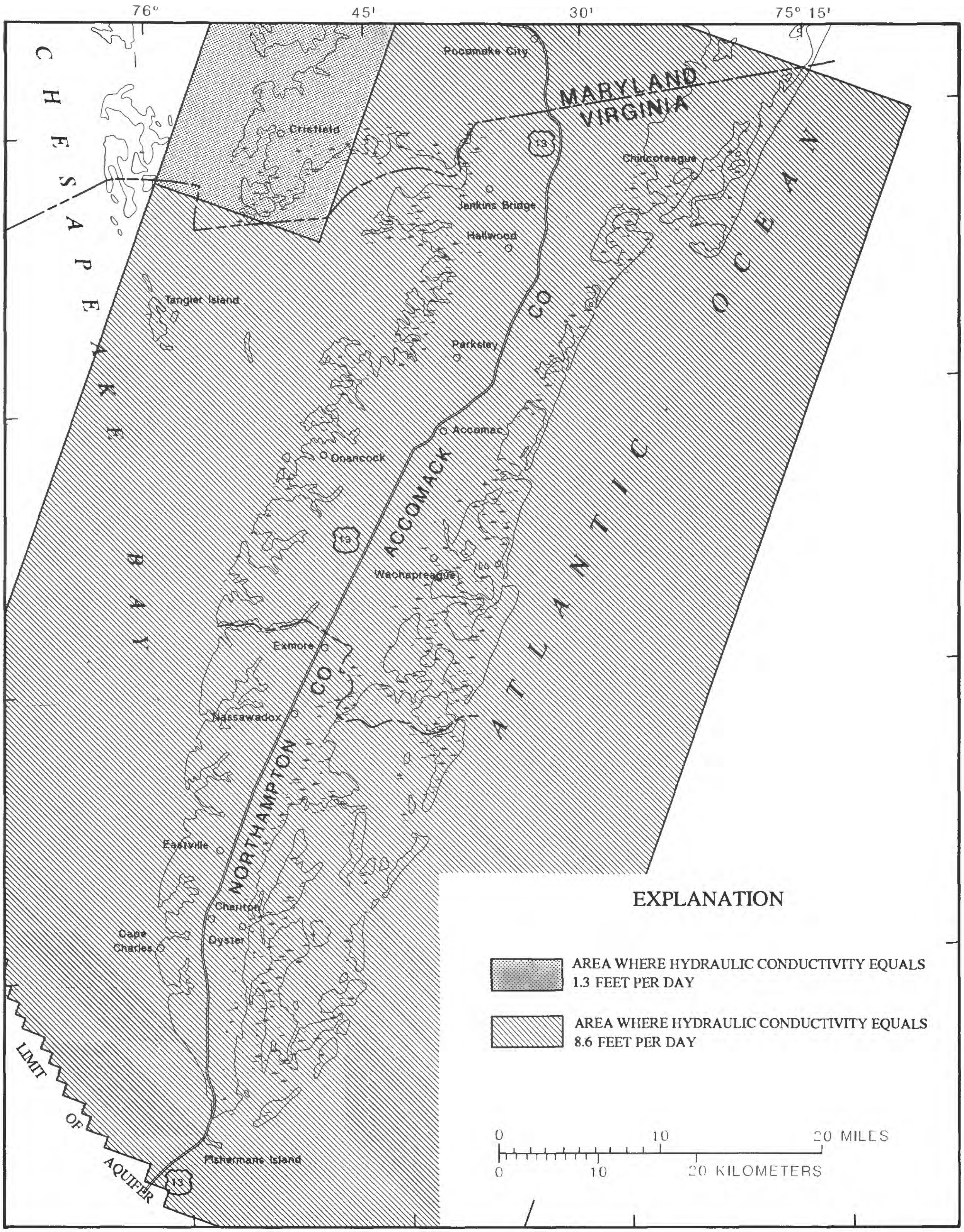


Figure 29. Hydraulic conductivity of the lower Yorktown-Eastover aquifer based on model calibration.

Table 12. Range of transmissivities estimated from specific-capacity data and from model calibration

[ft^2/d, foot squared per day]

Aquifer	Estimated transmissivity (ft^2/d)	
	Specific-capacity data	Model calibration
Upper Yorktown-Eastover	61 - 4,530	93 - 4,611
Middle Yorktown-Eastover	206 - 3,240	26 - 3,588
Lower Yorktown-Eastover	95 - 2,094	86 - 1,210

Table 13. Minimum and maximum values of model storage coefficient

[values, dimensionless, are not intended to imply accuracy to precision shown]

Aquifer	Storage coefficient	
	Minimum	Maximum
Upper Yorktown-Eastover	1.01×10^{-5}	1.52×10^{-4}
Middle Yorktown-Eastover	1.06×10^{-5}	8.31×10^{-5}
Lower Yorktown-Eastover	1.07×10^{-5}	1.83×10^{-4}

Table 14. Minimum and maximum values of model vertical leakance

Aquifer	Vertical leakance (days^{-1})	
	Minimum	Maximum
Upper Yorktown-Eastover	4.32×10^{-7}	4.52×10^{-4}
Middle Yorktown-Eastover	8.55×10^{-7}	5.18×10^{-4}
Lower Yorktown-Eastover	1.24×10^{-6}	3.95×10^{-4}

simulation is an approximation of the natural ground-water system prior to any major stresses, and it provides a starting point for transient simulations that examine the effects of increased ground-water withdrawals.

Simulated prepumping water levels for the Yorktown-Eastover aquifers are shown in figures 30–32. There are no reliable measurements of water levels for the confined aquifers on the Eastern Shore prior to 1940; however, the conceptualization of prepumping ground-water flow for the Eastern Shore assumes that water levels were a subdued replica of the land surface and that flow gradients were from topographic highs in the center of the peninsula to the Chesapeake Bay on the west and Atlantic Ocean on the east. Simulated water levels were compared with the prepumping water levels from a previous simulation of ground-water flow on the Eastern Shore (Bal, 1977). The simulated water levels and flow directions are consistent with Bal's study and are in agreement with the conceptualization of ground-water flow during prepumping conditions.

The calibration of the steady-state model was evaluated by analyzing estimates of rate of recharge. Simulated recharge to the confined system on the Eastern Shore was compared with results from a previous ground-water-modeling study in southeastern Virginia (Hamilton and Larson, 1988). The southeastern Virginia model of prepumping conditions estimated an average recharge rate to the confined-aquifer system of approximately 0.4 in/yr. The Eastern Shore ground-water-flow model for prestressed conditions indicates a similar but slightly higher average recharge rate of approximately 0.6 in/yr. The recharge rate estimated in the steady-state calibration for the Eastern Shore model is consistent with a previous analysis of a similar system in the Coastal Plain of Virginia.

The simulated position of the tip and toe of the saltwater-freshwater interface for each of the Yorktown-Eastover aquifers for prepumping conditions is shown in figures 33–35. The position of the interface is a function of the freshwater-flow and saltwater-flow regimes. The interface generally is farthest offshore in the upper Yorktown-Eastover aquifer and is progressively farther inland in the middle and lower Yorktown-Eastover aquifers, where the depths to the aquifers increase and the freshwater heads decrease. The simulated position of the saltwater-freshwater interface in the steady-state simulation is an equilibrium position; the actual position of the prepumping saltwater-freshwater interface is not known. Several studies indicate that in some coastal areas the saltwater-freshwater interface is still responding to long-term Pleistocene sea-level fluctuations and has not achieved equilibrium with the present-day sea level (Essaid, 1990b; Meisler and others, 1985). It is assumed for the purposes of this study that the prepumping saltwater-freshwater interface is in equilibrium with the present-day sea level. This approach provides a conservative estimate of saltwater-freshwater interface movement; a transitional interface would be moving landward because sea levels have been rising since the late Wisconsin glacial maximum (Meisler and others, 1985). The simulated prepumping position of

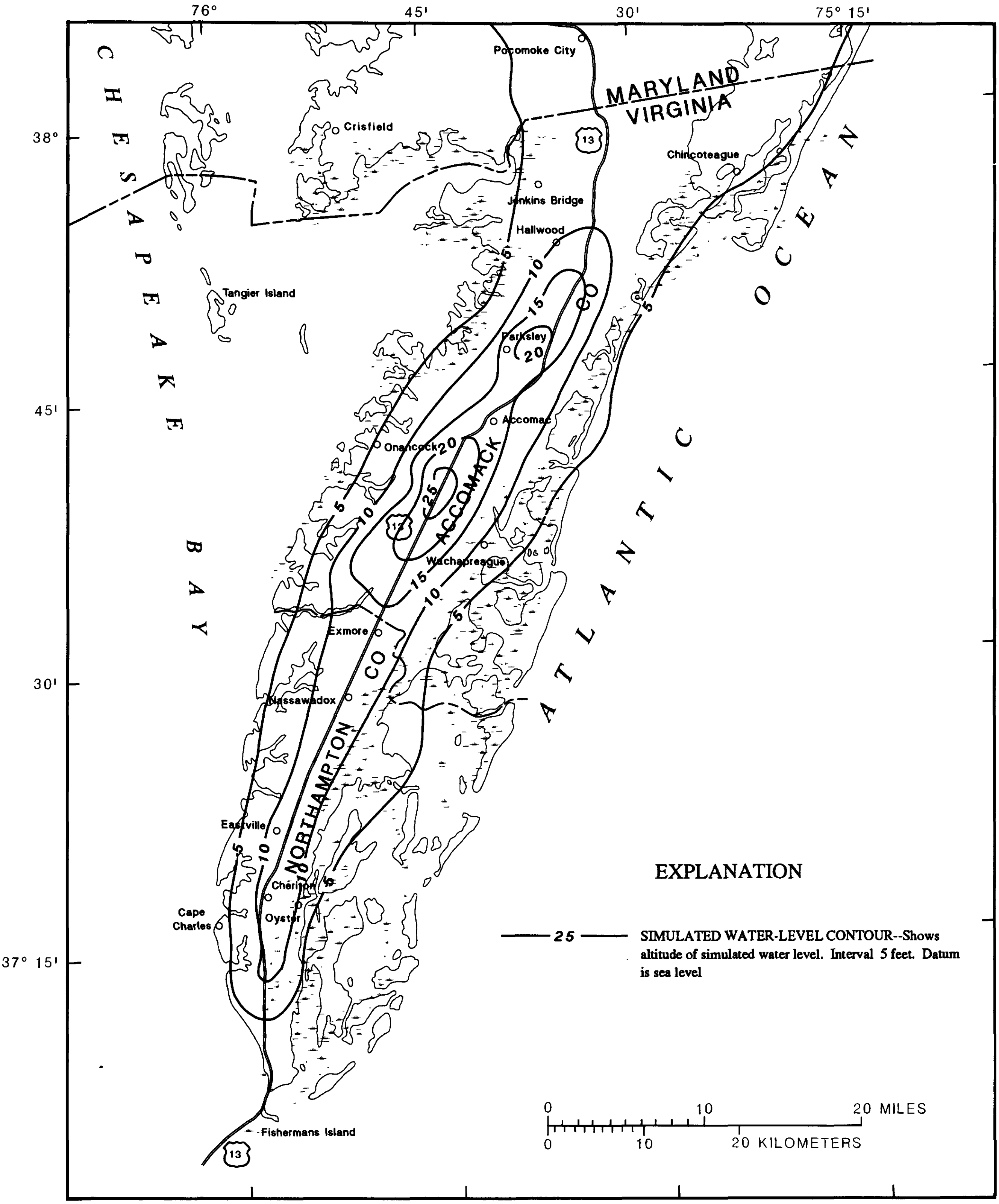


Figure 30. Simulated water levels in the upper Yorktown-Eastover aquifer for prepumping conditions.

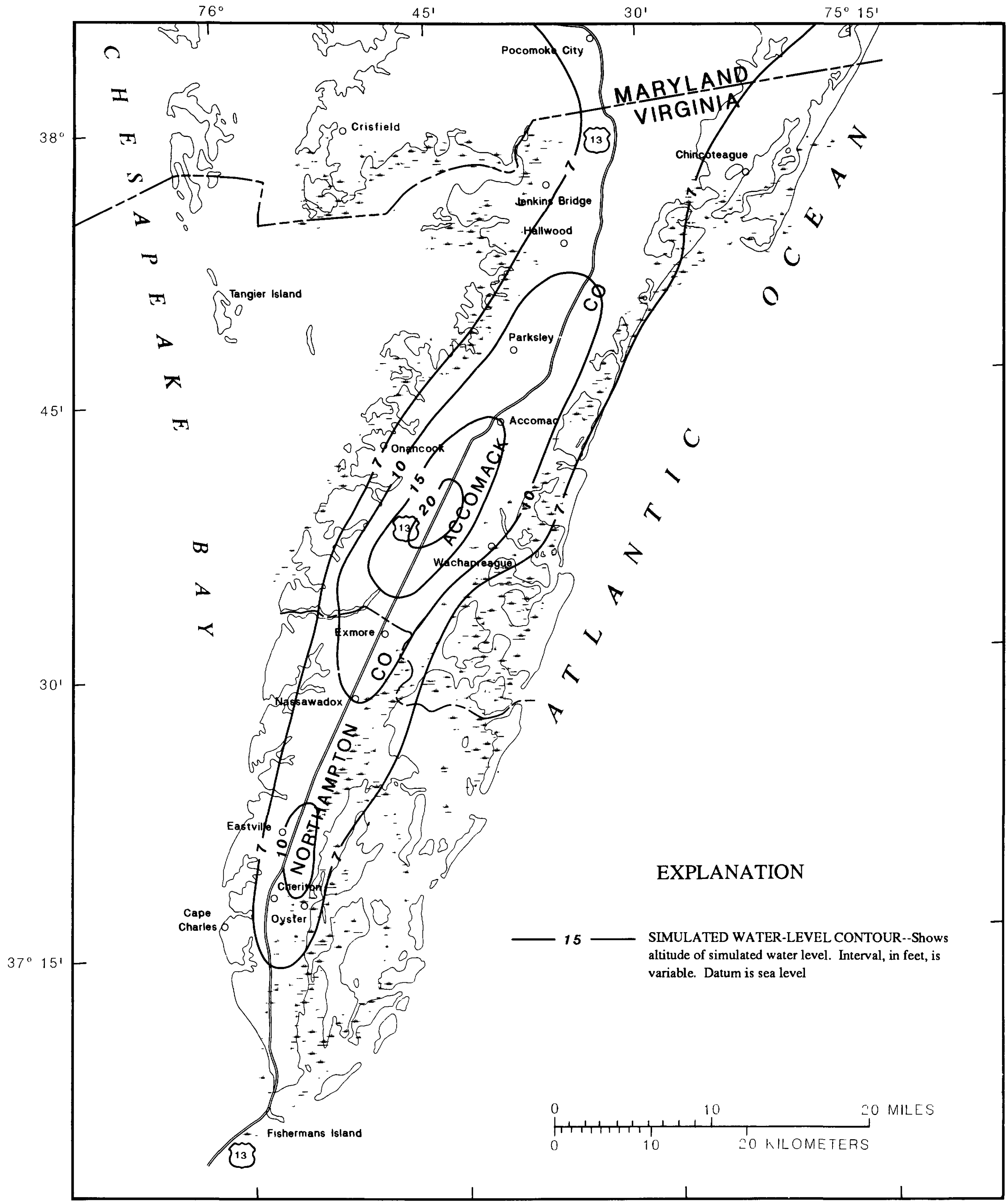


Figure 31. Simulated water levels in the middle Yorktown-Eastover aquifer for prepumping conditions.

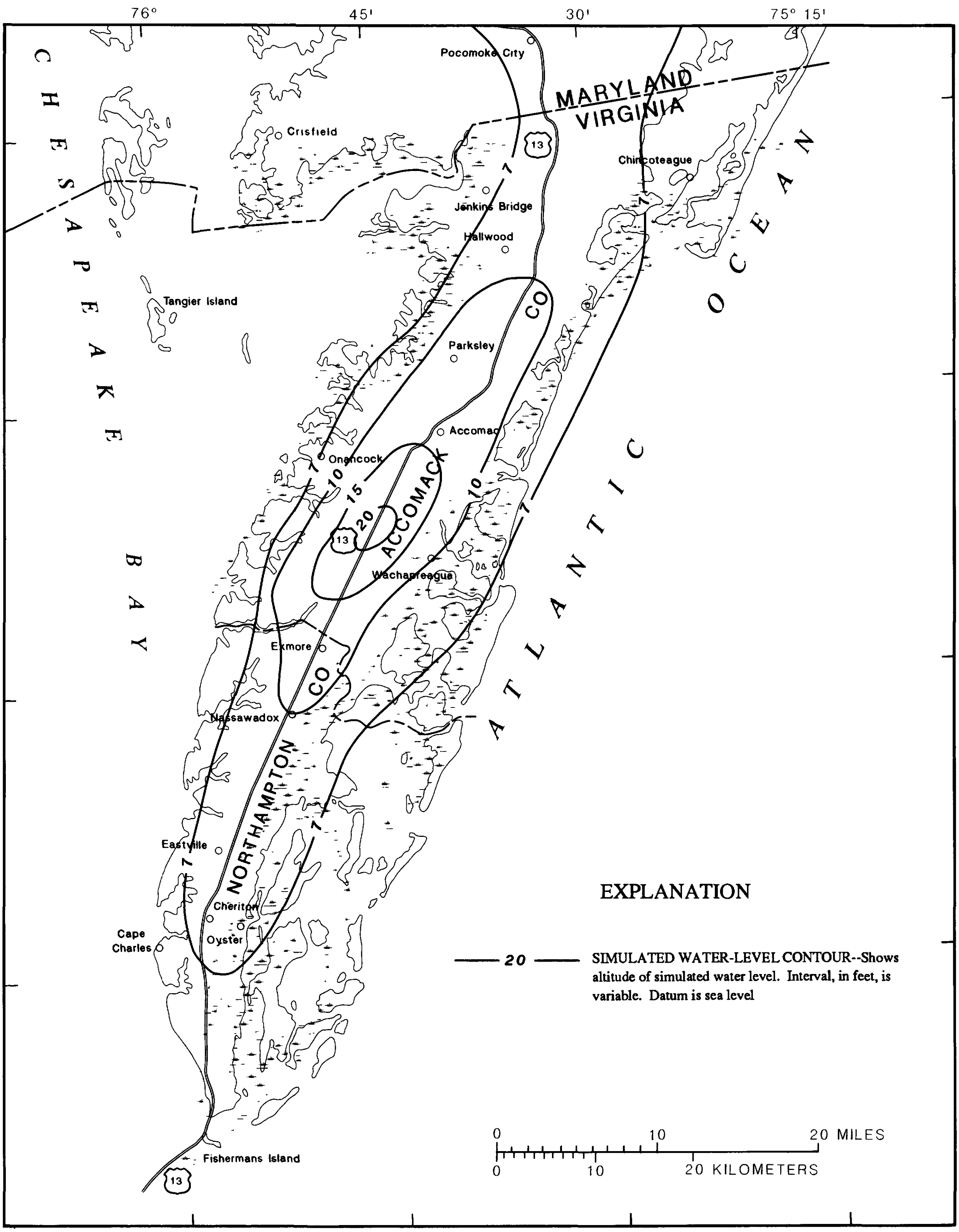


Figure 32. Simulated water levels in the lower Yorktown-Eastover aquifer for prepumping conditions.

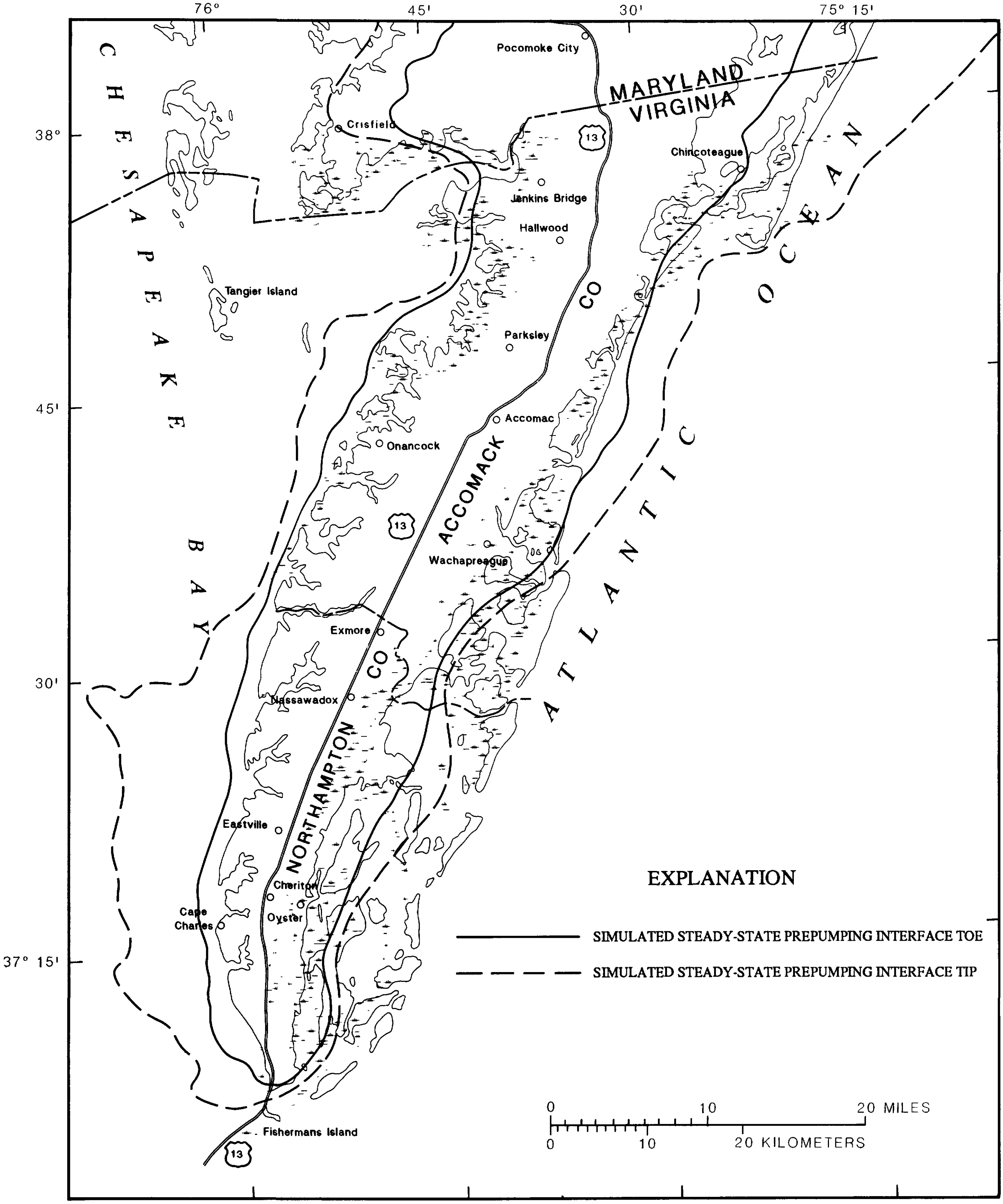


Figure 33. Simulated position of the saltwater-freshwater interface for the upper Yorktown-Eastover aquifer for prepumping conditions.

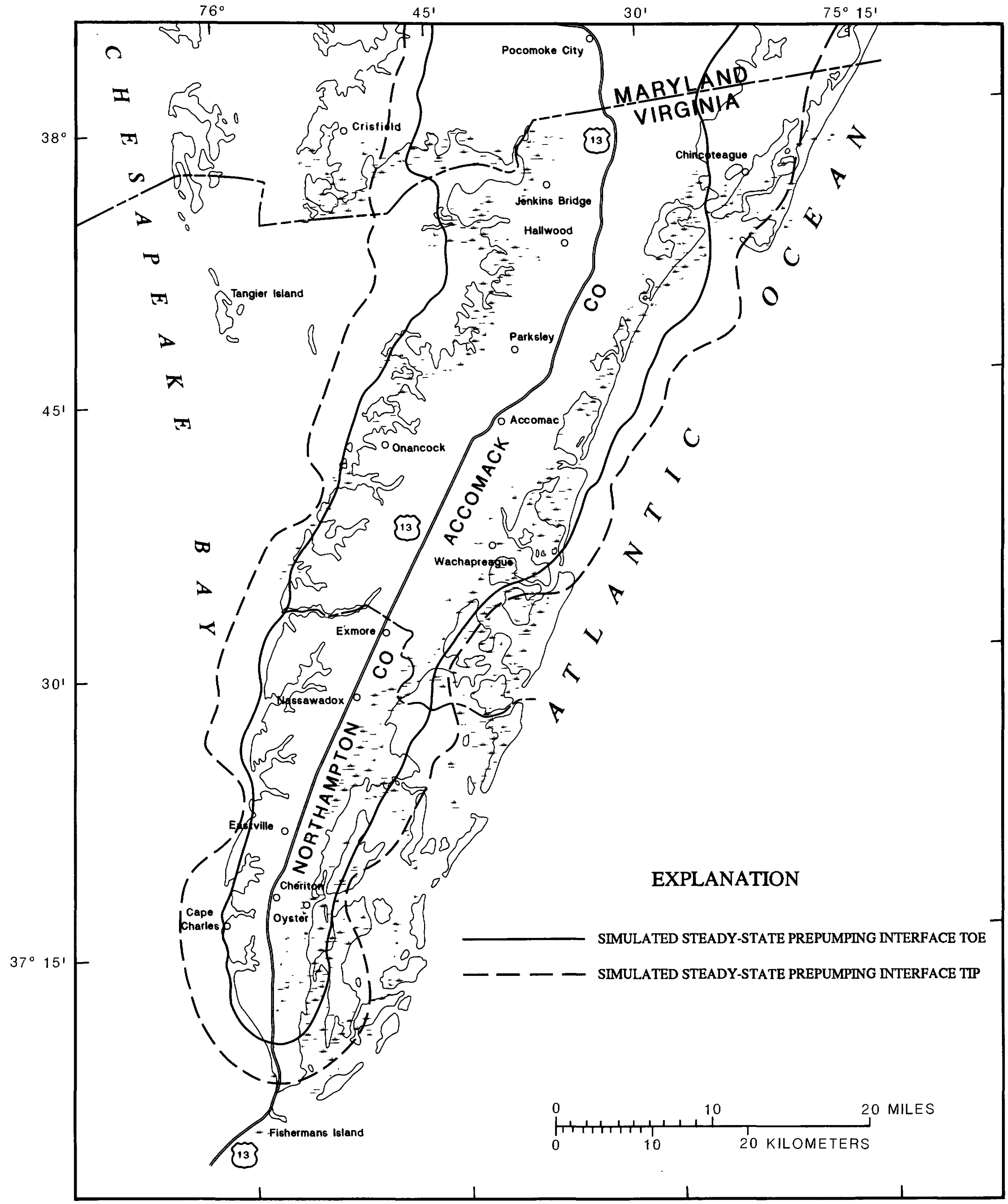


Figure 34. Simulated position of the saltwater-freshwater interface for the middle Yorktown-Eastover aquifer for prepumping conditions.

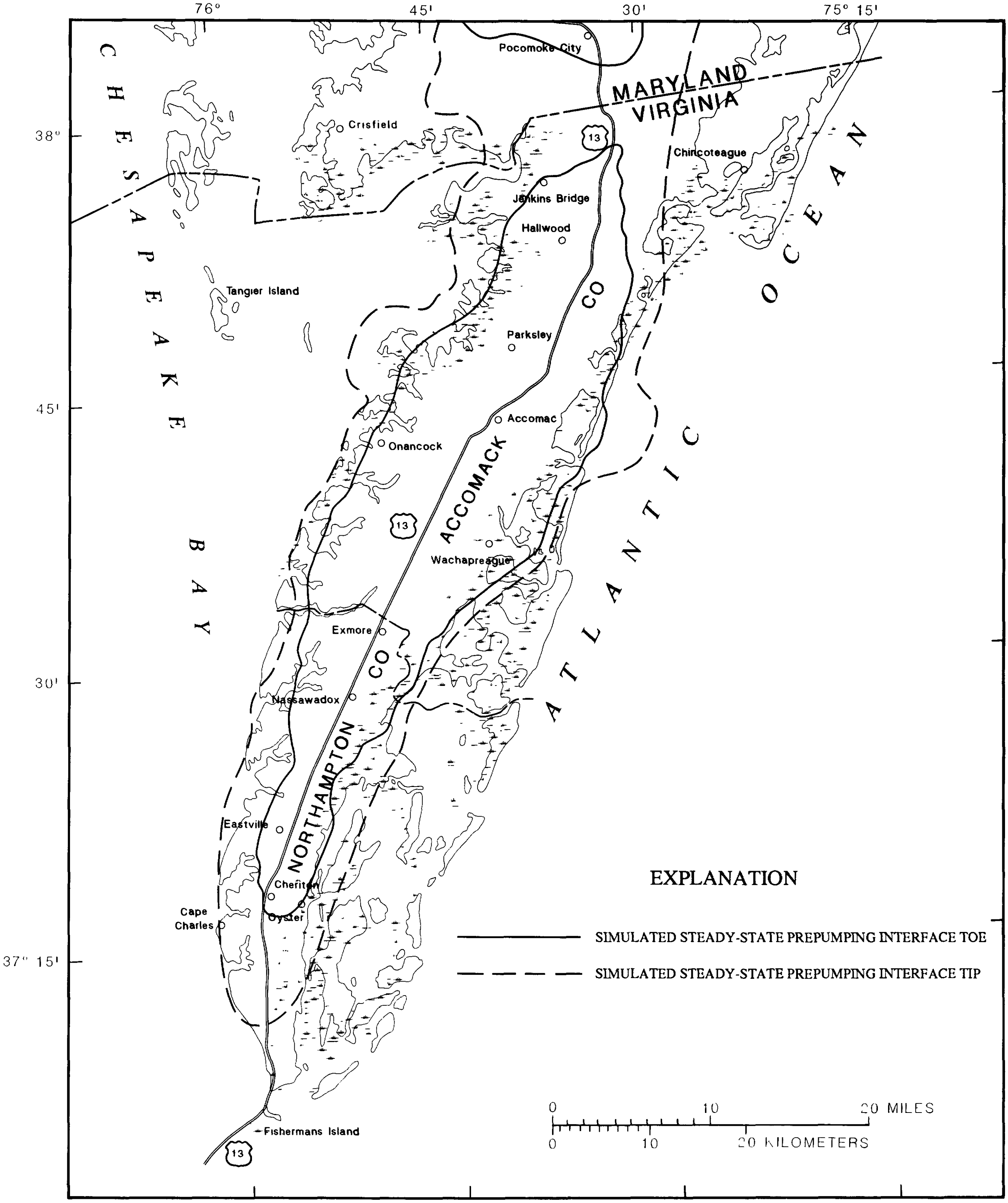


Figure 35. Simulated position of the saltwater-freshwater interface for the lower Yorktown-Eastover aquifer for prepumping conditions.

the saltwater-freshwater interface is a useful reference for examining the relative effects of withdrawals on the ground-water-flow system.

Transient-Model Simulation of Pumping Conditions

A transient-model simulation was conducted to simulate the effects of ground-water withdrawals on the Eastern Shore from 1940 to 1988. The water levels and interface position generated in the prepumping steady-state simulation were used as initial conditions in the transient-model analysis. Aquifer and confining-unit hydraulic characteristics were equivalent to those used when simulating prepumping conditions. The transient simulation shows the effects of historic withdrawals on the ground-water-flow system.

Time Discretization and Ground-Water Withdrawals

Pumpage has varied during the history of ground-water withdrawal on the Eastern Shore (fig. 36). The transient changes in withdrawals are accounted for in the model by dividing historical pumpage into 12 pumping periods. Model-simulated pumping periods are the years 1940–44, 1945–46, 1947–55, 1956–64, 1965–67, 1968–72, 1973–77, 1978–79, 1980–81, 1982–84, 1985–86, and 1987–88. Each pumping period starts on January 1 of its beginning year and ends on December 31 of its final year. Simulated withdrawals were calculated by aquifer for each pumping period from annual withdrawal data (fig. 18) using an average for the time period (fig. 36, table 15). Aquifer-top maps (figs. 3–9) and well-screen depth information were used to assign the withdrawals to the appropriate aquifer. Withdrawals for multiaquifer wells were determined by the percentage of the total screen present in each aquifer.

Results of Simulation

The transient simulation was evaluated by comparing simulated water levels to measured water levels. This comparison was made for a network of 48 observation wells distributed throughout the model area. Water levels for 12 of the observation wells are presented in figures 37–39. The observation wells selected are distributed throughout the model area, and water-level changes are representative of the total group of observation wells. Simulated water levels show reasonable agreement with measured water levels in all of the observation wells for the period of record. Some simulated water levels are slightly higher than measured water levels and some are slightly lower.

Simulated water levels for 1988 are shown in figures 40–42. Measured water levels are included on these maps to allow comparison between simulated and measured values. A comparison of simulated 1988 water levels with prepumping water levels (figs. 30–32) indicates a decline in water levels around the major pumping centers. The maximum simulated water-level declines in all three aquifers occur near the town of Accomac. Maximum water-level declines are 18, 30, and 53 ft in the upper, middle, and lower Yorktown-Eastover aquifers, respectively. Drawdown cones associated with the major pumping centers indicate a change in ground-water flow from prepumping conditions. Prior to ground-water withdrawals, flow was from the topographic highs in the center of the peninsula toward the Chesapeake Bay and Atlantic Ocean (figs. 30–32). By 1988, simulated water-level gradients show that water is diverted toward the major pumping centers (figs. 40–42). Top-of-aquifer maps can be compared with the simulated water levels to identify areas in which the water levels are approaching the top of the aquifer. Water levels that decline below the top of a confined aquifer cause unconfined conditions in the aquifer and can result in dewatering and associated irreversible changes in the aquifer. Dewatering can contribute to compaction of aquifer sediment and eventual decreases in aquifer yields. Simulated 1988 water levels are above the tops of the aquifers throughout the model area.

The amount of ground-water flow through the system also is changed as a result of withdrawals. The majority of the water for the increase in withdrawals comes from an increase in the amount of water recharging the confined-aquifer system from the unconfined aquifer and a decrease in the amount of discharge to the unconfined aquifer. In areas where pumpage causes water levels to decline in the confined aquifers, the head difference between the unconfined-aquifer and the confined-aquifer system increases. The increased head difference causes an increase in vertical leakage through the confining unit, and some freshwater that was previously discharging from the unconfined aquifer to

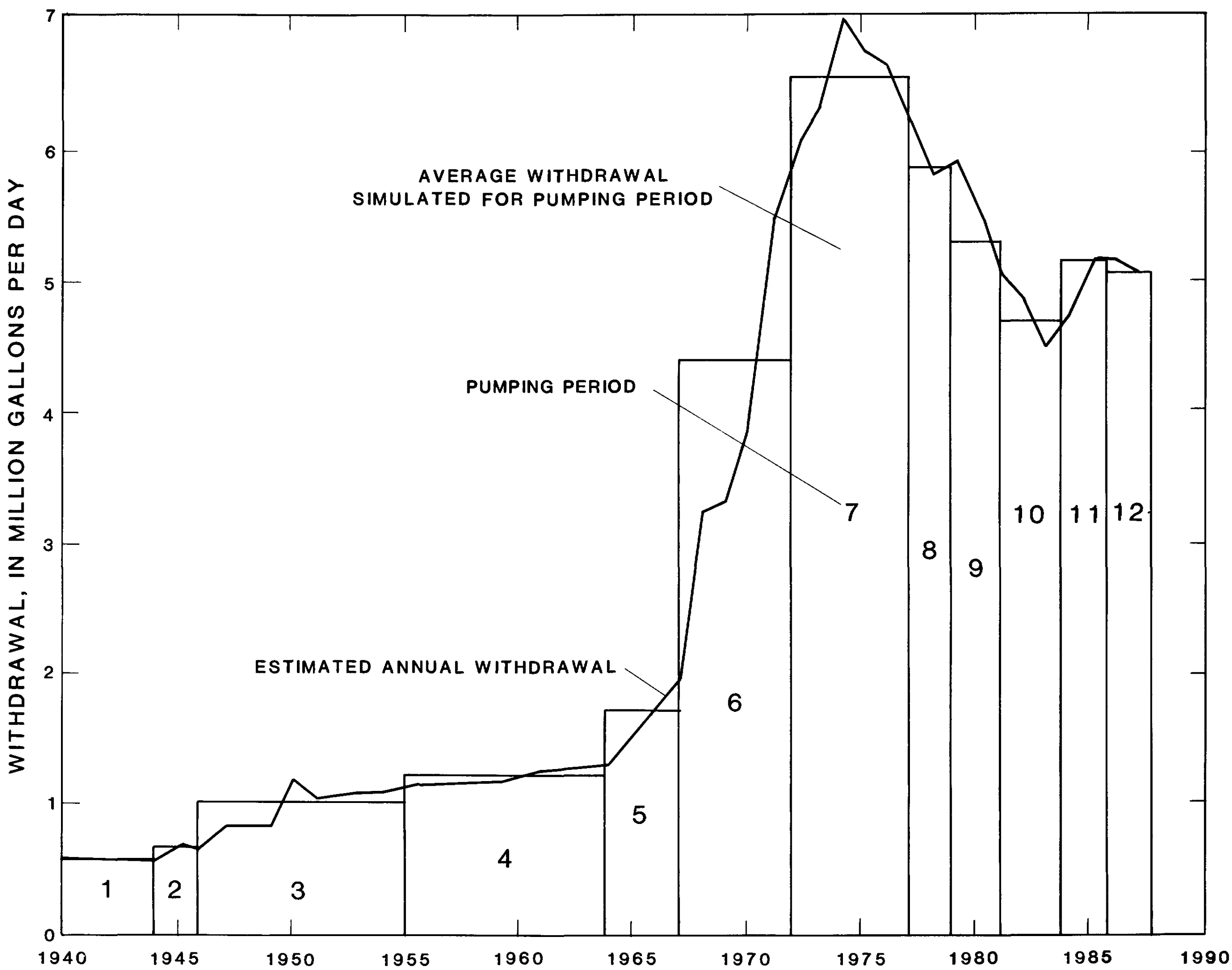


Figure 36. Estimated annual withdrawal and average withdrawal for simulated pumping periods.

surface-water bodies is diverted and flows into the confined-aquifer system. Any increase in withdrawals from the freshwater aquifers on the Eastern Shore results in a reduction in offshore freshwater discharge. A reduction in freshwater discharge affects the long-term position of the saltwater-freshwater interface in the aquifers and could cause increased salinity in sensitive estuarine environments. The steady-state prepumping simulation indicates that 11.07 Mgal/d recharges and discharges the confined ground-water-flow system (table 16). When 1988 withdrawals are simulated, the recharge to the confined aquifers increases to 13.11 Mgal/d, and natural discharge decreases to 8.64 Mgal/d.

The transient simulation of conditions for the period 1940–88 shows no movement of the saltwater-freshwater interface, although significant changes in the flow system occur. The simulated position of the saltwater-freshwater interface for 1988 conditions is identical to the simulated interface position for prepumping conditions (figs. 33–35). This result indicates that interface response is slow and takes place over long periods of time. Similar findings have been recorded in other saltwater-intrusion studies (Bond and Bredehoeft, 1987; Essaid, 1990b; Meisler and others, 1985). The investigation by Bond and Bredehoeft (1987) using a two-dimensional solute-transport model showed the main pathway for saltwater intrusion over short timeframes was downward vertical leakage of saltwater from surface-water bodies into the shallow aquifers. Simulated water-level gradients for

Table 15. Withdrawals for each pumping period by aquifer

[Values, in millions of gallons per day, are not intended to imply accuracy to precision shown]

Aquifer	Pumping period											
	1 1940-44	2 1945-46	3 1947-55	4 1956-64	5 1965-67	6 1968-72	7 1973-77	8 1978-79	9 1980-81	10 1982-84	11 1985-86	12 1987-88
Upper Yorktown-Eastover	0.440	0.521	0.750	0.815	1.032	1.819	2.171	2.104	1.937	1.659	1.809	1.885
Middle Yorktown-Eastover	.057	.087	.181	.309	.580	1.988	3.134	2.706	2.299	2.017	2.275	2.102
Lower Yorktown-Eastover	.054	.054	.074	.087	.097	.579	1.240	1.038	1.050	1.001	1.054	1.070
Total	0.551	0.662	1.005	1.211	1.709	4.386	6.545	5.848	5.286	4.677	5.138	5.057

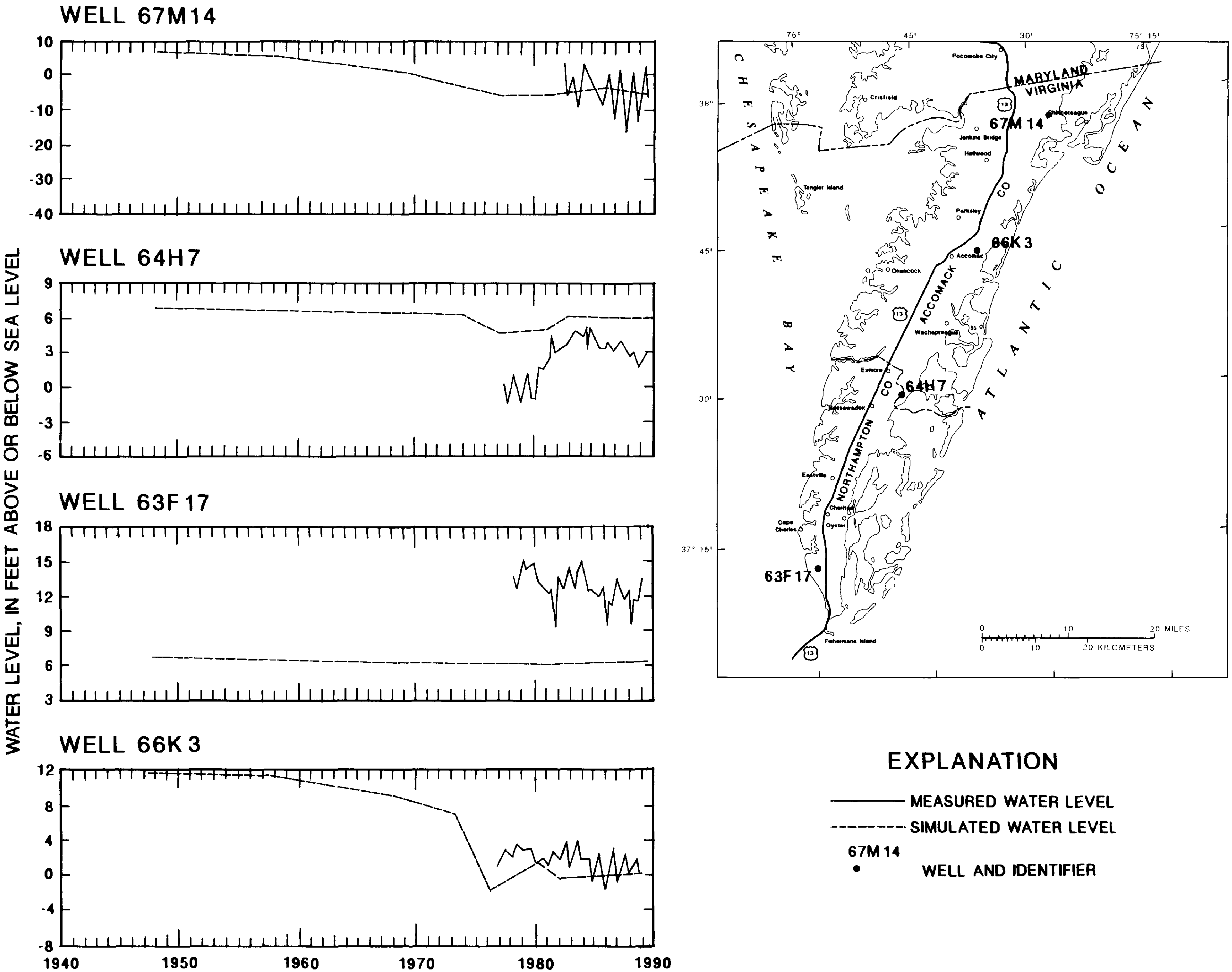


Figure 37. Simulated and measured water levels at selected observation wells in the upper Yorktown-Eastover aquifer.

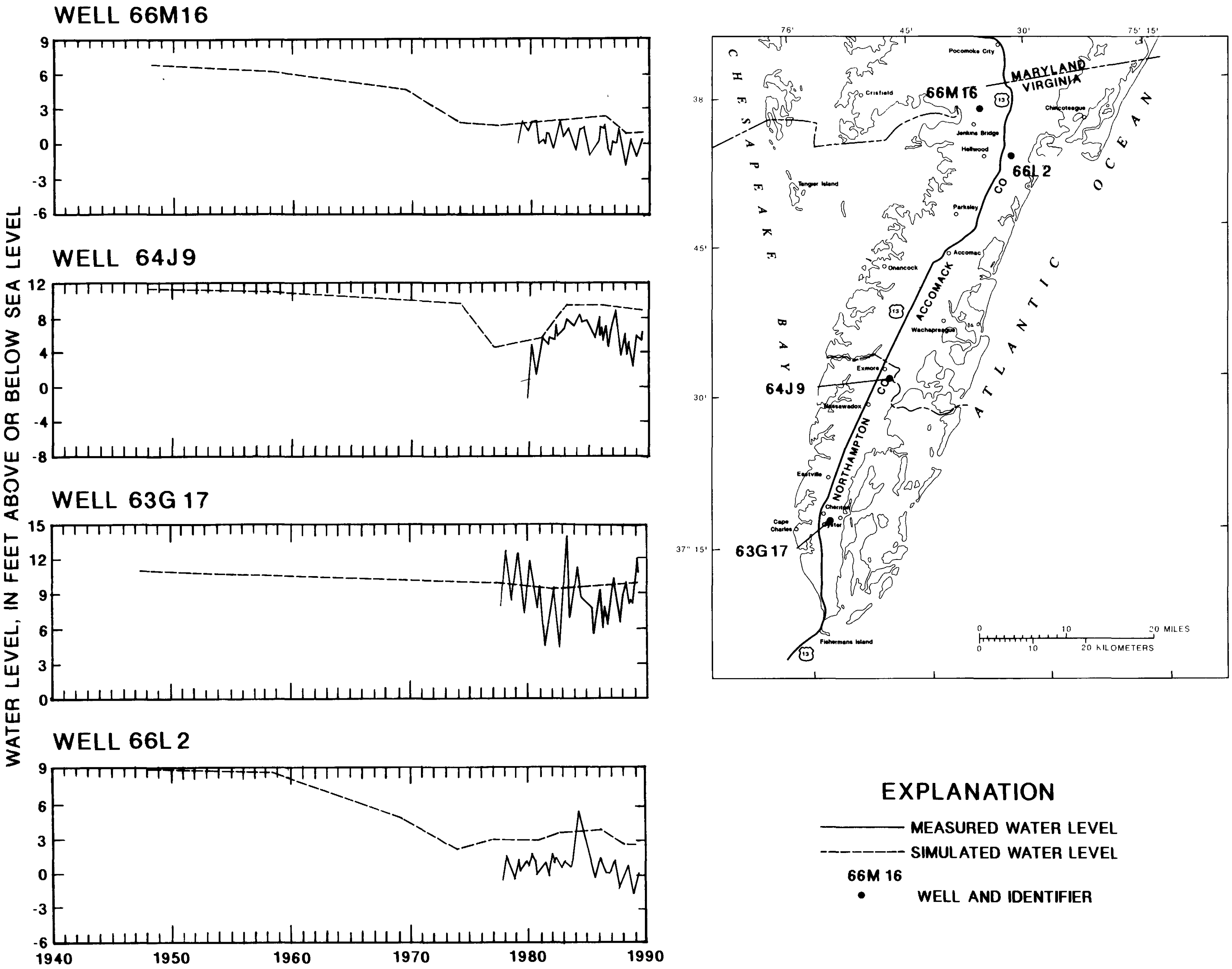


Figure 38. Simulated and measured water levels at selected observation wells in the middle Yorktown-Eastover aquifer.

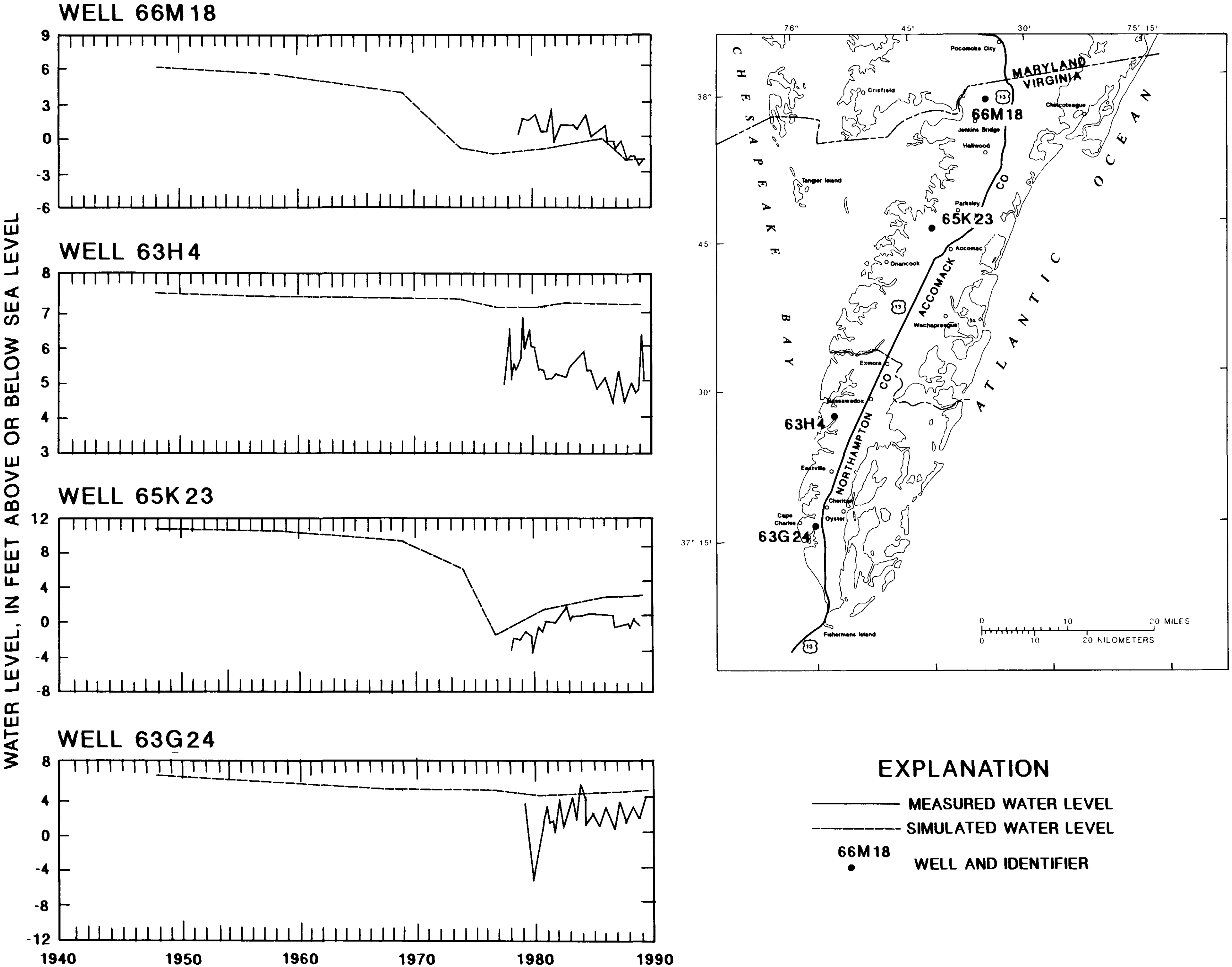


Figure 39. Simulated and measured water levels at selected observation wells in the lower Yorktown-Eastover aquifer.

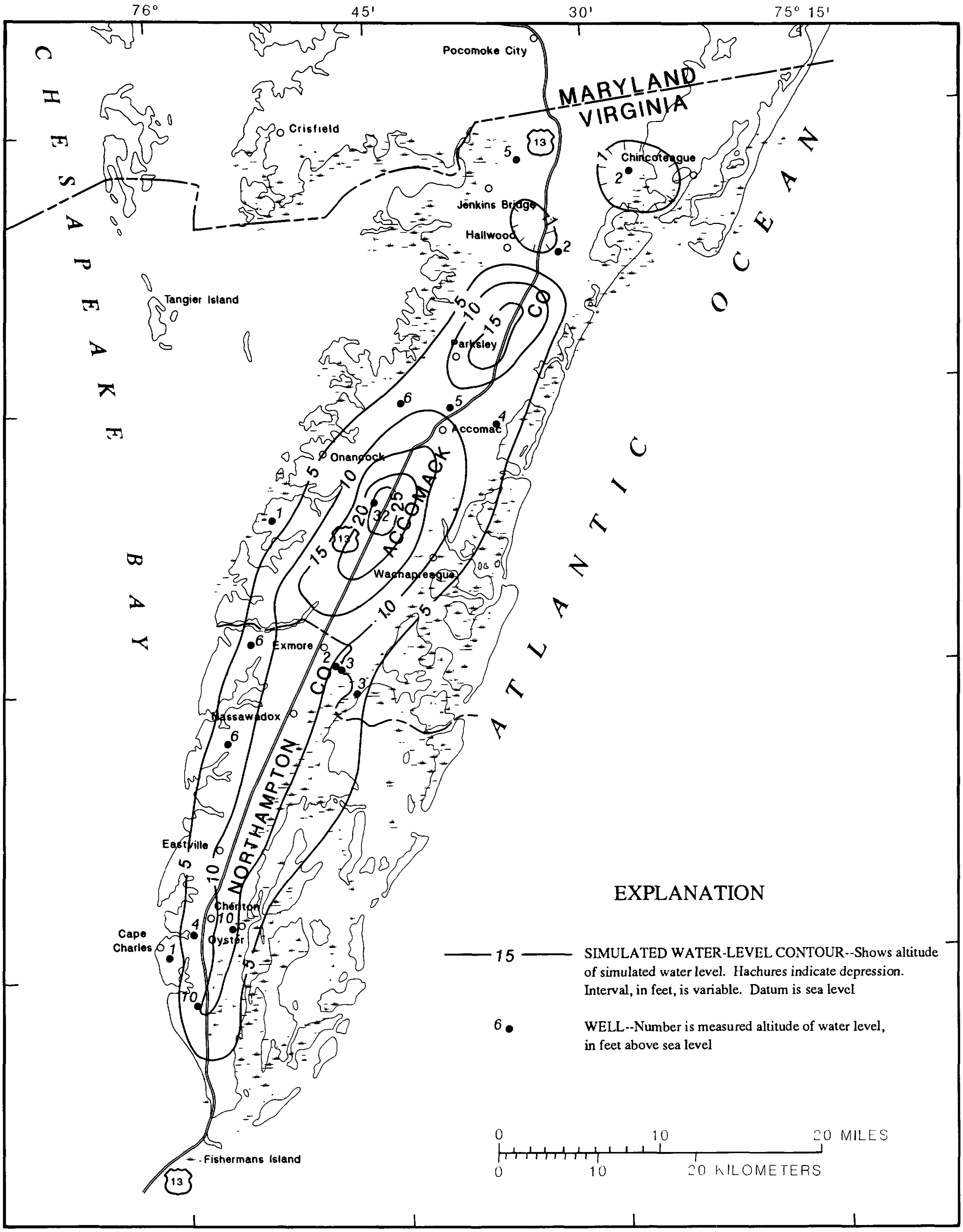


Figure 40. Simulated and measured water levels in the upper Yorktown-Eastover aquifer, 1988.

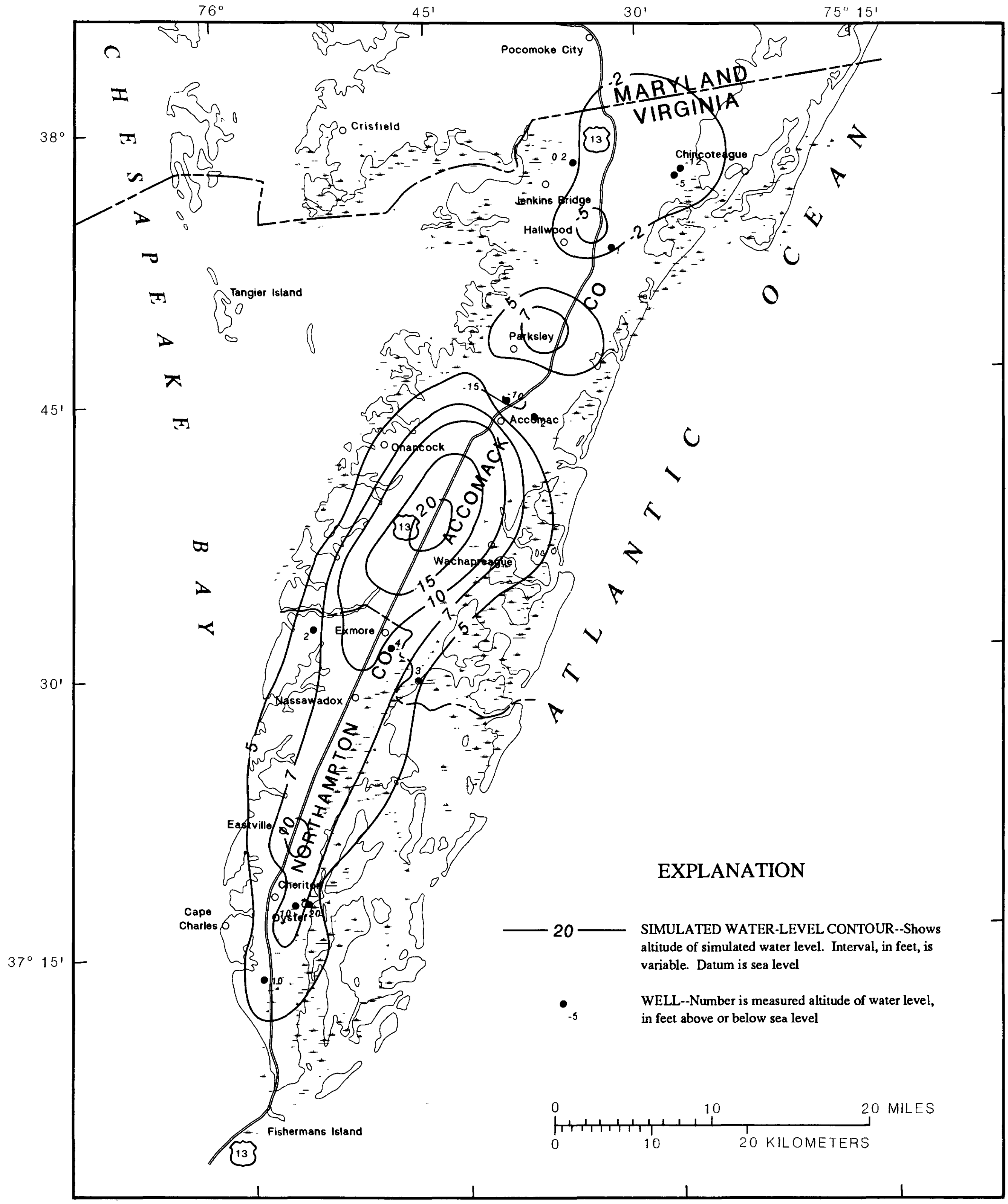


Figure 41. Simulated and measured water levels in the middle Yorktown-Eastover aquifer, 1988.

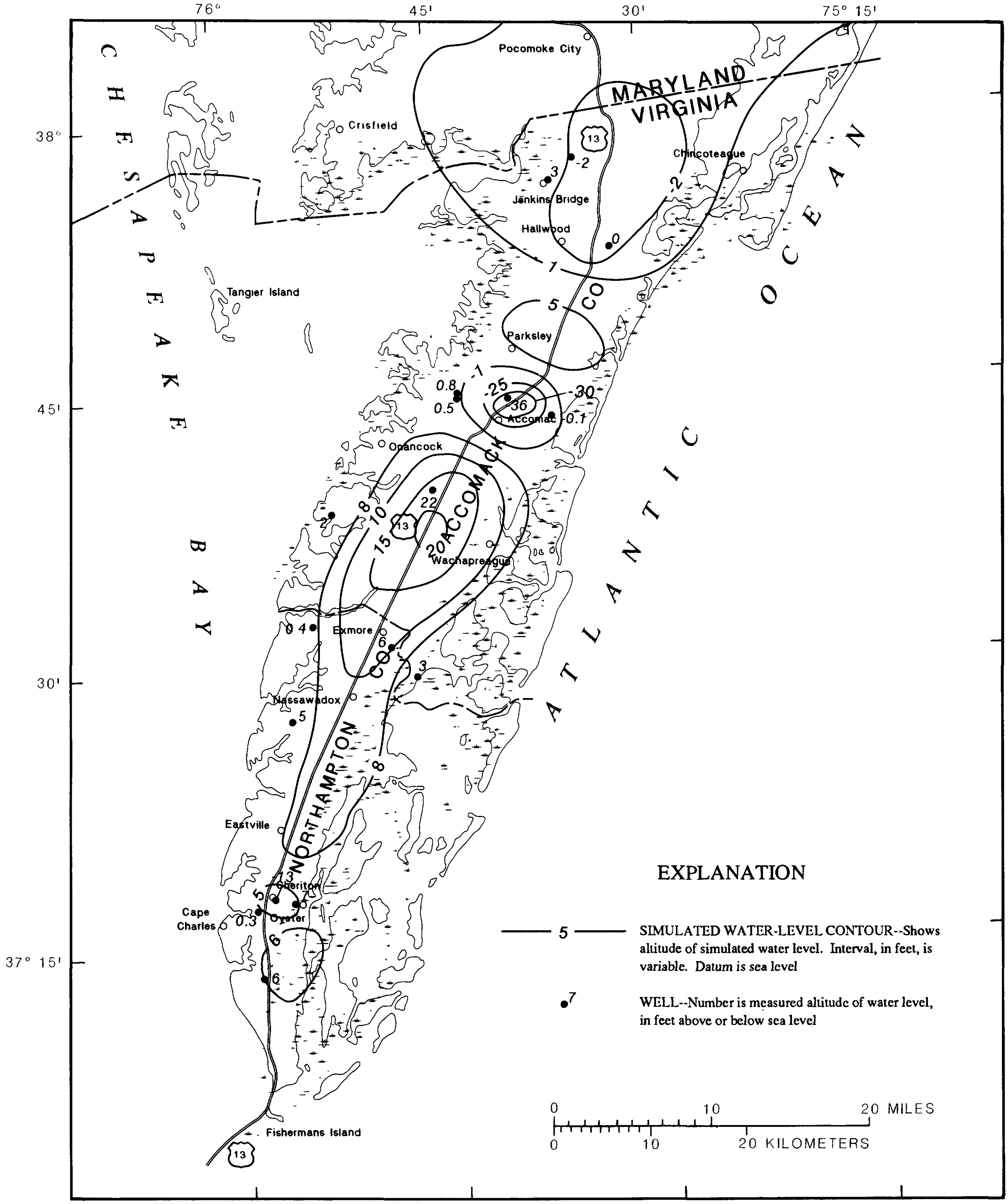


Figure 42. Simulated and measured water levels in the lower Yorktown-Eastover aquifer, 1988.

Table 16. Simulated ground-water budgets for the confined freshwater-flow system

[Modeled values, in million gallons per day, are not intended to imply accuracy to precision shown; the small error between sources and discharges is due to numerical truncation in digital simulation; --, budget component not applicable to the simulation]

Budget component	Simulation						
	Prepumping	1988 conditions	Southern Northampton simulation 1	Southern Northampton simulation 2	Northeastern Accomack simulation 1	Northeastern Accomack simulation 2	Permitted withdrawal
<u>Source</u>							
Recharge to confined system through uppermost confining unit	11.07	13.11	14.93	14.63	14.18	12.84	17.44
Water released from aquifer storage	.00	.64	.87	.96	1.09	1.09	1.92
Lateral boundary constant-head nodes	--	--	--	--	--	1.47	--
Total	11.07	13.75	15.80	15.59	15.27	15.40	19.36
<u>Discharge</u>							
Natural discharge from confined system through uppermost confining unit	11.08	8.64	7.52	7.29	8.11	8.27	5.65
Ground-water withdrawals from wells	.00	5.05	8.24	8.26	7.10	7.10	13.70
Water taken into aquifer storage	.00	.00	.00	.00	.00	.00	.00
Lateral boundary constant-head nodes	--	--	--	--	--	.00	--
Total	11.08	13.69	15.76	15.55	15.21	15.37	19.35

1988 conditions on the Eastern Shore show that there is no potential for downward vertical leakage of saltwater through the upper Yorktown-Eastover confining unit above the freshwater part of the upper Yorktown-Eastover aquifer.

The slow movement of the saltwater-freshwater interface was investigated using a transient simulation that continued 1988 withdrawals for 1,000 years. The model-simulated interface did not reach an equilibrium position for 1988 withdrawals by the end of the 1,000-year simulation period. The simulated position of the saltwater-freshwater interface toe for the 1,000-year run is shown along with the 1988 interface in figures 43–45. The position of the interface toe is shown because it is the most landward extension of the saltwater-freshwater interface. The locations of greatest interface movement in each aquifer correspond to the areas of greatest pumpage. Although the transient simulation from 1940 to 1988 shows no movement of the interface toe from the prepumping steady-state simulation, continuing 1988 withdrawals for 1,000 years causes landward movement of the interface toe along most of the coast in all three aquifers. The interface toe at the southern end of Northampton County in the upper Yorktown-Eastover aquifer (fig. 43) moved approximately 1 mi landward on the bay side of the peninsula and 0.5 mi landward on the ocean side of the peninsula. The interface toe also moved landward approximately 1 mi in the upper Yorktown-Eastover aquifer near the town of Chincoteague. Maximum landward movement of the interface toe is approximately 1.5 mi in the middle Yorktown-Eastover aquifer (fig. 44), also near the town of Chincoteague. The interface toe moves landward a maximum of approximately 1 mi in the lower Yorktown-Eastover aquifer (fig. 45) southwest of Chincoteague. The results of this simulation support previous findings that movement of the saltwater-freshwater interface is slow and takes place over long periods of time. It is important to remember, however, that a sharp-interface model provides no information on the rate of movement of dilute saltwater in the transition zone.

Application of Ground-Water-Flow Model

The prepumping, steady-state-model analysis and the historical transient-model analysis indicate that the model conceptualization is a reasonable representation of the ground-water-flow system of the Eastern Shore. Three scenarios of hypothetical increases in ground-water withdrawals were developed in cooperation with Accomack County, Northampton County, and the VWCB. The results of the simulations of the scenarios are examined to increase our understanding of the response of the ground-water-flow system to additional stress. The simulations are not intended to predict exact ground-water conditions in the future; however, the results provide information that could be useful in evaluating the ground-water resource and its ability to meet future water needs.

Southern Northampton County Scenario

The southern part of Northampton County is experiencing rapid growth. Protection of the ground-water resource in this area is of concern because most of the expected development is in coastal areas that could be susceptible to saltwater intrusion. In this scenario, withdrawals are increased in the southern part of Northampton County, and currently permitted users as well as potential projected users are included. The scenario consists of two separate model simulations that illustrate the effects of increased withdrawals with two different well distributions. In simulation 1, withdrawals are increased to permitted levels at existing well locations, and additional withdrawal wells are placed in the vicinity of expected growth areas (fig. 46). In simulation 2, withdrawals are increased by the same amount but are distributed evenly throughout hypothetical well fields in the center of the peninsula.

Simulation 1

Results from the transient simulation of 1988 conditions were used as initial conditions for a 50-year transient simulation to examine the effects of increased withdrawals in the southern part of Northampton County. A summary of locations and rates of hypothetical withdrawals and aquifers penetrated for the southern part of Northampton County in simulation 1 is presented in table 17. Total withdrawal for the area is 3.761 Mgal/d, which represents an increase of 3.213 Mgal/d over 1988 withdrawal. Withdrawals from existing wells in the southern part of the peninsula are increased to their permitted levels. Additional withdrawal wells were located by the VWCB according to preliminary or expected permit applications (fig. 46). Approximately 57, 29, and 14 percent of the additional

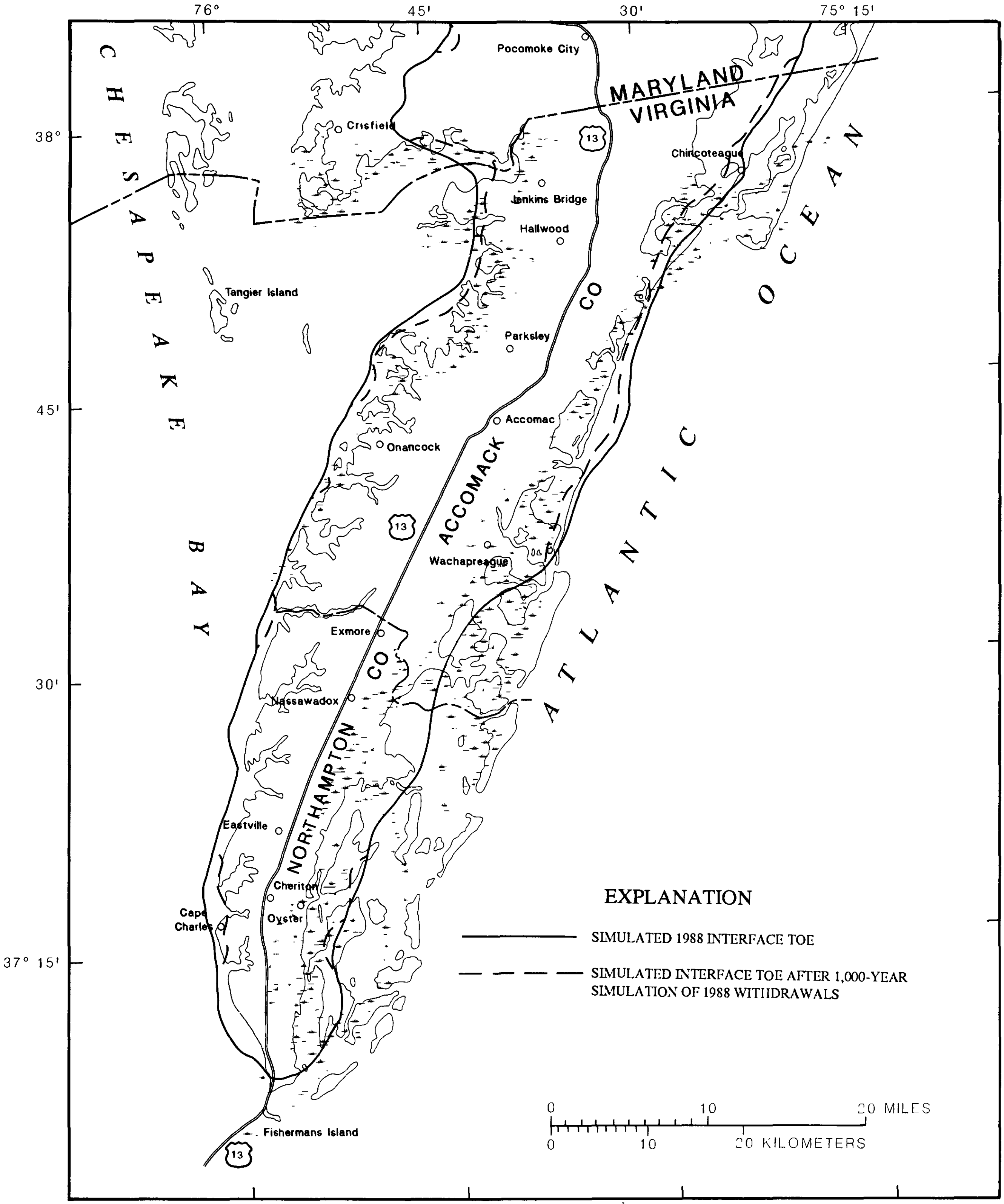


Figure 43. Simulated position of the saltwater-freshwater interface toe for a 1,000-year transient run using 1988 withdrawals in the upper Yorktown-Eastover aquifer.

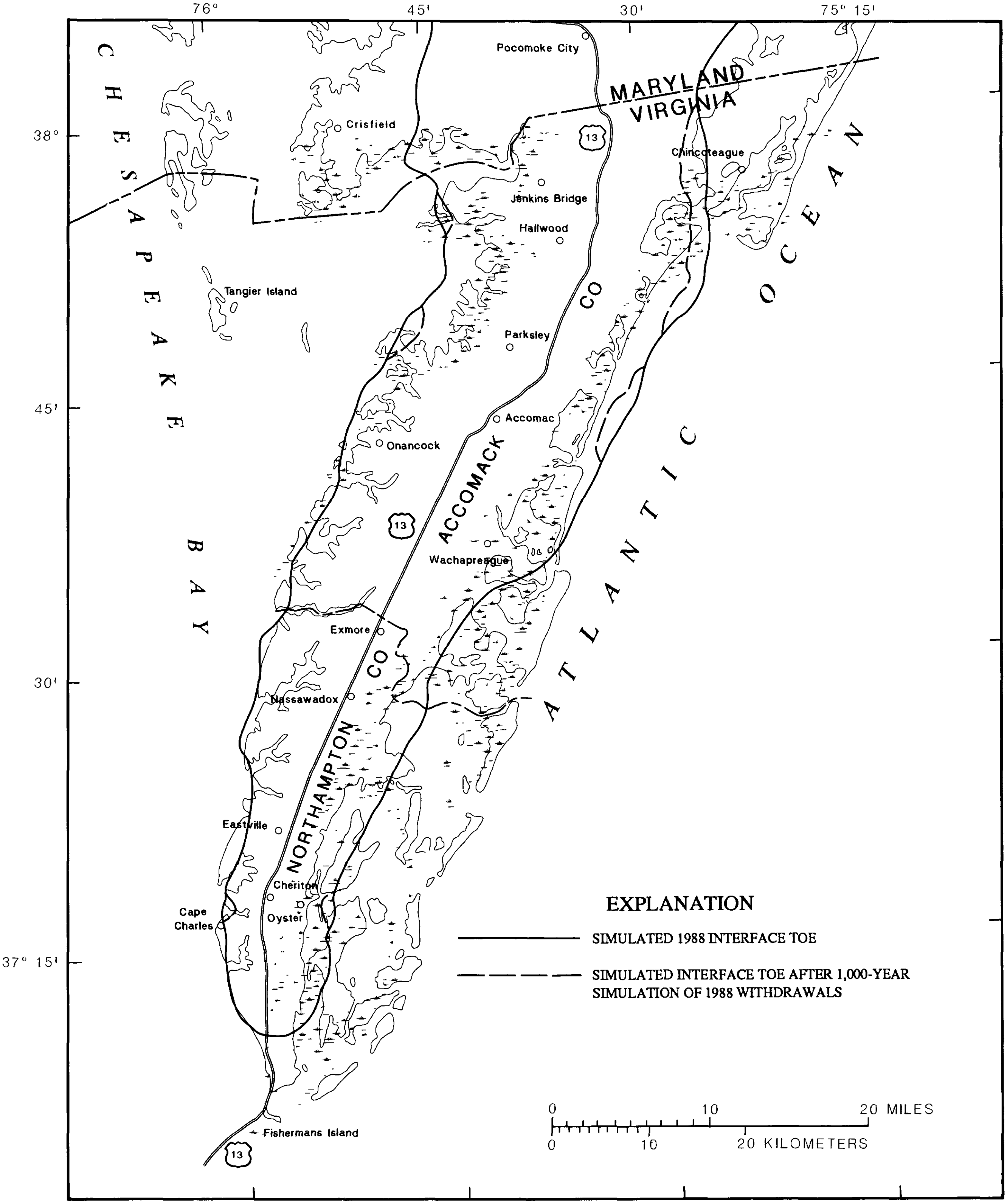


Figure 44. Simulated position of the saltwater-freshwater interface toe for a 1,000-year transient run using 1988 withdrawals in the middle Yorktown-Eastover aquifer.

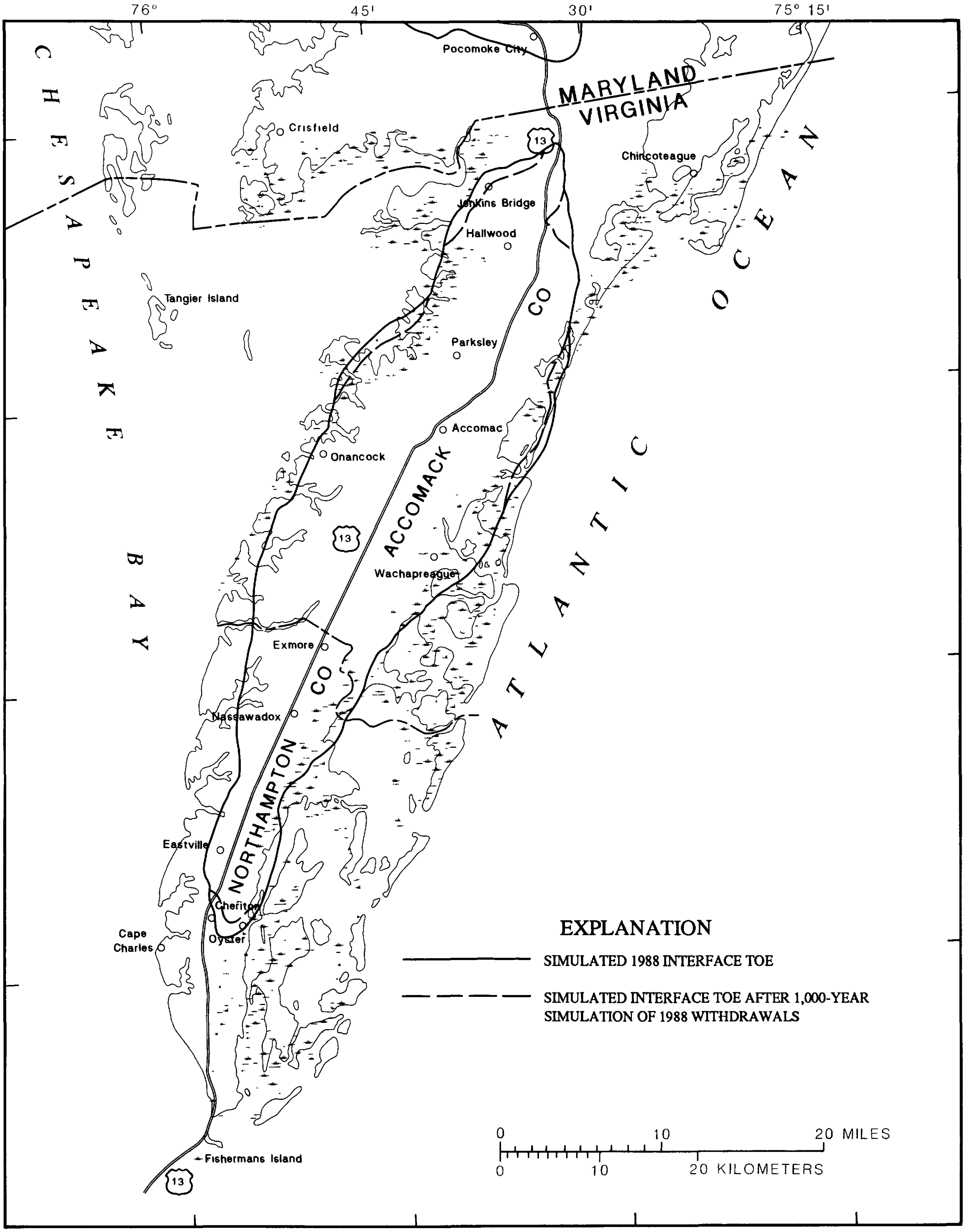


Figure 45. Simulated position of the saltwater-freshwater interface toe for a 1,000-year transient run using 1988 withdrawals in the lower Yorktown-Eastover aquifer.

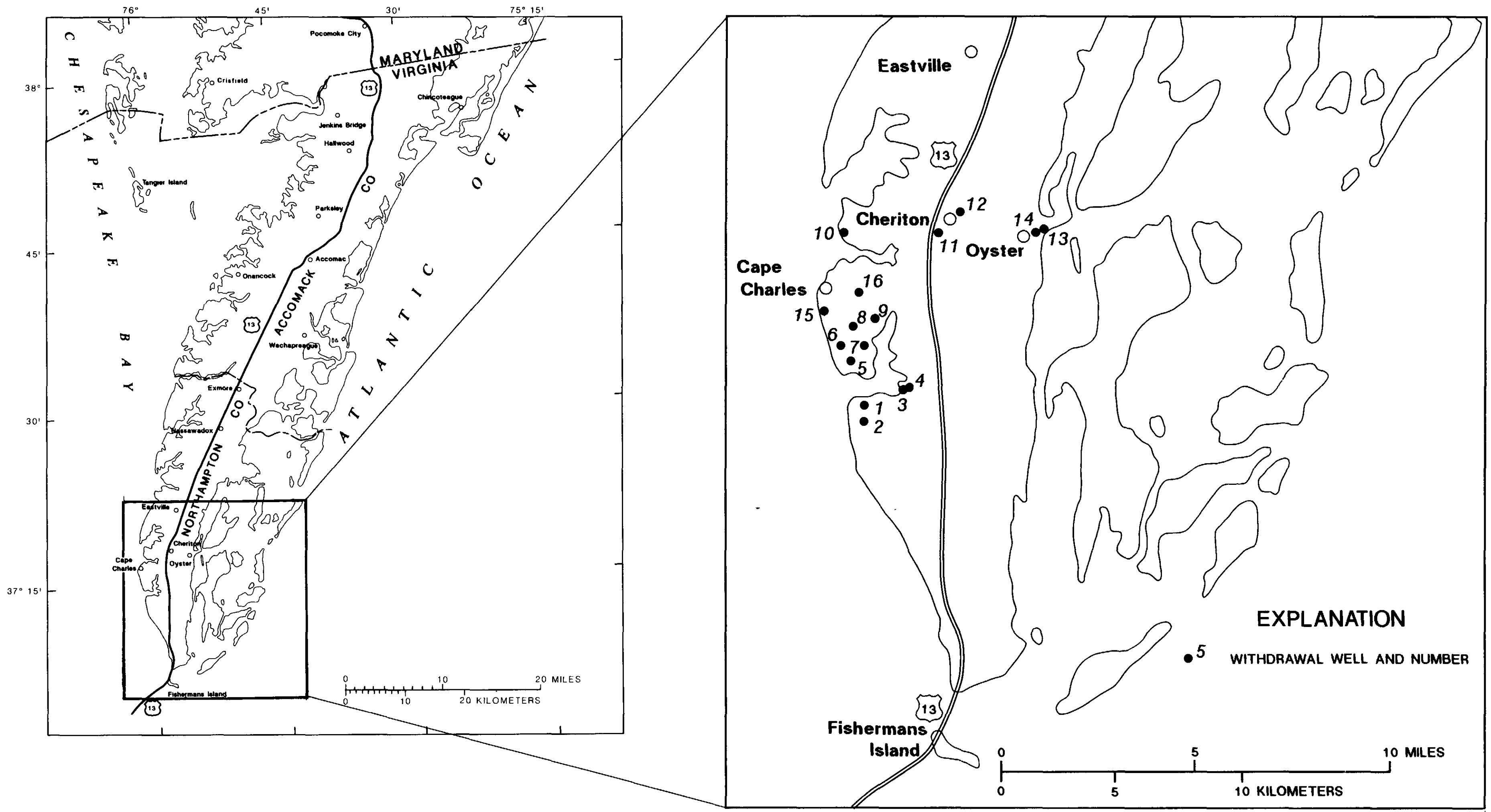


Figure 46. Location of hypothetical withdrawals for the southern Northampton County scenario, simulation 1.

Table 17. Withdrawals for southern Northampton County scenario, simulation 1

[Mgal/d, million gallons per day; latitude and longitude are reported in degrees, arc minutes, arc seconds]

Map number[1]	Latitude	Longitude	Withdrawal (Mgal/d)	Aquifer penetrated
1	37 13 36	076 00 19	0.047	Upper Yorktown-Eastover
2	37 13 14	076 00 21	.047	Upper Yorktown-Eastover
3	37 13 53	075 59 23	.093	Upper Yorktown-Eastover
4	37 13 54	075 59 08	.093	Upper Yorktown-Eastover
5	37 14 35	076 00 34	.200	Upper Yorktown-Eastover
6	37 14 56	076 00 52	.200	Upper Yorktown-Eastover
7	37 14 55	076 00 08	.200	Upper Yorktown-Eastover
8	37 15 20	076 00 31	.200	Upper Yorktown-Eastover
9	37 15 28	075 59 56	.200	Upper Yorktown-Eastover
10	37 17 20	076 00 51	.004	Upper Yorktown-Eastover
11	37 17 20	075 58 10	.190	Upper Yorktown-Eastover
12	37 17 46	075 57 28	1.600	Upper, middle, and lower Yorktown-Eastover
13	37 17 15	075 55 12	.150	Middle Yorktown-Eastover
14	37 17 11	075 55 24	.152	Middle Yorktown-Eastover
15	37 15 40	076 01 21	.125	Upper and middle Yorktown-Eastover
16	37 16 05	076 00 19	.260	Upper and middle Yorktown-Eastover

[1]Locations shown on figure 46.

pumpage comes from the upper, middle, and lower Yorktown-Eastover aquifers, respectively. Pumpage for the rest of the model area is held constant at the average pumping rate for the final pumping period (pumping period 12) in the historic transient simulation. Total withdrawals for the entire model area for simulation 1 are greatest in the upper Yorktown-Eastover aquifer and least in the lower Yorktown-Eastover aquifer (table 18).

The hypothetical increased pumpage in the southern part of Northampton County results in water-level declines of greater than 15 ft in each of the confined freshwater aquifers (figs. 47–49). The maximum water-level decline for the upper Yorktown-Eastover aquifer is 16.2 ft near the town of Cape Charles. Maximum water-level declines of 38.8 and 48.7 ft occur east of the town of Cheriton for the middle and lower Yorktown-Eastover aquifers, respectively (table 19). The predicted declines are in addition to declines caused by ground-water withdrawals in 1988. Simulated water levels throughout the model area remain above the tops of the aquifers, indicating that dewatering would not occur at this rate and distribution of withdrawal.

The majority of the water for the increased ground-water withdrawal is provided by an increase in the amount of recharge entering the confined system and a decrease in the amount of discharge leaving the confined system (table 16). The simulated water budget presented in table 16 is for the confined freshwater-flow system; the withdrawal amounts are slightly less than the total ground-water withdrawals for the simulations (table 18) because a small part of the withdrawals are from the saltwater-flow system. The increase in freshwater withdrawal of 3.19 Mgal/d in the southern part of Northampton County causes a 1.82 Mgal/d increase in the amount of recharge to the confined aquifer system over 1988 conditions. The amount of natural discharge from the confined aquifers is reduced by 1.12 Mgal/d from 1988 conditions.

The 50-year simulation of increased pumpage in southern Northampton County results in slight landward movement of the simulated saltwater-freshwater interface on the Chesapeake Bay side of the peninsula off Cape Charles (figs. 47–49). The interface toe in the upper Yorktown-Eastover aquifer moves inland from the 1988 interface toe position along approximately 12 mi of the western coastline in southern Northampton County (fig. 47); maximum landward movement is approximately 1 mi. The simulated position of the interface toe in the middle Yorktown-Eastover aquifer does not change in response to the hypothetical increase in withdrawals. Slight landward movement of the saltwater-freshwater interface toe occurs in the lower Yorktown-Eastover aquifer (fig. 49). The simulated 1988 interface toe position is onshore at this loca-

Table 18. Withdrawal by aquifer for model scenarios
[Values in millions of gallons per day]

Aquifer	Pumping period 12 (1987–88)	Scenario: Southern Northampton simulation 1	Scenario: Southern Northampton simulation 2	Scenario: Northeastern Accomack simulations 1&2	Scenario: Permitted withdrawal
Upper Yorktown-Eastover	1.888	3.801	2.951	2.531	4.446
Middle Yorktown-Eastover	2.103	2.915	3.088	3.431	6.959
Lower Yorktown-Eastover	1.070	1.558	2.235	1.201	2.419
Total	5.061	8.274	8.274	7.163	13.824

Table 19. Maximum water-level decline from 1988 flow conditions for model scenarios

Aquifer	Decline (feet)	Grid row	Grid column	Approximate areal location
		Southern Northampton County simulation 1		
Upper Yorktown-Eastover	16.2	85	24	Town of Cape Charles
Middle Yorktown-Eastover	38.8	80	29	East of Cheriton
Lower Yorktown-Eastover	48.7	80	26	Town of Cheriton
		Southern Northampton County simulation 2		
Upper Yorktown-Eastover	8.0	68	26	Town of Nassawadox
Middle Yorktown-Eastover	22.0	76	26	Town of Eastville
Lower Yorktown-Eastover	22.4	76	26	Town of Eastville
		Northeastern Accomack County simulation 1		
Upper Yorktown-Eastover	17.2	19	34	Town of Hallwood
Middle Yorktown-Eastover	29.7	19	34	Town of Hallwood
Lower Yorktown-Eastover	26.4	19	34	Town of Hallwood
		Northeastern Accomack County simulation 2		
Upper Yorktown-Eastover	15.8	19	34	Town of Hallwood
Middle Yorktown-Eastover	27.9	19	34	Town of Hallwood
Lower Yorktown-Eastover	24.6	19	34	Town of Hallwood
		Permitted withdrawal		
Upper Yorktown-Eastover	29.1	56	28	Town of Exmore
Middle Yorktown-Eastover	95.3	56	28	Town of Exmore
Lower Yorktown-Eastover	68.0	34	32	Town of Accomac

tion on the southern tip of the peninsula. The hypothetical increase in withdrawals causes the western boundary of the 1988 interface position to move approximately 0.5 mi in the lower Yorktown-Eastover aquifer.

Although saltwater intrusion due to horizontal movement of the saltwater-freshwater interface takes place over long periods of time, saltwater intrusion due to induced downward vertical leakage can occur rapidly as a result of large changes in head gradient. Simulated water levels show offshore water-level declines that cause a reversal of ground-water flow from 1988 conditions (fig. 47). Simulated water-level declines in the upper Yorktown-Eastover aquifer show that the increased withdrawals on the coast cause drawdowns of greater than 5 ft to extend offshore. The area of reversed flow indicates a potential for downward vertical leakage of saltwater from the Chesapeake Bay and nearshore estuaries into the freshwater part of the upper Yorktown-Eastover aquifer. The amount of saltwater that is introduced into the freshwater system vertically through the confining unit is probably relatively small; however, salt concentrations could be high and could significantly affect the quality of the water withdrawn. This area is further complicated because of the present-day channel in the Chesapeake Bay (figs. 3 and 11). The upper Yorktown-Eastover confining unit probably has been eroded, and rates of saltwater intrusion could be increased because of a direct

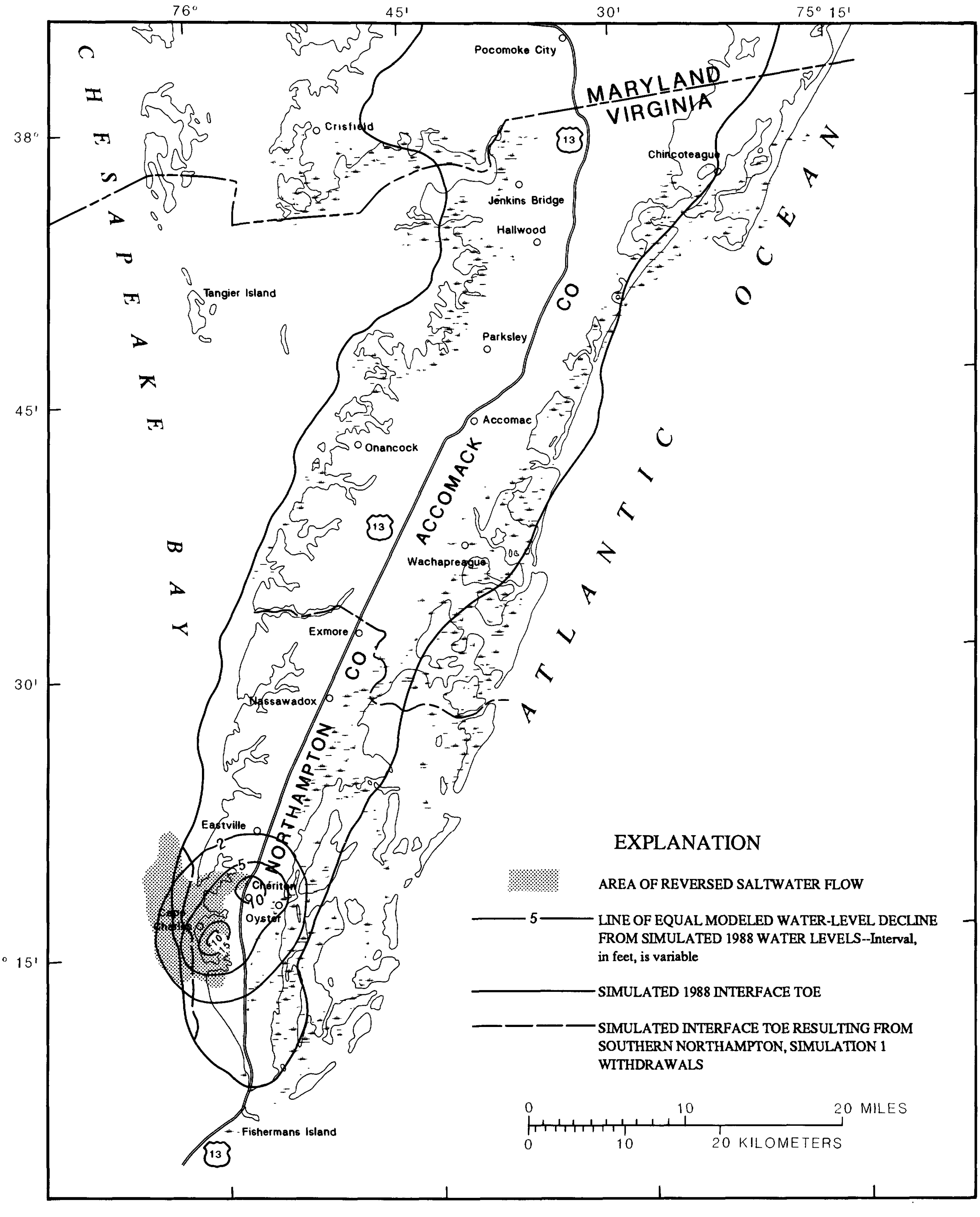


Figure 47. Water-level decline from simulated 1988 water levels, simulated position of the saltwater-freshwater interface toe, and area of reversed saltwater flow in the upper Yorktown-Eastover aquifer, southern Northampton County scenario, simulation 1.

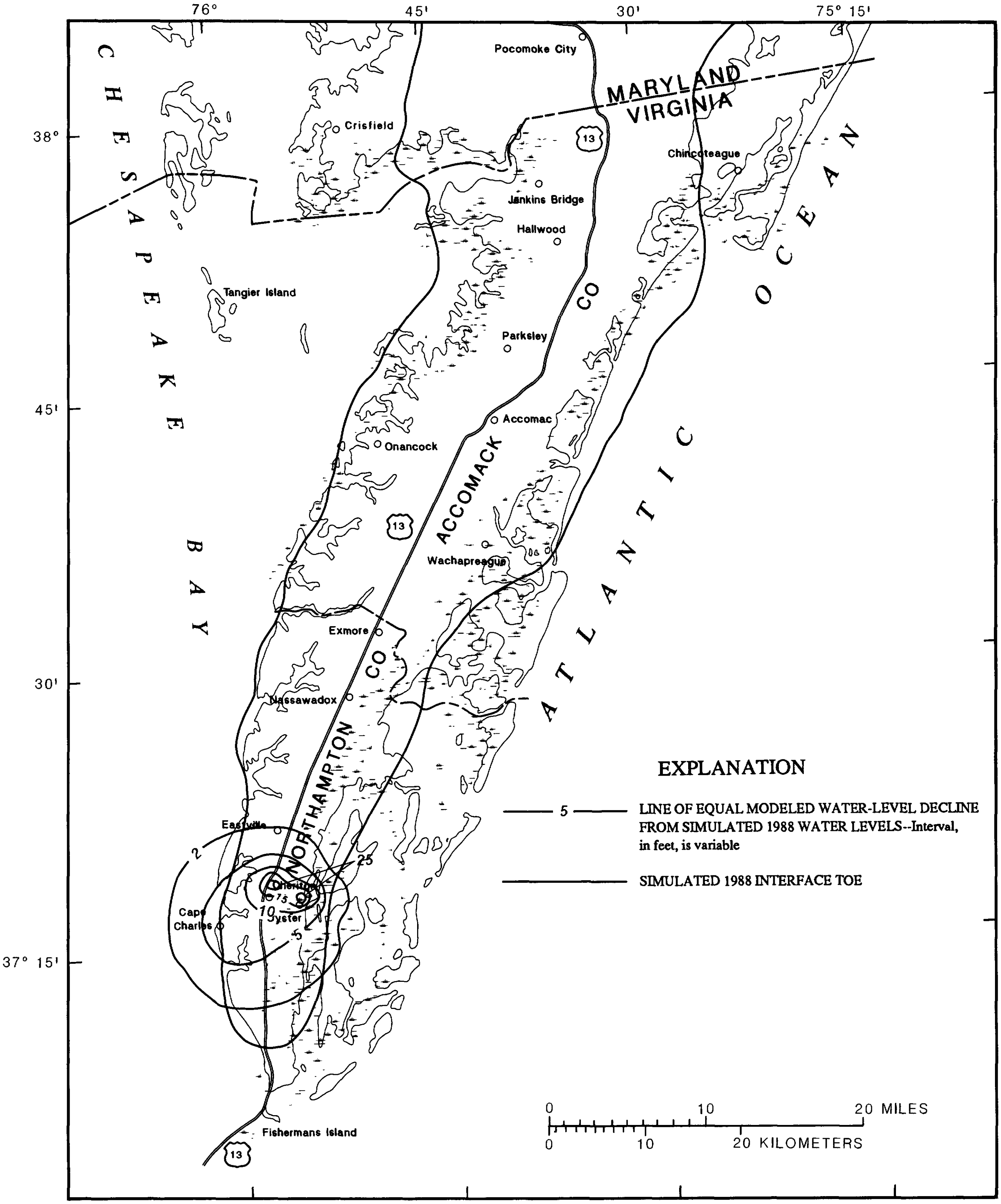


Figure 48. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the middle Yorktown-Eastover aquifer, southern Northampton County scenario, simulation 1.

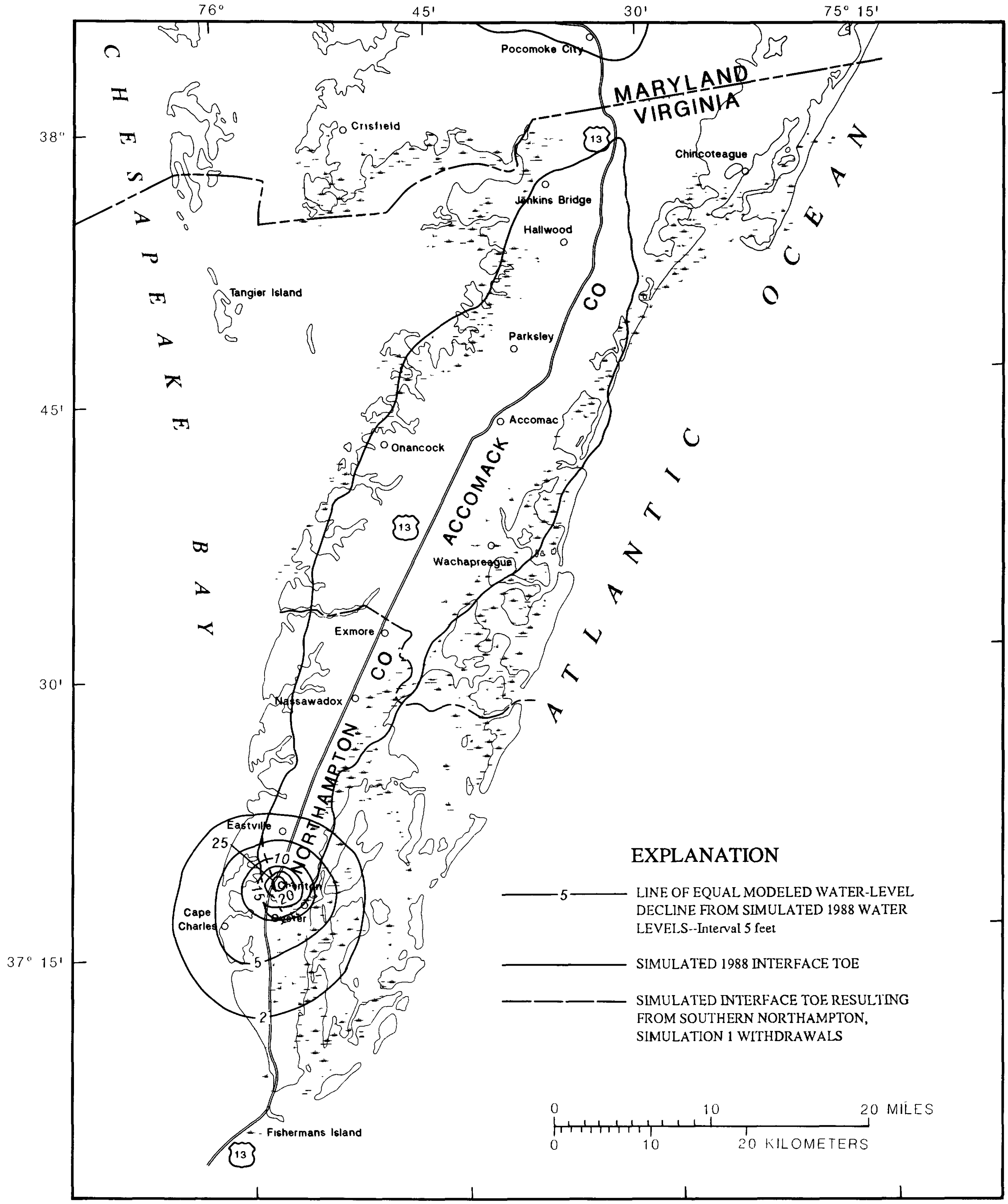


Figure 49. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the lower Yorktown-Eastover aquifer, southern Northampton County scenario, simulation 1.

connection between the upper Yorktown-Eastover aquifer and the saltwater in the Chesapeake Bay. The model results indicate that the hypothetical increase in pumpage in southern Northampton County at current well locations could create water-quality problems. Heavy pumpage along the coast in the upper Yorktown-Eastover aquifer could cause water levels to decline offshore and induce leakage of saltwater from the Chesapeake Bay into the freshwater part of the aquifer. The amount of water-quality degradation that could result from this process cannot be quantified by this study. Model results indicate that this is a potential concern and needs to be considered in future studies.

Simulation 2

In the second simulation, withdrawals are increased in southern Northampton County by the same amount as simulation 1; however, the withdrawals are removed from the coast and redistributed throughout Northampton County to hypothetical well fields in the center of the peninsula. The total withdrawal for the area is divided equally among 10 hypothetical well fields and is distributed equally among all three confined aquifers (table 20). Pumpage for the rest of the model area is held constant at the average pumping rate for the final pumping period in the historic transient simulation (1987–88). As in the previous simulation, the results of the transient simulation of 1988 conditions are used as initial conditions, and the simulation is continued for a period of 50 years. Withdrawals by aquifer are presented in table 18 for all of the model scenarios.

Modeled water-level declines from simulated 1988 water levels are shown in figures 50–52. Declines are centered in the middle of the peninsula, and the maximum water-level declines are 8.0, 22.0, and 22.4 ft for the upper, middle, and lower Yorktown-Eastover aquifers, respectively (table 19). Since pumpage is no longer concentrated in the Cape Charles area, water-level declines are smaller in each aquifer for simulation 2 than they are in simulation 1. Water-level declines are greatest in the lower Yorktown-Eastover aquifer because transmissivities are smaller there than in the middle or upper Yorktown-Eastover aquifers. The placement of the wells in the center of the peninsula causes the water-level contours to follow the shape of the peninsula, and less drawdown occurs in offshore areas. As in simulation 1, the simulated water levels throughout the model area remain above the top of the aquifers.

Table 20. Location of southern Northampton scenario withdrawals, simulation 2
[Mgal/d, million gallons per day]

Grid location		Withdrawal (Mgal/d)	Aquifer
Row	Column		
64	26	0.376	Upper, middle, and lower Yorktown-Eastover
66	26	.376	Upper, middle, and lower Yorktown-Eastover
68	26	.376	Upper, middle, and lower Yorktown-Eastover
70	26	.376	Upper, middle, and lower Yorktown-Eastover
72	26	.376	Upper, middle, and lower Yorktown-Eastover
74	26	.376	Upper, middle, and lower Yorktown-Eastover
76	26	.376	Upper, middle, and lower Yorktown-Eastover
78	26	.376	Upper, middle, and lower Yorktown-Eastover
80	26	.376	Upper, middle, and lower Yorktown-Eastover
82	26	.376	Upper, middle, and lower Yorktown-Eastover

The simulated ground-water budgets for the freshwater-flow system indicate recharge to the confined system increases by 1.52 Mgal/d over 1988 conditions, whereas natural discharge from the confined aquifers decreases by 1.35 Mgal/d from the simulated 1988 discharge rate (table 16). The change in flow through the system is a result of the 3.21 Mgal/d increase in freshwater withdrawals over 1988 rates. Although the total ground-water withdrawal for simulation 1 is identical to simulation 2, the freshwater withdrawal is slightly less. The withdrawal locations in simulation 1 are near the coast and result in more withdrawal from the saltwater-flow system. A comparison of recharge and discharge for the two southern Northampton simulations shows that the same withdrawal amount and a different areal distribution can produce a change in the flux through the system. Slightly less water (0.30 Mgal/d) enters the confined system in simulation 2, and slightly less water (0.23 Mgal/d) is discharged naturally from the confined system. The decrease in flow through the system in simulation 2 is balanced by a small increase in the amount of water that is released from aquifer storage (table 16).

Slight landward movement of the simulated saltwater-freshwater interface from the 1988 position occurs during the 50-year transient simulation in the upper Yorktown-Eastover aquifer (fig. 50). The interface position for the middle and lower Yorktown-Eastover aquifers does not change from

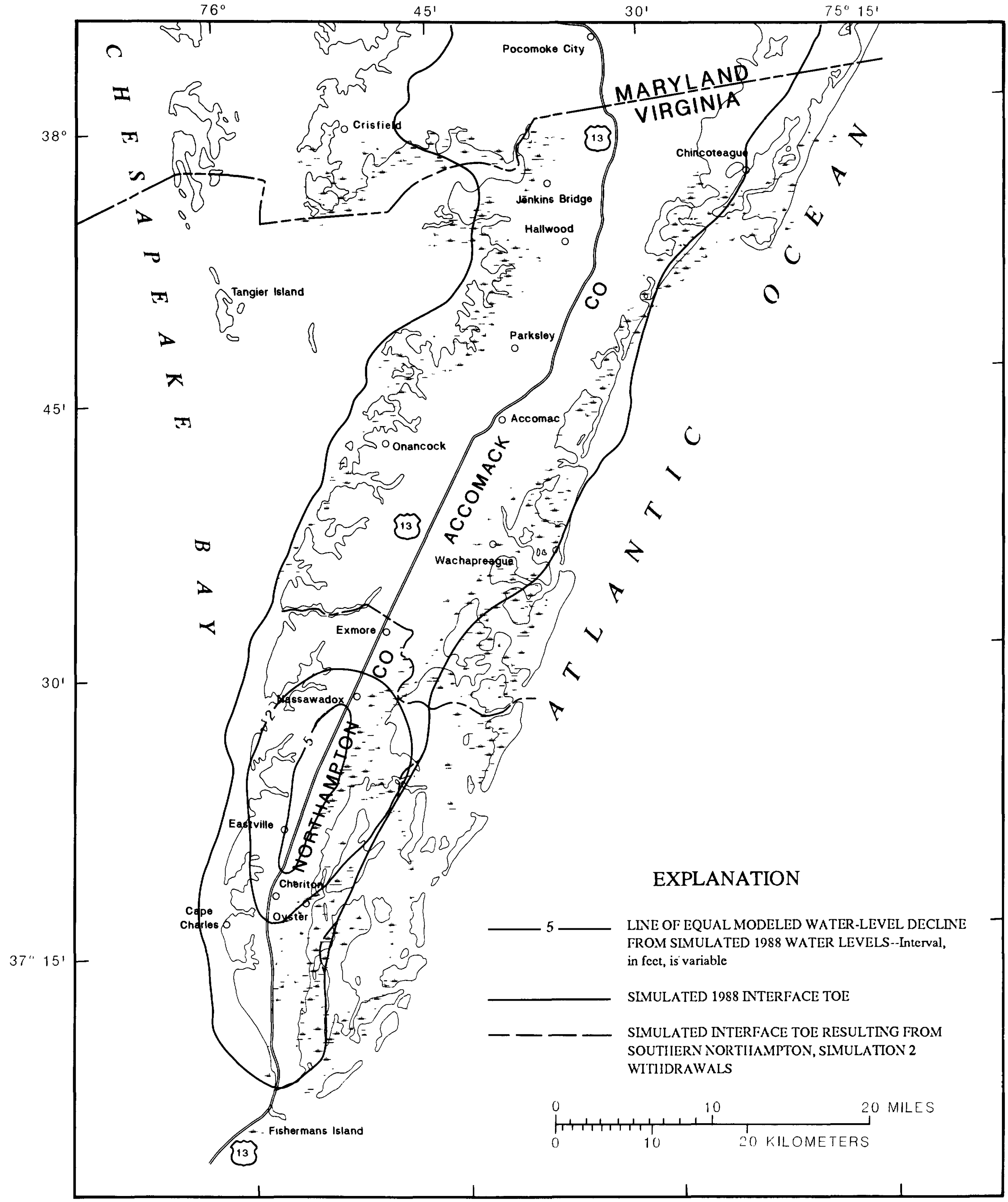


Figure 50. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the upper Yorktown-Eastover aquifer, southern Northampton County scenario, simulation 2.

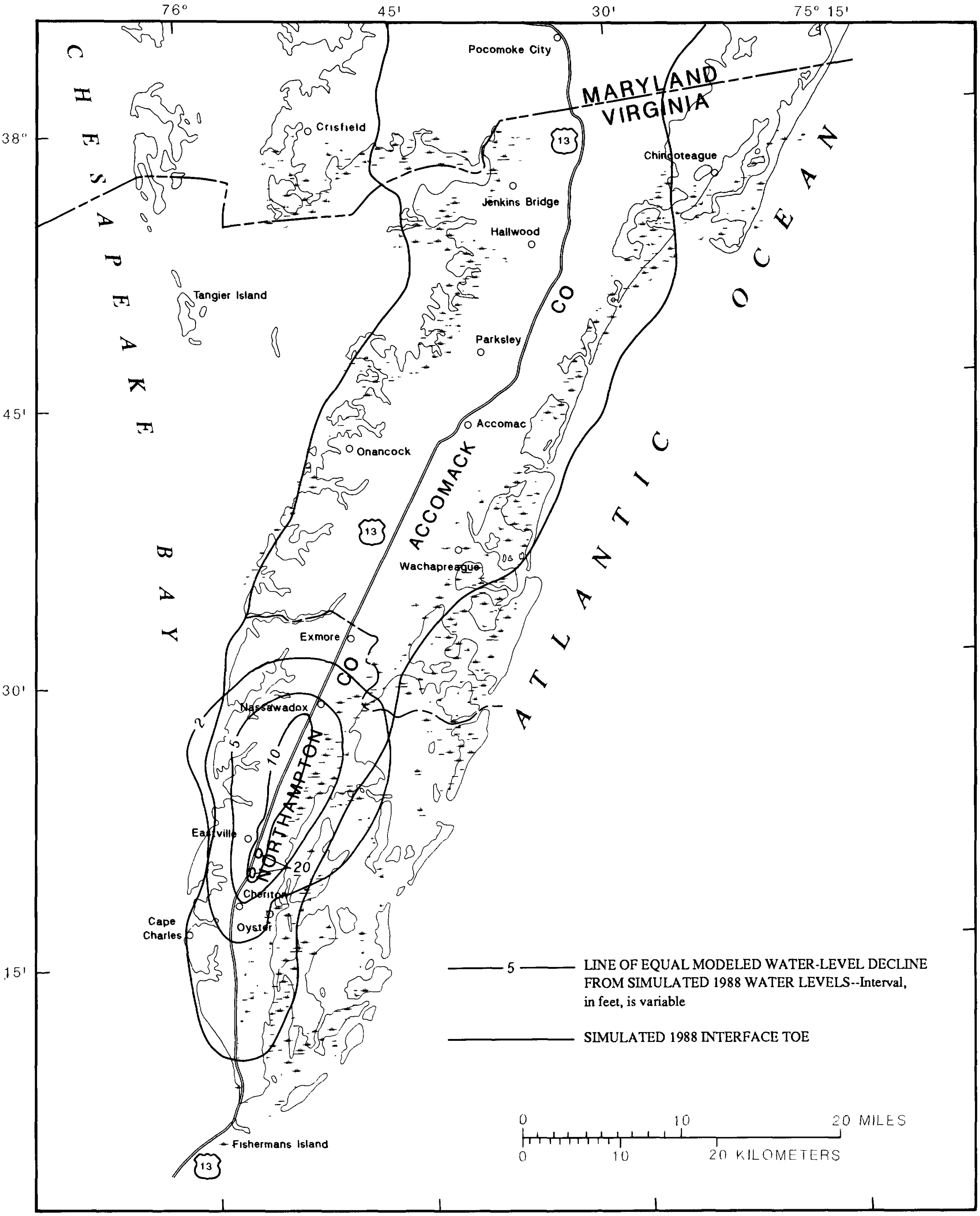


Figure 51. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the middle Yorktown-Eastover aquifer, southern Northampton County scenario, simulation 2.

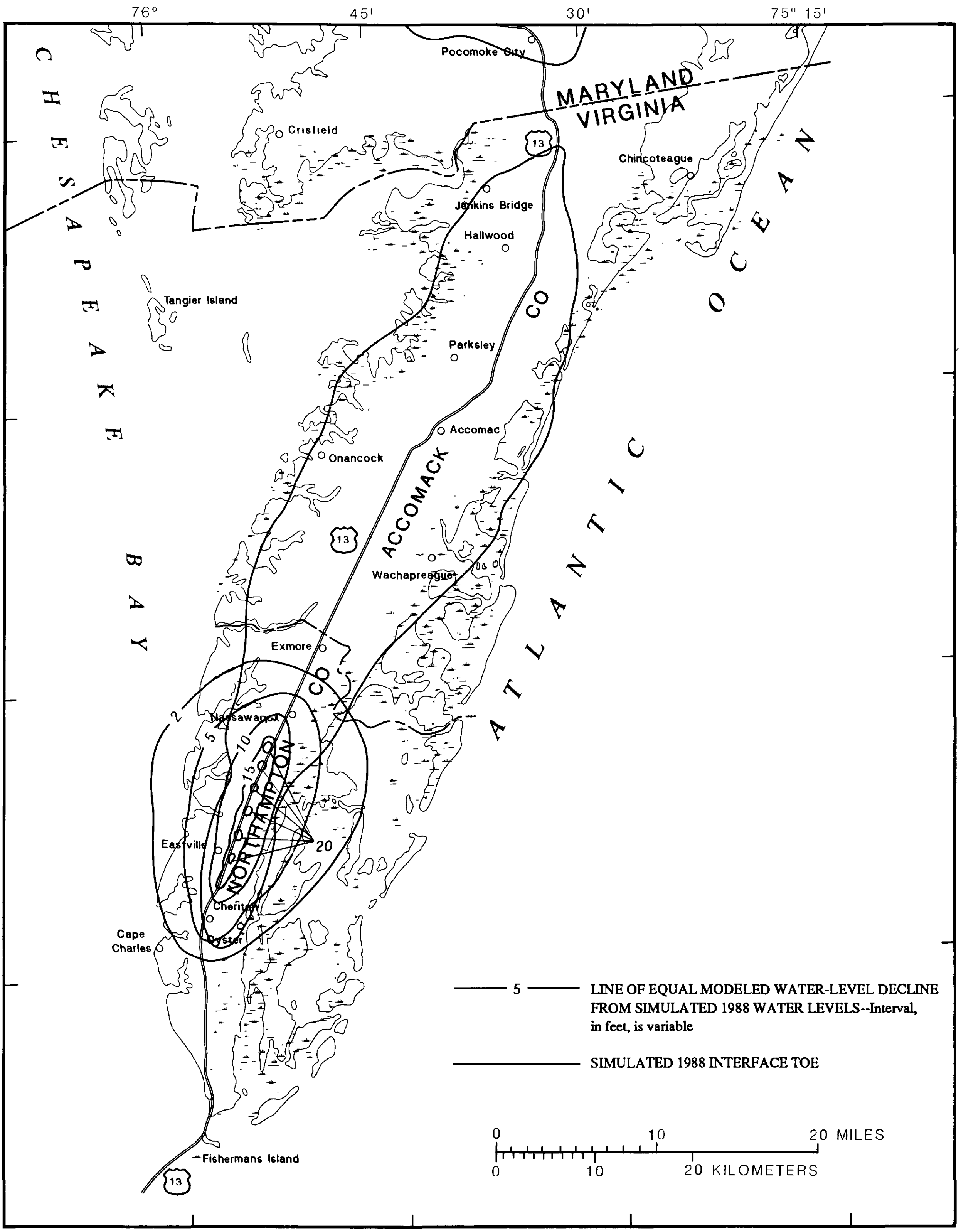


Figure 52. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the lower Yorktown-Eastover aquifer, southern Northampton County scenario, simulation 2.

the 1988 position. The simulated interface toe moves landward a maximum of approximately 0.5 mi in the upper Yorktown-Eastover aquifer. Although the position of the interface does not move as much as it did in simulation 1, this model result illustrates the sensitivity of the fresh-ground-water system in southern Northampton County. The additional withdrawal of 3.21 Mgal/d results in some movement of the saltwater-freshwater interface in the uppermost confined aquifer, even with well fields placed as far away from the interface as possible. The peninsula in this area is narrow (4–5 mi wide), which limits its ability to sustain large ground-water withdrawals.

Simulated water levels show that saltwater intrusion into the uppermost confined aquifer through downward vertical leakage does not occur when withdrawals are distributed equally to all three aquifers and placed in the center of the peninsula. Freshwater is flowing from the upper Yorktown-Eastover aquifer; water-level declines offshore are not large enough to reverse the hydraulic gradient and induce saltwater leakage through the confining unit.

Northeastern Accomack County Scenario

Chincoteague Island is a popular tourist location in northeastern Accomack County that requires a large supply of freshwater in the summer months. This area is on the easternmost boundary of the Eastern Shore's freshwater-flow system and has a high potential for water-quality degradation by saltwater intrusion. The northeastern part of Accomack County has several major ground-water users, and in this scenario, the response of the ground-water-flow system to increased withdrawals is examined.

Two simulations are included in this scenario in order to evaluate model-boundary effects. The scenario consists of large increases in withdrawals over calibrated 1988 conditions in the northeastern corner of the model grid. At this level of withdrawal, the effects of the increased stress extend to the northern and eastern boundary of the model; therefore, the results of the simulation are affected by the model-boundary conditions. The boundary effects were quantified by simulating two different types of boundary conditions. In simulation 1, a no-flow boundary (no water available across the boundary) is used to represent the most severe case, namely, maximum water-level decline. In simulation 2, a constant-head boundary (an unlimited supply of water across the boundary) is used to represent a less severe case, or minimum water-level decline. The response of the actual ground-water system would most likely fall somewhere between the two cases.

The initial conditions for both 50-year transient simulations of increased withdrawals in northeastern Accomack County are provided by the results of the transient simulation of 1988 conditions. Withdrawal locations are near the shore of the peninsula (fig. 53); the total hypothetical withdrawal for the area is 3.5 Mgal/d (table 21), an increase of 2.05 Mgal/d over 1988 withdrawals. Approximately 31, 63, and 6 percent of the total withdrawals come from the upper, middle, and lower Yorktown-Eastover aquifers, respectively (table 18). Pumpage for the rest of the model area was held constant at the average pumping rate for the final pumping period in the historic transient simulation (1987–88). The withdrawals for these scenarios are concentrated in the upper two aquifers because the area is too far east to obtain good-quality water from the lower Yorktown-Eastover aquifer. Many of the withdrawals in this area come from the unconfined aquifer, which is not included in this model; therefore, the pumpage for simulations 1 and 2 is lower than the total projected increase for the northeastern part of Accomack County.

Simulation 1: No-Flow Boundary

The results of simulation 1 show that modeled water levels decline from simulated 1988 water levels throughout much of the northern model area (figs. 54–56). The maximum water-level declines are 17.2, 29.7, and 26.4 ft for the upper, middle, and lower Yorktown-Eastover aquifers, respectively (table 19). The location of the maximum water-level decline is near the town of Hallwood for all three aquifers. Simulated water levels are above the tops of the aquifers, indicating that the dewatering of the confined aquifers is not a concern for this simulation.

The simulated ground-water budget for the freshwater-flow system is presented in table 16. The increase in freshwater withdrawals of 2.05 Mgal/d over 1988 amounts results in a 1.07 Mgal/d increase in flow into the confined system and a 0.53 Mgal/d decrease in natural flow out of the confined system.

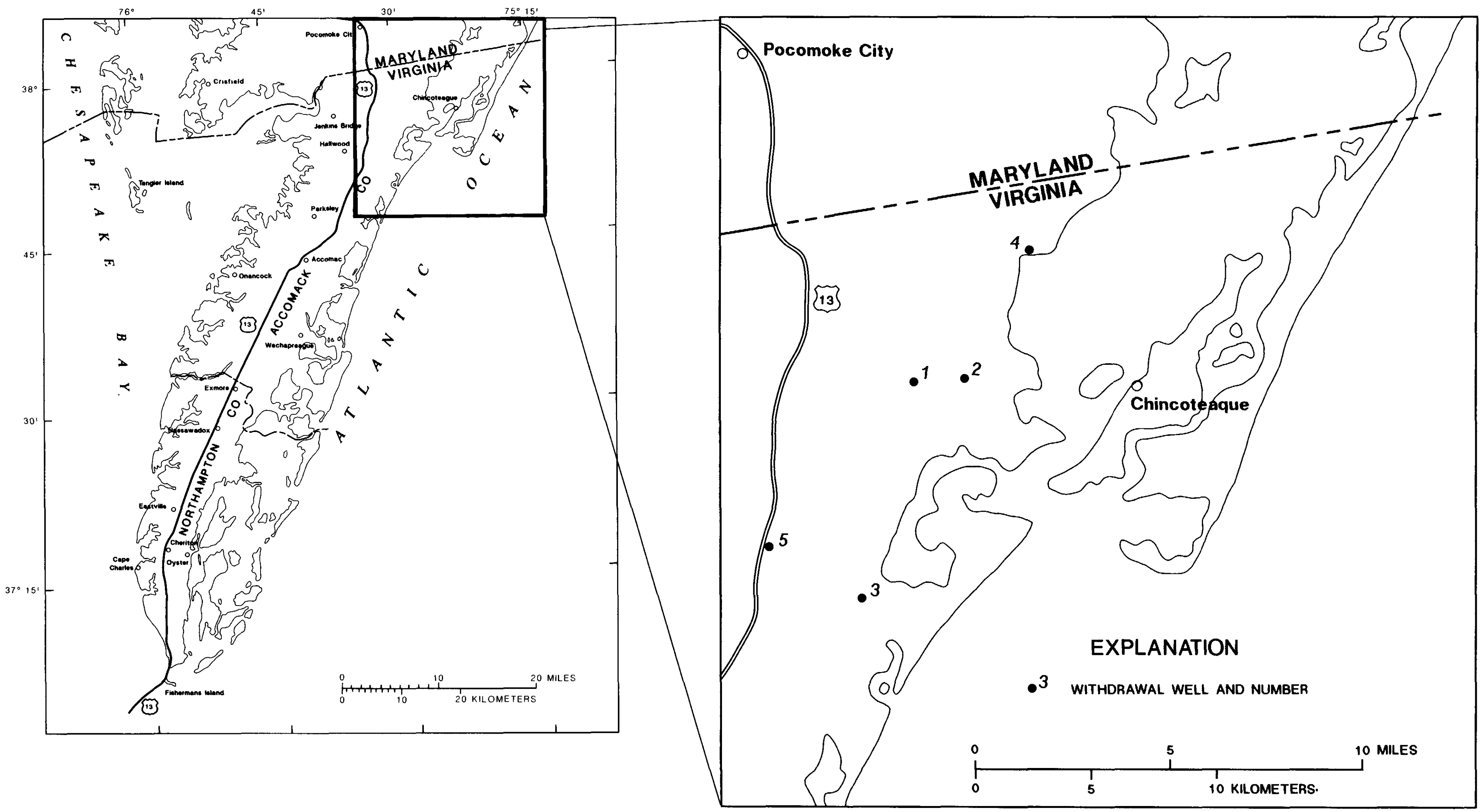


Figure 53. Location of hypothetical withdrawals in the northeastern Accomack County scenarios.

Table 21. Hypothetical withdrawals for the northeastern Accomack County scenario

[Mgal/d, million gallons per day; latitude and longitude are reported in degrees, arc minutes, arc seconds]

Map number [1]	Latitude	Longitude	Withdrawal (Mgal/d)	Yorktown-Eastover aquifer penetrated
1	37 56 26	075 28 44	0.314	Upper, middle
2	37 56 26	075 27 23	1.217	Upper, middle
3	37 51 34	075 30 41	.128	Upper
4	37 59 11	075 25 28	.055	Upper, middle
5	37 52 56	075 33 24	1.800	Upper, middle, and lower

[1]Locations shown on figure 53.

Simulation of the increase in withdrawals in the northeastern part of Accomack County with a no-flow boundary condition results in a slight landward movement of the simulated saltwater-freshwater interface in the upper and middle Yorktown-Eastover aquifers (figs. 54–56). The interface toe moves approximately 0.5 mi landward in the upper and middle Yorktown-Eastover aquifers. The interface position in the lower Yorktown-Eastover aquifer does not change from the simulated 1988 position during this 50-year simulation.

Simulated water levels indicate several areas in northern Accomack County where offshore water-level declines resulting from the hypothetical increase in ground-water withdrawal have caused a reversal in ground-water flow from 1988 conditions (fig. 54). There is a potential for downward vertical leakage of saltwater into the freshwater part of the upper Yorktown-Eastover aquifer as a result of the increase in withdrawals in northeastern Accomack County.

Simulation 2: Constant-Head Boundary

Simulation 2 is identical to simulation 1 except that the northern and northeastern grid boundaries in simulation 2 are represented by a constant-head boundary instead of a no-flow boundary. The water levels for the boundary nodes are held constant at the simulated 1988 values of the nearest nodes. This type of boundary condition provides an unlimited source of water; therefore, the results indicate smaller head declines in simulation 2 than in simulation 1 from an increase in pumpage.

The water-level declines for the constant-head simulation are presented in figures 57–59. Comparison with figures 54–56 shows water-level declines north and northeast of the pumping center are less in the constant-head simulation (simulation 2) than in the no-flow simulation (simulation 1). Although the boundary conditions influence water levels in the north and northeastern part of the model area, water-level declines in the Virginia part of the Eastern Shore are similar for both simulations, indicating that the boundary conditions do not greatly affect results in the study area. The maximum water-level declines are 15.8, 27.9, and 24.6 ft in the upper, middle, and lower Yorktown-Eastover aquifers, respectively (table 19). The location of the maximum water-level declines is near the town of Hallwood for all three aquifers. The maximum water-level declines in simulation 2 differ from those in simulation 1 by less than 2 ft in all three aquifers. As in simulation 1, the water levels are above the tops of the aquifers throughout the model area.

The amount of ground-water flow through the system in simulation 2 is affected by the constant-head boundary condition (table 16). The flow into the confined system for simulation 2 decreases by 0.27 Mgal/d over simulated 1988 conditions, even though withdrawals are increased by 2.05 Mgal/d. The boundary nodes are supplying the water needed for the increase in withdrawal. A comparison of the results of the two simulations in the northeastern part of Accomack County further indicates the effects of the different boundary conditions. The flow into the confined system through the uppermost confining unit in simulation 2 is 1.34 Mgal/d less than the flow into the confined system for simulation 1. The pumpage in both simulations is identical. In simulation 1 (no-flow boundary), the source of the water withdrawn is increased recharge and decreased discharge, whereas in simulation 2 (constant-head boundary), much of the water withdrawn is derived from flow from the boundary nodes.

The simulated position of the saltwater-freshwater interface toe for simulation 2 (figs. 57–59) is similar to the interface-toe position for simulation 1 (figs. 54–56). Changing the boundary conditions from a no-flow to a constant-head boundary in this situation does not affect the ground-water-flow system enough to cause a substantial difference in the movement of the saltwater-freshwater interface during the 50-year simulation. The saltwater-freshwater interface for simulation 2 in the upper Yorktown-Eastover aquifer does not move landward for as long a distance along the coast as it

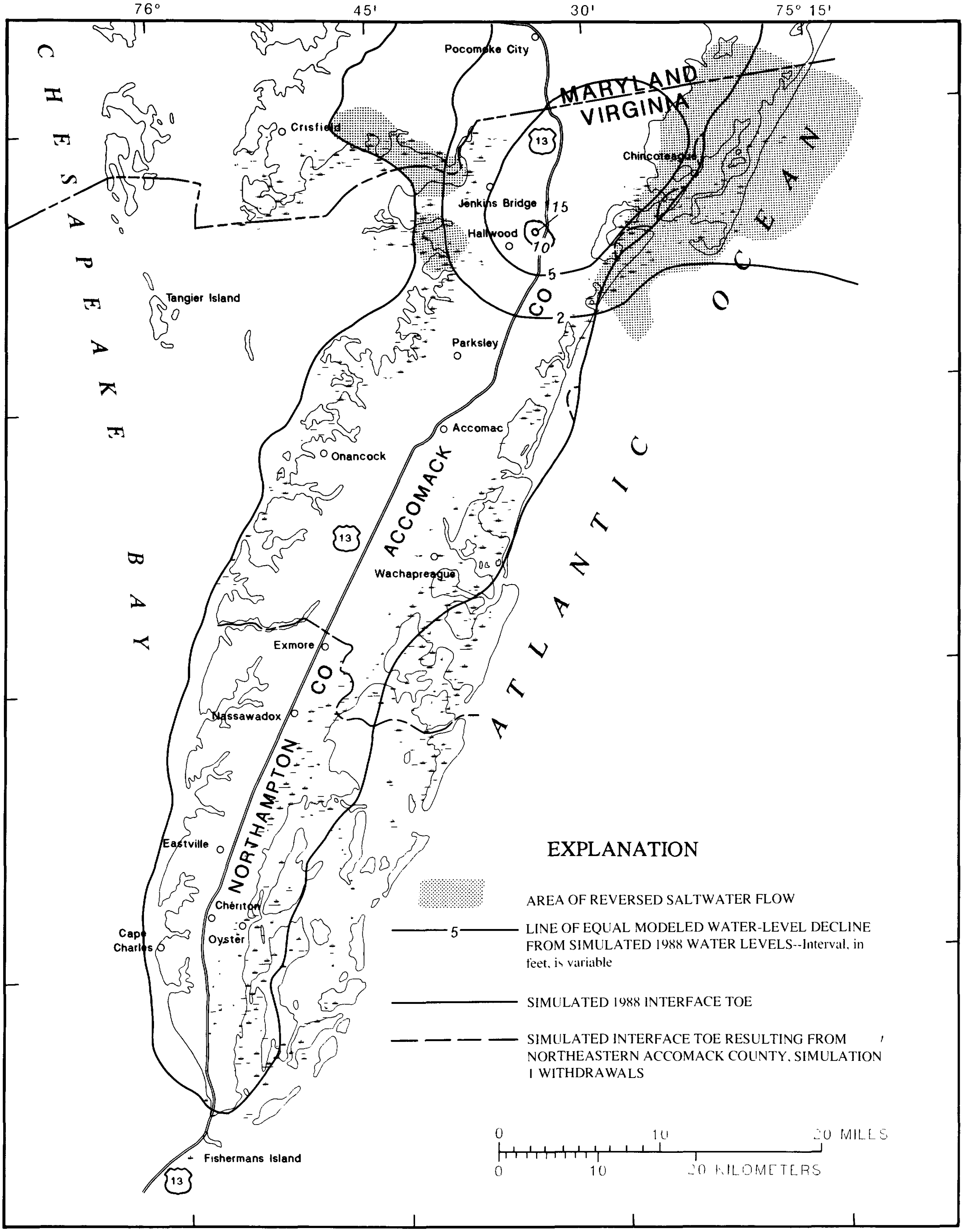


Figure 54. Water-level decline from simulated 1988 water levels, simulated position of the saltwater-freshwater interface toe, and area of reversed saltwater flow in the upper Yorktown-Eastover aquifer, northeastern Accomack County scenario, simulation 1.

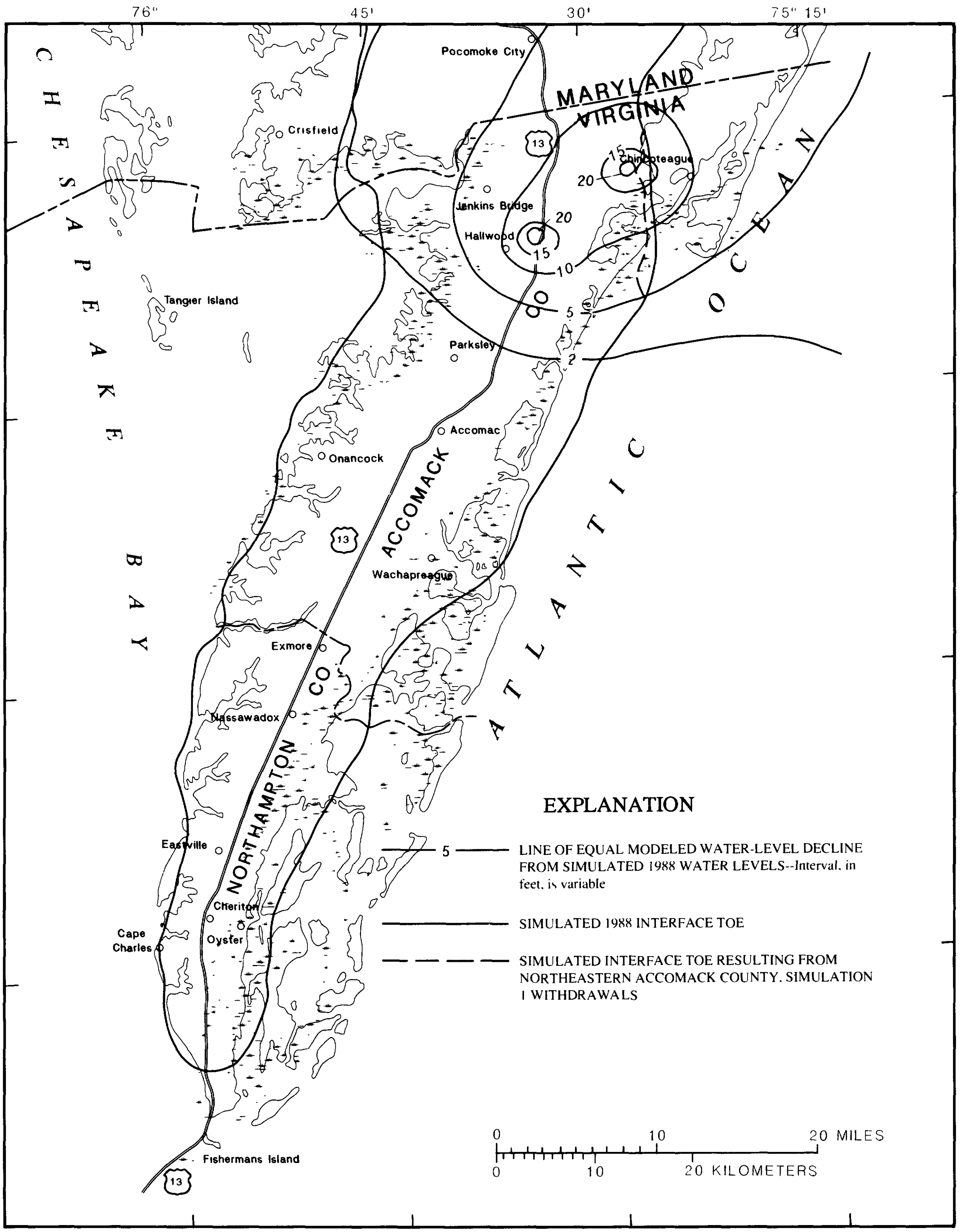


Figure 55. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the middle Yorktown-Eastover aquifer, northeastern Accomack County scenario, simulation 1.

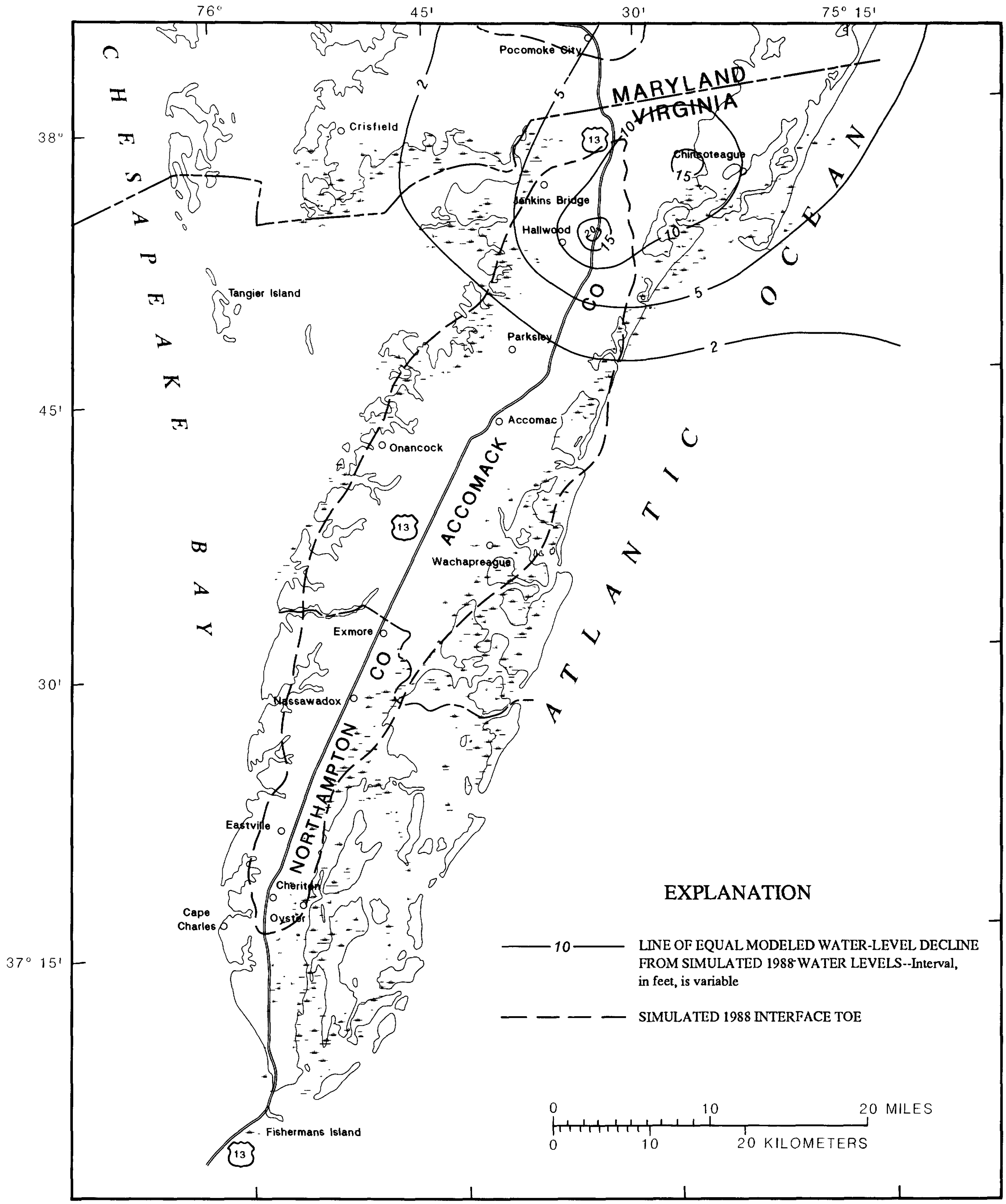


Figure 56. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the lower Yorktown-Eastover aquifer, northeastern Accomack County scenario, simulation 1.

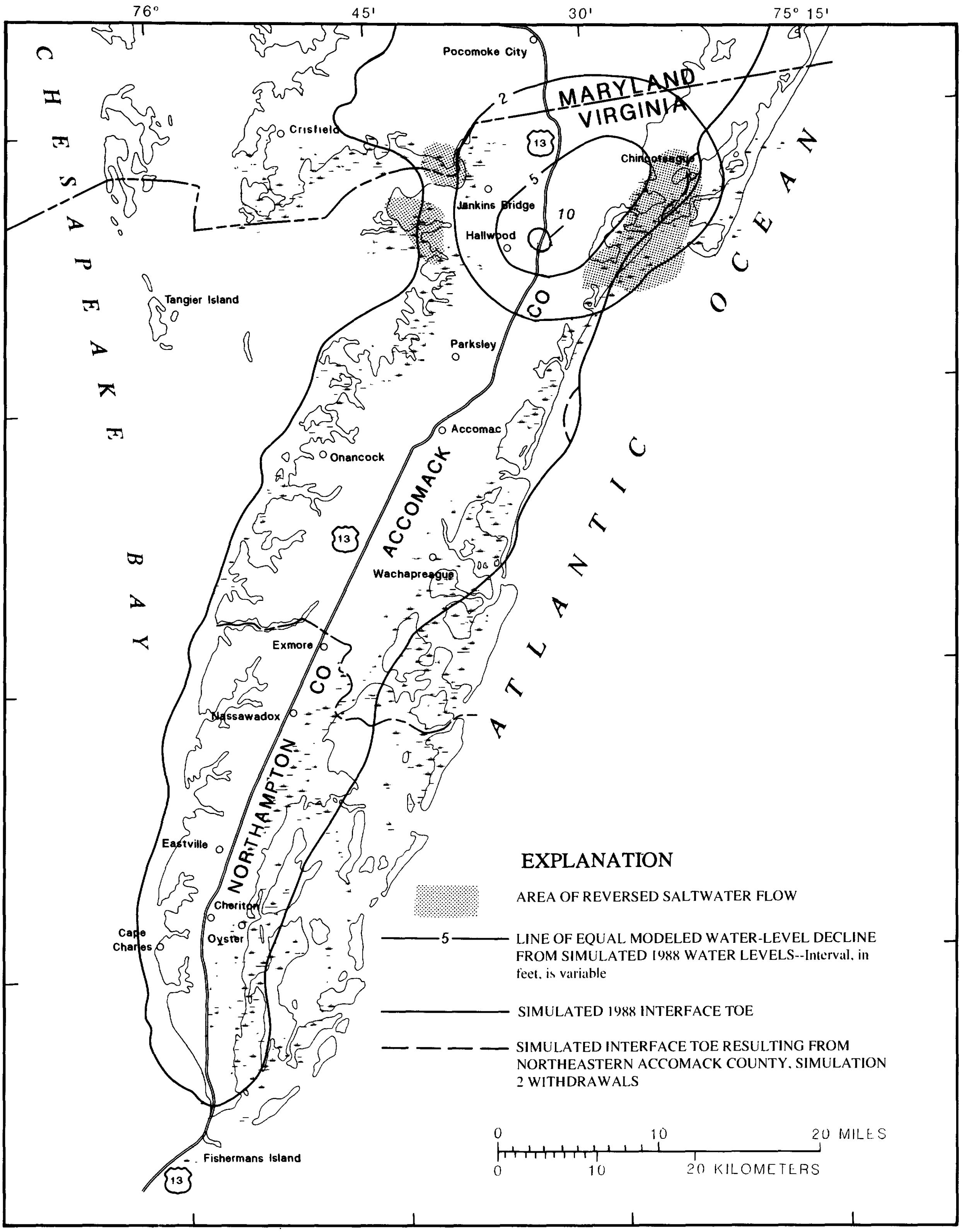


Figure 57. Water-level decline from simulated 1988 water levels, simulated position of the saltwater-freshwater interface toe, and area of reversed saltwater flow in the upper Yorktown-Eastover aquifer, northeastern Accomack County scenario, simulation 2.

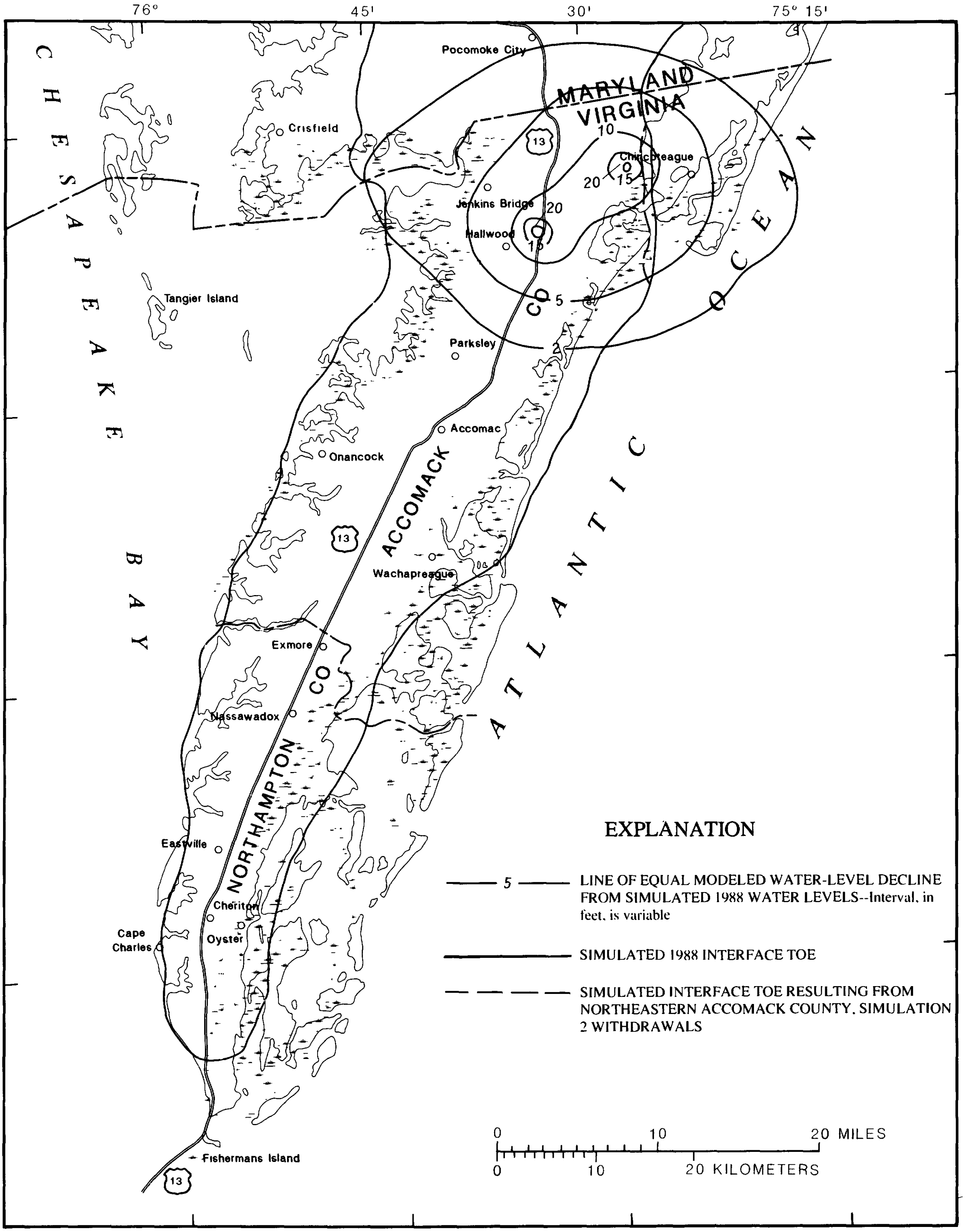


Figure 58. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the middle Yorktown-Eastover aquifer, northeastern Accomack County scenario, simulation 2.

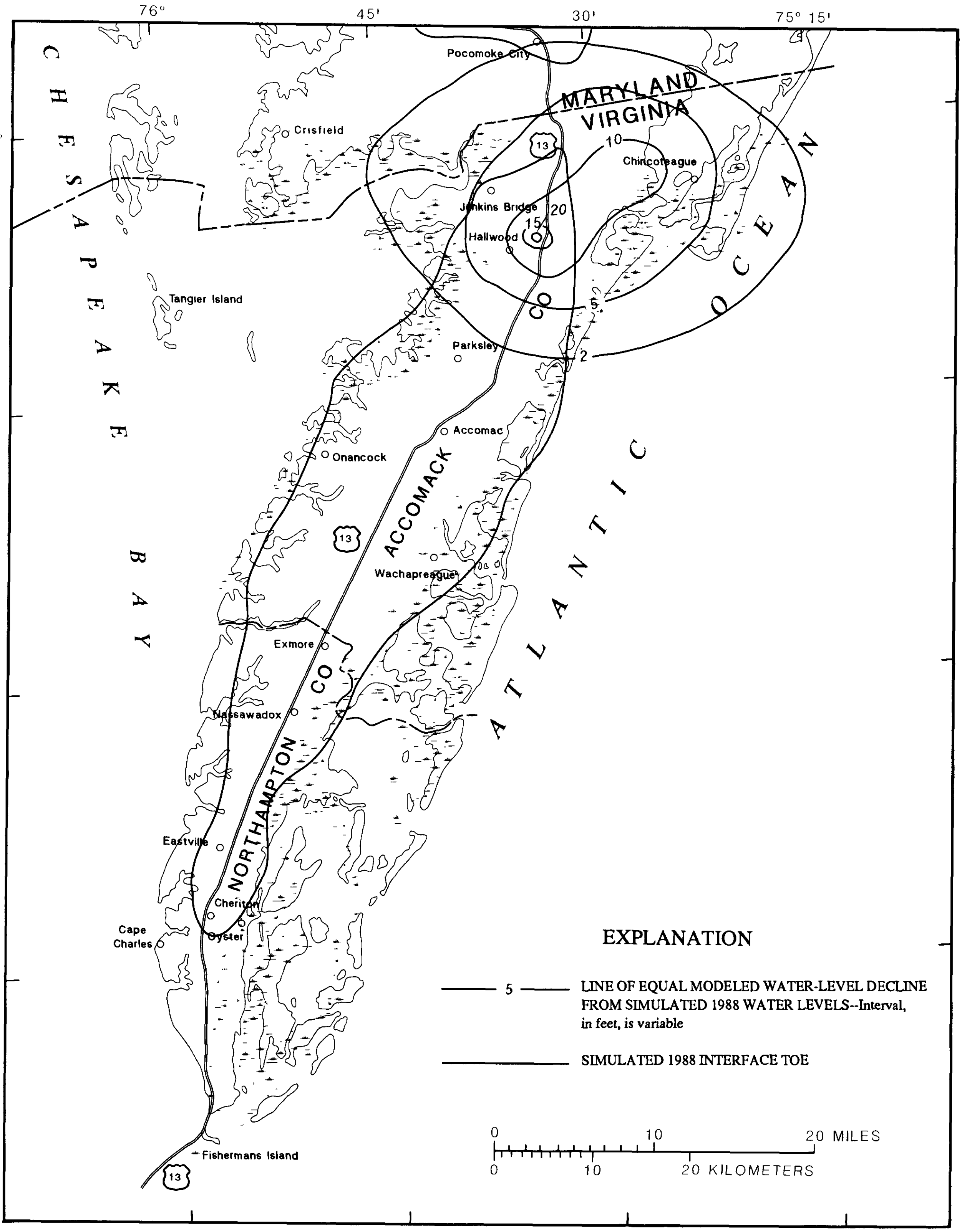


Figure 59. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the lower Yorktown-Eastover aquifer, northeastern Accomack County scenario, simulation 2.

Table 22. Permitted withdrawals as of January 1, 1990

[Latitude and longitude are reported in degrees, arc minutes, arc seconds; Mgal/d, million gallons per day]

Map number [1]	Facility	Latitude	Longitude	Permitted withdrawal (Mgal/d)
1	Accomack Nursing Home	37 45 28	075 37 21	0.029
2	American Original	37 30 45	075 48 28	.250
3	Bayshore Concrete	37 15 40	076 01 21	.125
4	Byrd Foods	37 45 30	075 40 10	.600
5	C&D Seafood	37 17 11	075 55 24	.152
6	Custis Enterprises	37 21 50	075 55 22	.441
7	Dicanio	37 13 36	076 00 19	.047
8	Dicanio	37 13 14	076 00 21	.047
9	Dicanio	37 13 53	075 59 23	.093
10	Dicanio	37 13 54	075 59 08	.093
11	Eastern Shore Seafood	37 51 21	075 33 37	.300
12	Exmore Foods	37 32 01	075 49 16	2.001
13	Holly Farms	37 52 56	075 33 24	1.800
14	JW Taylor Packing	37 52 39	075 35 27	.549
15	KMC Food	37 17 46	075 57 28	1.600
16	NASA, Wallops Island	37 51 34	075 30 41	.127
17	NASA, main base	37 56 26	075 28 44	.263
18	New Church Energy	37 58 23	075 32 13	.336
19	Peaceful Beach	37 31 05	075 56 50	.229
20	Perdue	37 44 29	075 39 20	2.639
21	H. Allen Smith	37 17 15	075 55 12	.150
22	Town of Cape Charles	37 16 05	076 00 19	.260
23	Town of Chincoteague	37 56 26	075 27 23	1.340
24	Town of Exmore	37 32 31	075 49 14	.320

[1]Locations shown on figure 60.

does in simulation 1. The maximum amount of landward movement is approximately 0.5 mi in each simulation. The movement of the interface in the middle Yorktown-Eastover aquifer is identical for both the no-flow and the constant-head simulations (figs. 55 and 58). The location of the saltwater-freshwater interface toe in simulation 2 remains unchanged from 1988 conditions for the lower Yorktown-Eastover aquifer.

Simulated water levels indicate several areas of reversed ground-water flow (fig. 57) where there is potential for induced downward vertical leakage of saltwater into the freshwater parts of the upper Yorktown-Eastover aquifer. A comparison with the area of reversed flow from simulation 1 (fig. 54) shows that simulation 2 identifies a smaller area of potential induced saltwater leakage. The area of reversed ground-water flow is smaller for simulation 2 than simulation 1 because the water-level decline is reduced as a result of the unlimited supply of water from the constant-head boundary. The results of simulation 2 indicate that, even when an infinite amount of water is allowed through the northern and eastern boundaries, saltwater intrusion through downward vertical leakage is possible, given the hypothetical projected increase in ground-water withdrawal in northeastern Accomack County.

Permitted-Withdrawal Scenario

The final scenario presented in this report examines the ground-water-flow system's response to currently (1990) permitted withdrawals. In 1976, the State of Virginia established Accomack and Northampton Counties as a Ground-Water Management Area. Thus, all nonagricultural ground-water users withdrawing more than 300,000 gal/month must obtain a permit from the VWCB. As of 1990, most of the permitted ground-water users on the Eastern Shore were withdrawing less water than their permits allowed. In this scenario, ground-water conditions are simulated that would result from increasing withdrawal on the Eastern Shore to 1990 permitted levels.

Permitted withdrawal amounts as of January 1, 1990, ranged from 0.029 to 2.639 Mgal/d (table 22). Permitted withdrawals are widely spread over the northern and southern ends of the peninsula (fig. 60). Withdrawals for ground-water users that do not have permits were continued at 1988 rates. Pumpage for the permitted scenario (13.824 Mgal/d) represents a 173 percent increase (8.763 Mgal/d) over 1988 withdrawals (table 18). Simulated 1988 conditions were used as initial conditions for a 100-year transient simulation of 1990 permitted withdrawals. Although water levels respond quickly to changes in stress, the movement of the saltwater-freshwater interface takes place over long periods of time. The simulation was carried out to 100 years to provide insight into the long-term effects of increased withdrawals on the movement of the saltwater-freshwater interface.

Modeled water-level decline from simulated 1988 water levels is shown in figures 61–63. Water-level declines exceed 25 ft in the upper Yorktown-Eastover aquifers and 65 ft in the middle and lower Yorktown-Eastover aquifers. A maximum water-level decline of approximately 95 ft occurs in the middle Yorktown-Eastover aquifer near the town of Exmore (table 19). Water levels remain above the tops of the aquifers, indicating from a regional perspective that dewatering would be minimal at permitted-withdrawal levels.

The permitted-withdrawal scenario involves a greater increase in withdrawals over 1988 pumpage than any of the previous scenarios; therefore, the changes in the flow into and out of the confined system are the most dramatic (table 16). The increase in freshwater withdrawals of 8.65 Mgal/d over 1988 amounts results in an increase in flow into the confined-aquifer system by 4.33 Mgal/d and a decrease in natural flow out of the confined-aquifer system by 2.99 Mgal/d.

The position of the simulated saltwater-freshwater interface for the 100-year transient permitted-withdrawal scenario is shown in figures 61–63. Interface movement coincides with the areas of greatest water-level decline due to increased pumpage. Maximum inland movement of the saltwater-freshwater interface toe is approximately 1mi in the upper Yorktown-Eastover aquifer near the town of Cape Charles and in the middle Yorktown-Eastover aquifer near the town of Chincoteague. Maximum inland movement of the interface toe is approximately 1 mi in the lower Yorktown-Eastover aquifer near the town of Hallwood. The water-quality effects on the width of the mixing zone between saltwater and freshwater cannot be simulated by the sharp-interface model. The chloride concentrations in the mixing zone probably fluctuate more rapidly than the position of the sharp interface.

Water-level declines caused by pumpage in nearshore and coastal areas indicate several areas of reversed ground-water flow from the Atlantic Ocean and Chesapeake Bay to the freshwater parts of the upper Yorktown-Eastover aquifer (fig. 61). The areas of reversed flow indicate a potential for vertical leakage of saltwater into the freshwater parts of the upper Yorktown-Eastover aquifer. The rate of vertical leakage of saltwater is highly dependent on the vertical hydraulic conductivity of the upper Yorktown-Eastover confining unit in the vicinity of the flow reversal.

Discussion of Model Results

The model results from the three scenarios of increased ground-water withdrawals provide information on the regional response of the ground-water system to additional stress and its ability to meet future water needs. The simulations are not intended to predict exact ground-water conditions in the future; however, a comparison of model results provides useful information for the evaluation of alternative withdrawal scenarios.

The distribution of ground-water withdrawals directly affects the ability of the ground-water system to sustain increased withdrawals without incurring saltwater intrusion. An increase in ground-water withdrawals lowers ground-water levels around the pumping centers. Ground-water flow is diverted to the major pumping centers; water from adjacent parts of the aquifer and from adjacent aquifers or confining units replaces the water withdrawn. Large water-level declines could necessitate lowering of pump intakes, could increase the rate of movement of the offshore interface between saltwater and freshwater, and could induce leakage of poor-quality water from adjacent aquifers or surface-water bodies. Excessive head declines and detrimental effects on water quality can be minimized with proper well placement. Withdrawal wells can be placed in areas that would minimize interference with other major ground-water users.

Any increase in withdrawals from the confined freshwater aquifers on the Eastern Shore increases the amount of recharge to and decreases the amount of natural discharge from the confined-aquifer system

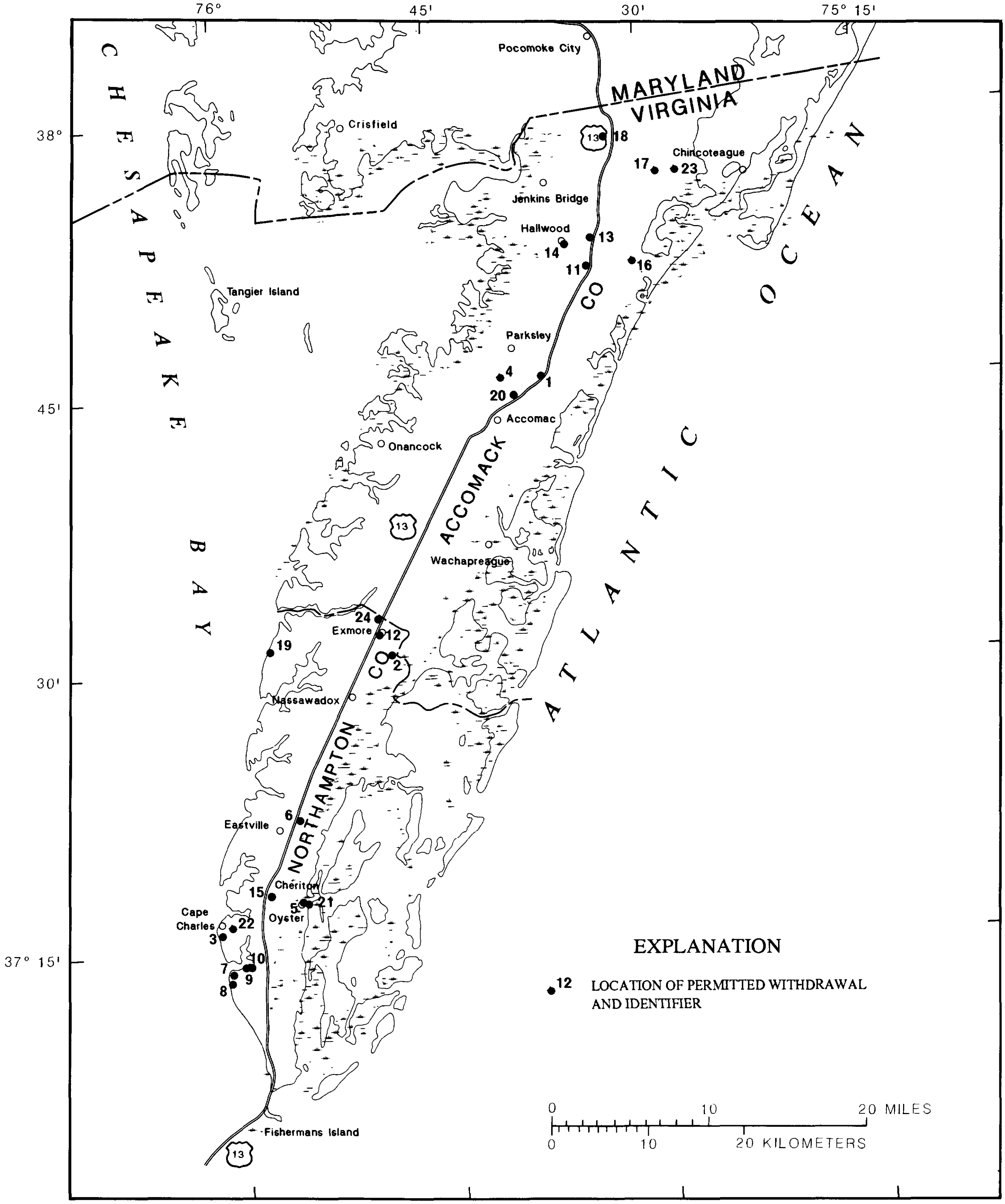


Figure 60. Location of permitted withdrawals.

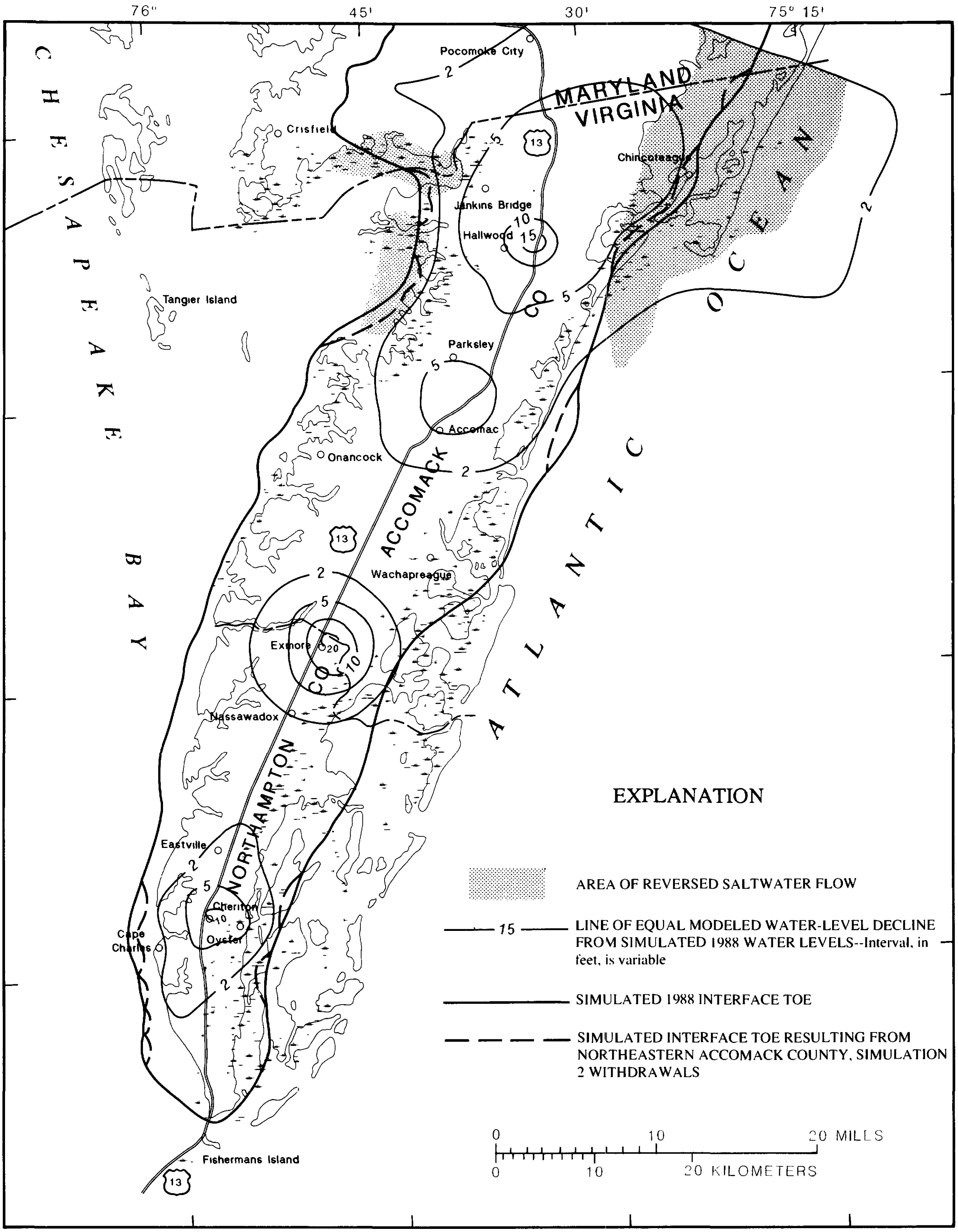


Figure 61. Water-level decline from simulated 1988 water levels, simulated position of the saltwater-freshwater interface toe, and area of reversed saltwater flow in the upper Yorktown-Eastover aquifer, permitted-withdrawal scenario.

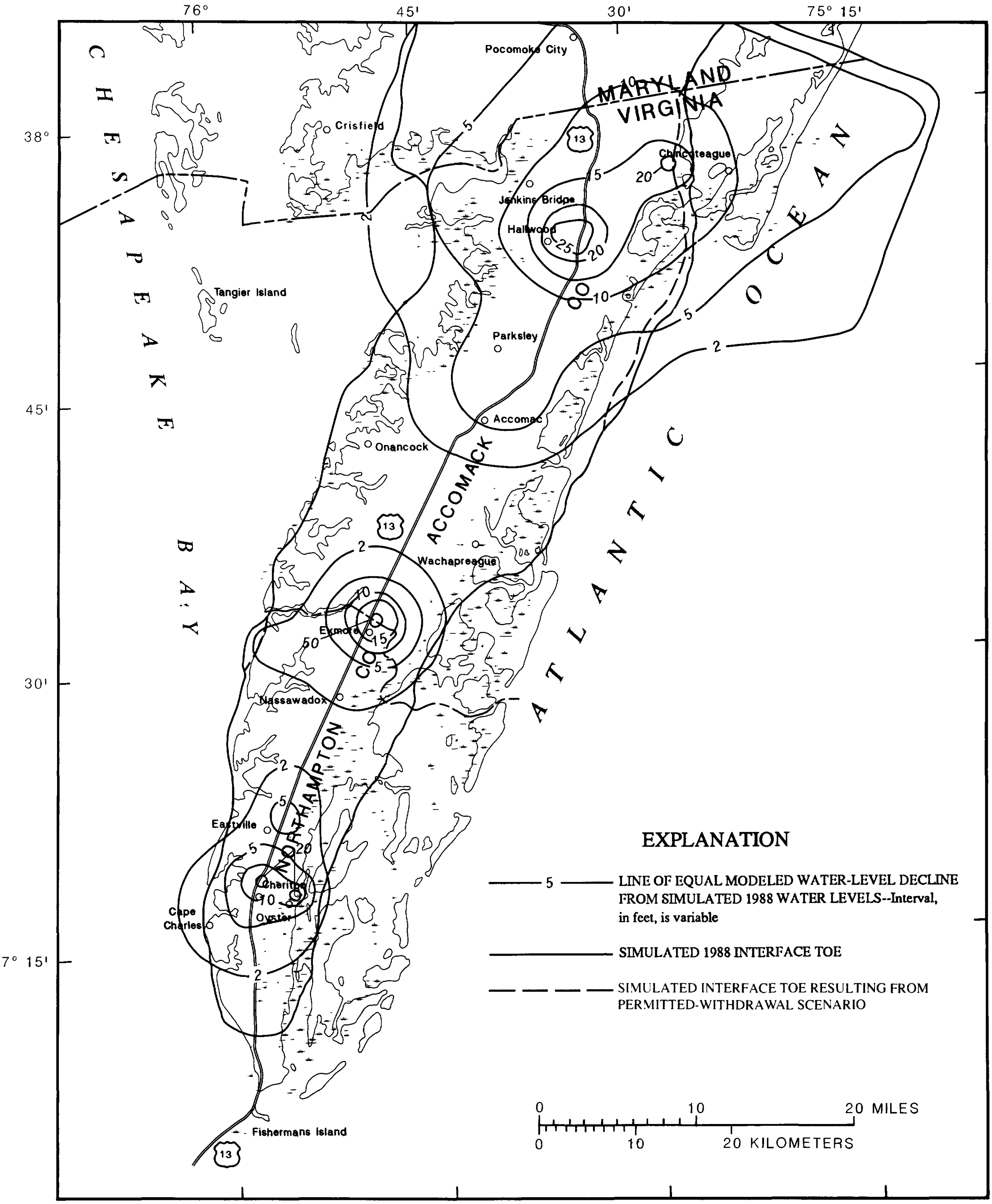


Figure 62. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the middle Yorktown-Eastover aquifer, permitted-withdrawal scenario.

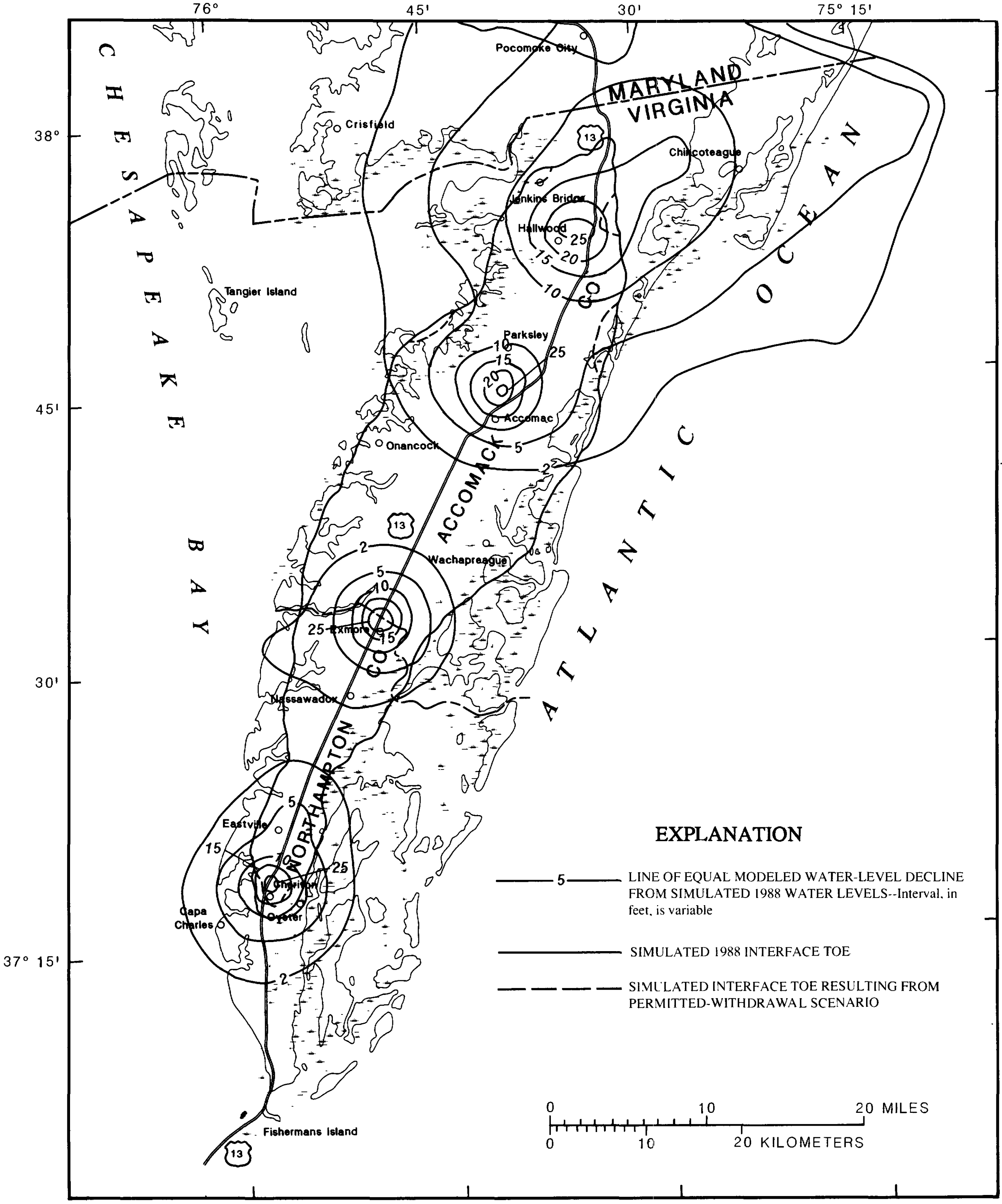


Figure 63. Water-level decline from simulated 1988 water levels and simulated position of the saltwater-freshwater interface toe in the lower Yorktown-Eastover aquifer, permitted-withdrawal scenario.

A reduction in freshwater discharge to the Chesapeake Bay and Atlantic Ocean changes the equilibrium between the freshwater and the surrounding saltwater. The interface between freshwater and saltwater begins to move inland as saltwater replaces the withdrawn freshwater. A reduction in freshwater discharge also could affect salinity levels at freshwater-discharge sites in nearshore inlets, bays, and estuaries.

Model results indicate that water-level declines in close proximity to the simulated location of the saltwater-freshwater interface have the most dramatic effect on the rate of interface movement. Large water-level declines in the center of the peninsula have a minimal effect on the rate of movement of the saltwater-freshwater interface; however, small water-level declines in coastal areas adjacent to the interface position cause a noticeable increase in the rate of interface movement.

Two potential pathways for saltwater intrusion into the freshwater aquifers of the Eastern Shore were examined in this report. Model simulations show saltwater intrusion through lateral movement of the saltwater-freshwater interface and through downward vertical leakage of saltwater in areas where a saltwater source overlies the freshwater part of the uppermost confined aquifer. Model simulations indicate that lateral movement of the saltwater-freshwater interface is slow and takes place over long periods of time. However, a reversal of the ground-water-flow direction can take place in short timeframes and could result in induced vertical leakage of saltwater through the confining unit into the freshwater part of an aquifer. Areas of reversed flow of saltwater into freshwater areas are seen in scenario results where heavy withdrawals are present in coastal areas and water-level declines extend offshore.

Sensitivity Analysis

Model-sensitivity analyses were conducted to examine the response of the calibrated model to changes in boundary conditions and estimated hydraulic characteristics. The model sensitivity to the northern no-flow boundary condition is illustrated in the section of this report describing simulation 2 of the northeastern Accomack County scenario. Model runs also were conducted to determine the sensitivity of the model to changes in the overlying constant-head boundary. Increasing the overlying constant heads (that represent the water table) resulted in a slight increase in the heads in the simulated confined aquifers. Correspondingly, decreasing the overlying constant heads resulted in lower heads in the simulated confined aquifers. The hydraulic property that dominates flow through the system is the vertical leakance of the uppermost confining unit, and as a result, the model is more sensitive to changes in confining-unit vertical leakance than it is to changes in the overlying constant heads. The results of the sensitivity analysis of the calibrated model to changes in horizontal hydraulic conductivity of aquifers and leakance of confining units are presented in this section. Sensitivity simulations were conducted by increasing or decreasing an individual parameter while all other characteristics remained unchanged. The larger the resulting changes in water levels are, the more sensitive the model is to that parameter, and the smaller the change, the less sensitive the model is.

Withdrawal conditions from simulation 1 of the southern Northampton County scenario were used to examine the model's sensitivity to large increases in withdrawals. Variations in hydraulic characteristics were compared by simulating a 50-percent increase and decrease in hydraulic conductivity and vertical leakance. Water-level differences that resulted from changing the calibrated hydraulic parameters are shown in figures 64–67. The maximum water-level changes for each aquifer for each sensitivity run (table 23) show that the model is most sensitive near major pumping areas. Generally, the water levels simulated by the model are more sensitive to decreases than they are to increases in hydraulic conductivity and vertical leakance. The responses of the saltwater-freshwater interface to changes in hydraulic conductivity and vertical leakance were slow and not sensitive over the 50-year simulation period. Increasing hydraulic conductivity and decreasing vertical leakance result in an interface position that is slightly closer to the shore in a few locations than the calibrated-scenario interface position. Decreasing hydraulic conductivity and increasing vertical leakance result in an interface position that is slightly farther offshore in a few locations than the calibrated scenario.

Model Limitations

The ground-water-flow model developed for the Eastern Shore is a tool that was used to assist in

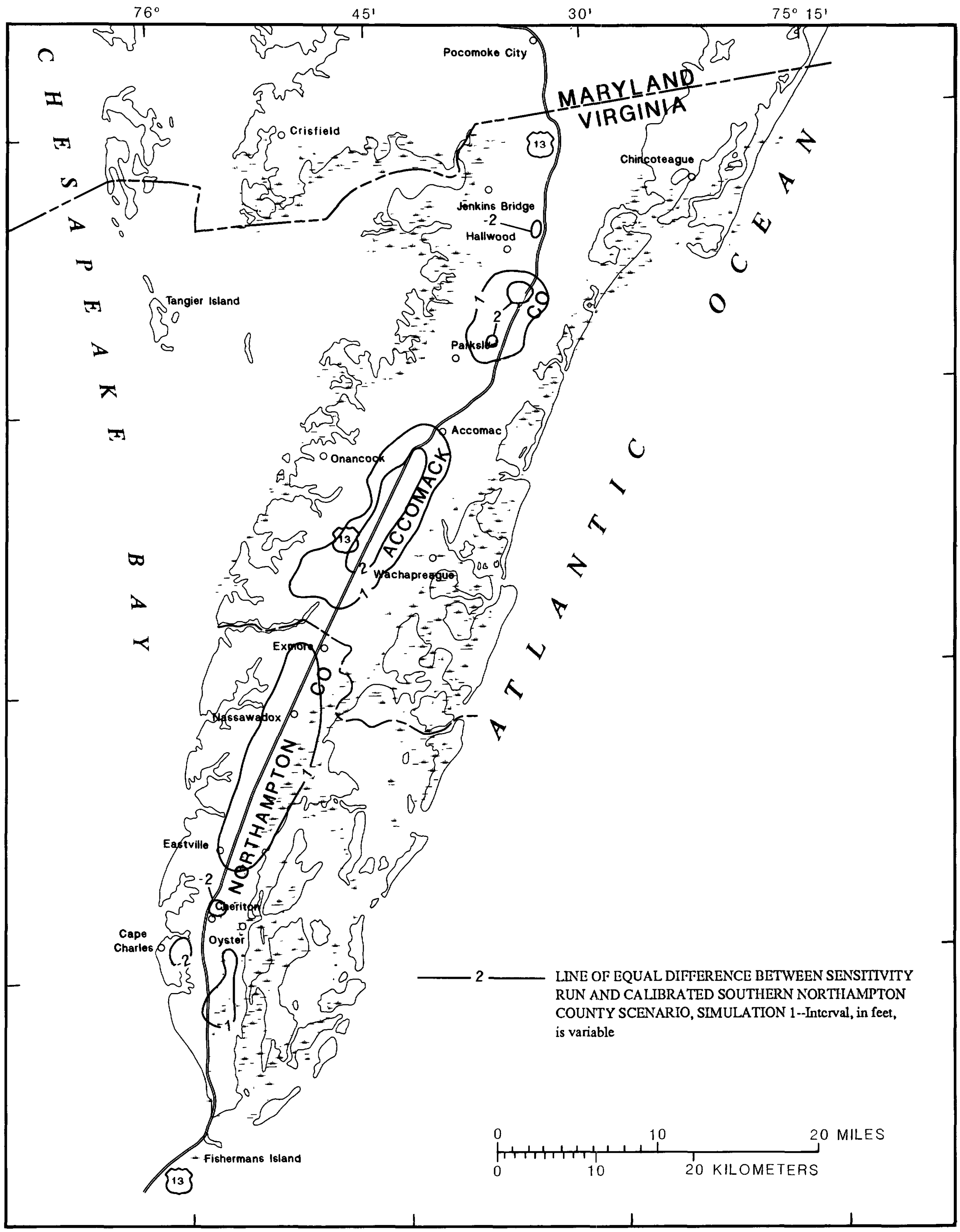


Figure 64. Difference in simulated water levels resulting from a 50-percent increase in horizontal hydraulic conductivity for the southern Northampton County scenario—simulation 1, upper Yorktown-Eastover aquifer.

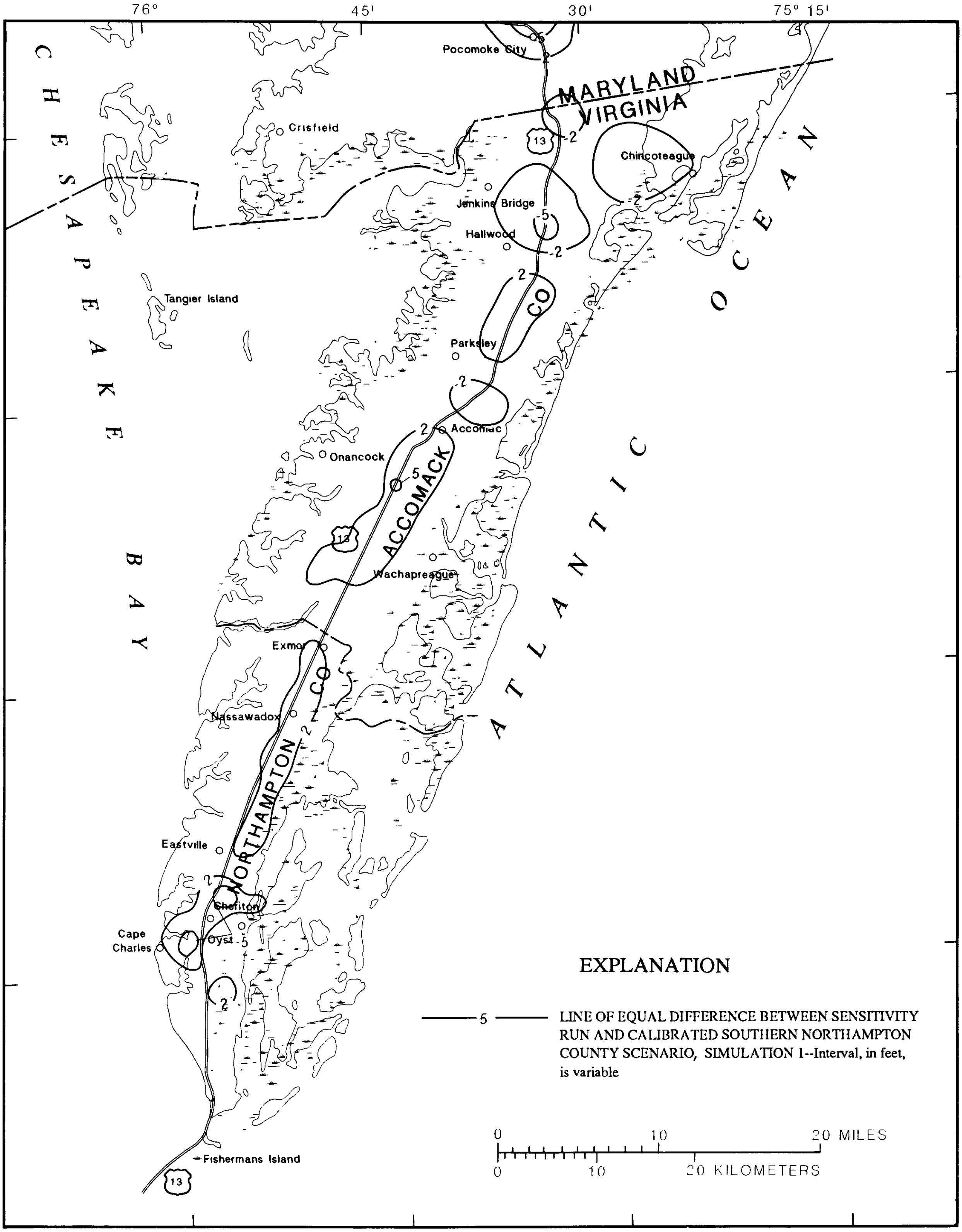


Figure 65. Difference in simulated water levels resulting from a 50-percent decrease in horizontal hydraulic conductivity for the southern Northampton County scenario—simulation 1, upper Yorktown-Eastover aquifer.

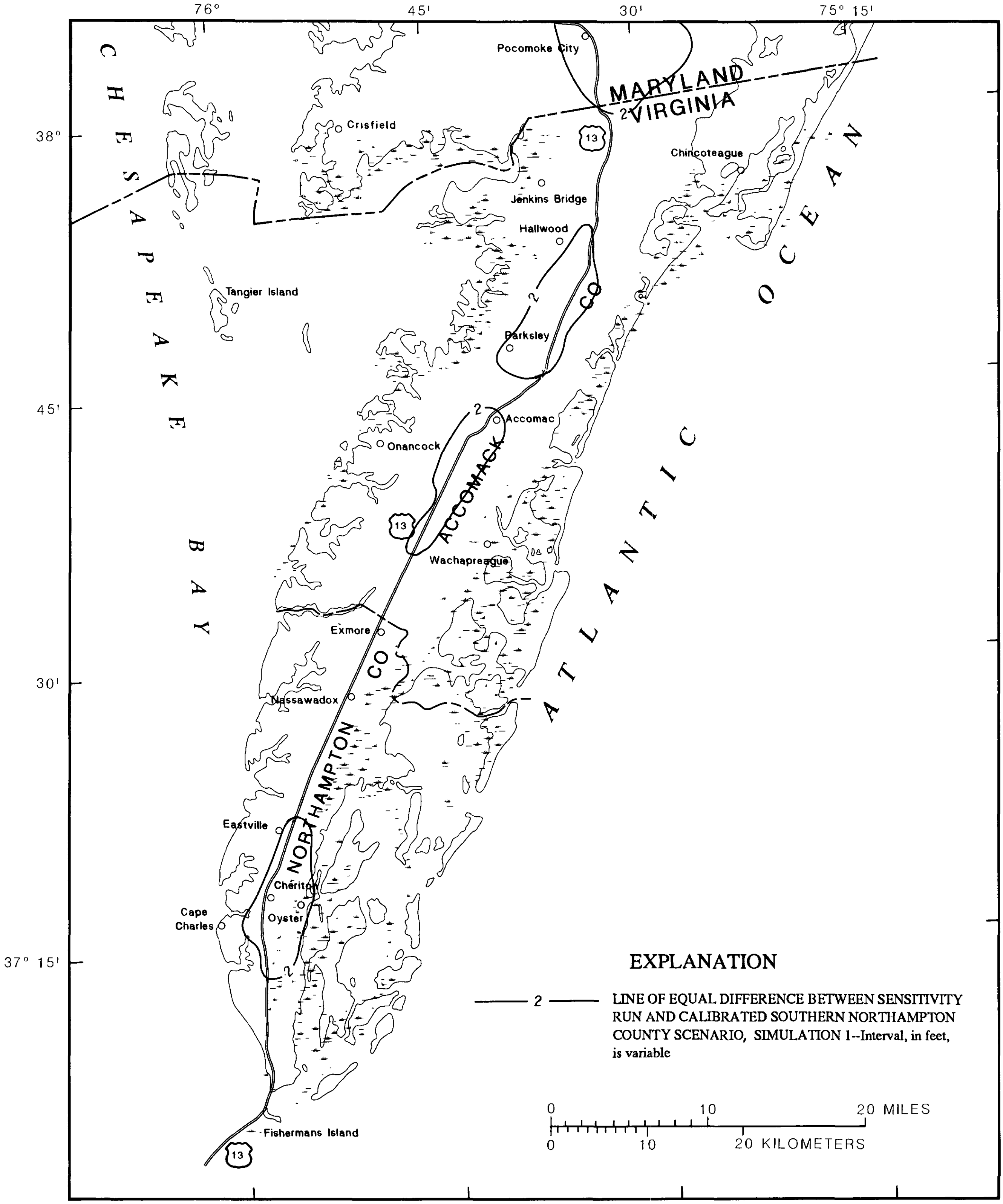


Figure 66. Difference in simulated water levels resulting from a 50-percent increase in confining unit leakance for the southern Northampton County scenario—simulation 1, upper Yorktown-Eastover aquifer.

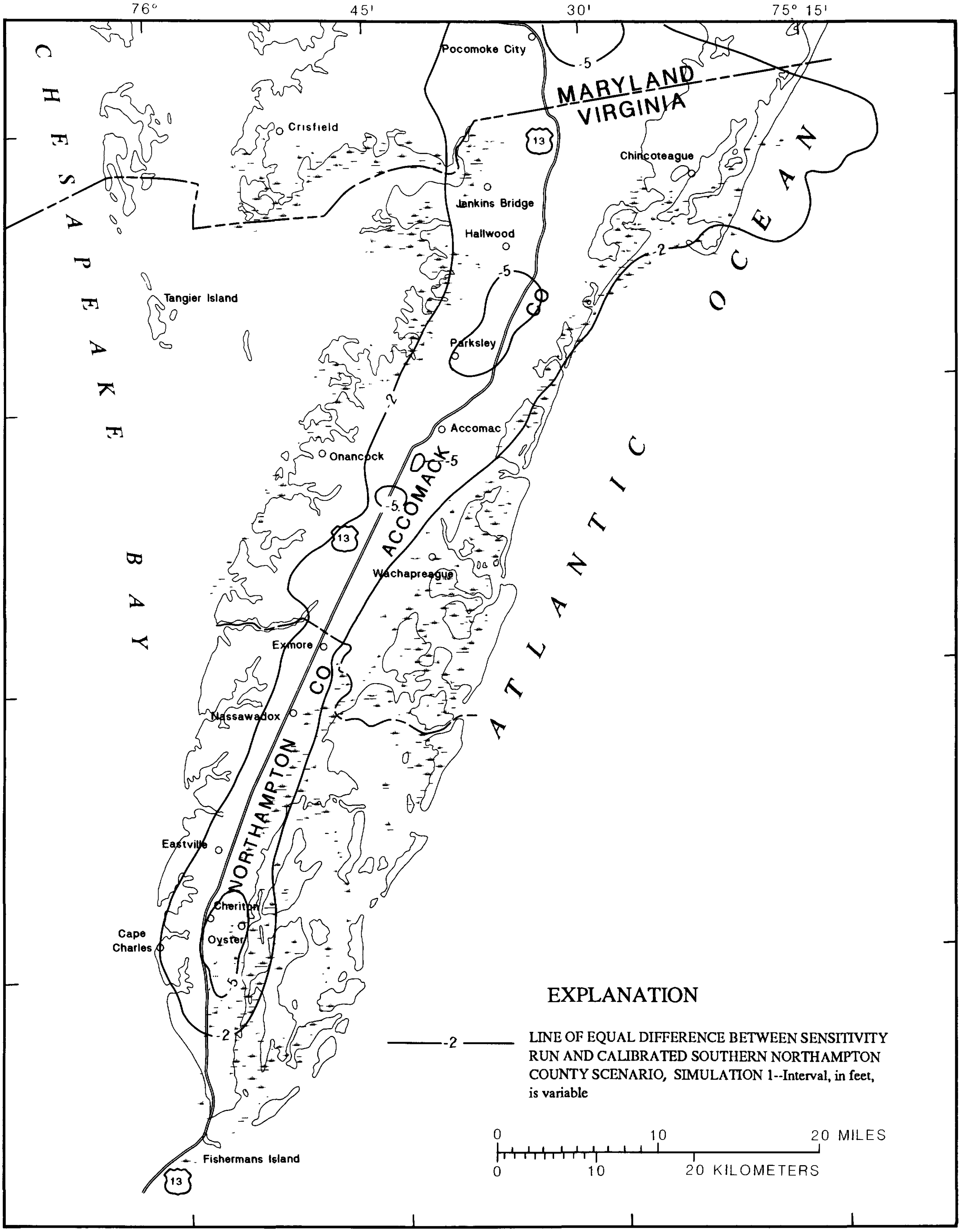


Figure 67. Difference in simulated water levels resulting from a 50-percent decrease in confining unit leakance for the southern Northampton County scenario—simulation 1, upper Yorktown-Eastover aquifer.

Table 23. Maximum water-level changes resulting from sensitivity runs

	Maximum water-level increase (feet)	Grid location of increase		Maximum water-level decline (feet)	Grid location of decrease	
		Row	Column		Row	Column
<u>50-percent increase in hydraulic conductivity</u>						
Upper Yorktown-Eastover	4.0	3	27	-3.5	43	28
Middle Yorktown-Eastover	10.5	80	29	-3.3	45	28
Lower Yorktown-Eastover	14.6	80	26	-3.2	45	29
<u>50-percent decrease in hydraulic conductivity</u>						
Upper Yorktown-Eastover	5.8	43	28	-10.7	3	27
Middle Yorktown-Eastover	5.4	43	29	-24.5	80	29
Lower Yorktown-Eastover	5.5	45	29	-39.5	80	26
<u>50-percent increase in confining unit leakance</u>						
Upper Yorktown-Eastover	3.6	30	31	-1.5	58	42
Middle Yorktown-Eastover	7.6	80	29	-2.3	60	43
Lower Yorktown-Eastover	5.6	80	26	-3.0	57	40
<u>50-percent decrease in confining unit leakance</u>						
Upper Yorktown-Eastover	1.0	51	39	-6.7	29	33
Middle Yorktown-Eastover	.9	66	37	-13.9	80	29
Lower Yorktown-Eastover	1.0	63	37	-10.0	80	26

the analysis of the ground-water-flow system. The model is an approximate representation of a complex physical system. The hydrogeologic characteristics of a conceptualized three-dimensional system of aquifers and confining units are integrated in the model. Stresses can be applied to this quasi-three-dimensional representation of the system, and the relative effects of those stresses on the water levels, the water budget, and the saltwater-freshwater interface can be examined.

The model was developed to simulate regional effects of hydrologic stresses on the ground-water-flow system. The large spatial and temporal scale of the model makes it unsuitable for the analysis of local effects, short-term effects, and small-scale withdrawals. A small-scale analysis of the flow system would require spatial and temporal refinement of the aquifer and confining-unit characteristics and hydrologic stresses.

The model simulates ground-water flow in the Eastern Shore's freshwater-bearing confined aquifers, from which the majority of withdrawals are made. The water table in the unconfined aquifer was specified in the model as a constant-head boundary to simulate the regional recharge-discharge relation between the unconfined aquifer and the confined system, but flow in the unconfined aquifer was not simulated. The deep, saltwater aquifers (approximately 300 ft below land surface) also are not simulated by the model. As of 1990, no water was being pumped from the deep aquifers in the study area.

The saltwater-freshwater interface is represented in the model as a sharp interface. There are no offshore data for the Eastern Shore; therefore, the actual position of the saltwater-freshwater interface and the width of the transition zone are unknown. Saltwater and freshwater are simulated as immiscible fluids, and mixing due to hydrodynamic dispersion is neglected. Leakage between the saltwater and freshwater zone is restricted by the model. Saltwater is not allowed to leak into the freshwater zone. The leakage of freshwater is distributed between the saltwater and freshwater zones based on the amounts of each type of water in the node receiving the leakage. The approach is designed to reproduce the general response of the interface and does not provide information concerning the nature of the transition zone between saltwater and freshwater. Vertical leakage of saltwater into freshwater is not directly simulated; evidence of vertical saltwater intrusion from overlying salty-surface-water bodies is provided by examination of the water-level gradients and areas of reversed ground-water flow. The model is not able to simulate upconing of saltwater as a result of pumpage. This approach is considered an initial step in the process of characterizing the interactions between saltwater and freshwater around the Eastern Shore. Data concerning the dispersive properties of the sediments and a solute-transport-modeling approach to the saltwater-freshwater interface are needed to fully characterize the water quality in the transition zone between saltwater and freshwater.

The location of the historical and present-day saltwater-freshwater interface is not known. The model simulates the location of the interface by simulating saltwater and freshwater flow and balancing pressures along the interface. The historic prestressed position of the interface is assumed, for the purposes of this report, to be in equilibrium with present-day sea levels. However, the interface position may not have reached an equilibrium position and may still be responding to long-term sea-level fluctuations.

SUMMARY

The Eastern Shore of Virginia is totally dependent on ground water for its freshwater supply. Increased pumpage due to intensifying agricultural, industrial, commercial, and urban development could limit the continued use of this resource. Ground-water withdrawal has caused lowering of water levels and has created cones of depression around areas of heavy ground-water use. The water-level decline has resulted in well interference in several localities. Continued water-level decline could result in additional well interference among the ground-water users and intrusion of saltwater into the freshwater parts of aquifers.

This report describes the hydrogeology and ground-water flow system of the Eastern Shore. A model that includes the ability to track the movement of the saltwater-freshwater interface was used to aid in the hydrologic analysis of the effects of withdrawals on the ground-water-flow system.

The sediment of the Eastern Shore forms a layered sequence of aquifers and intervening confining units. This report focuses on the aquifers and confining units (approximately the upper 300 ft) that make up the fresh-ground-water system. The aquifers that contain freshwater are the unconfined Columbia aquifer and the upper three confined aquifers, the upper, middle, and lower Yorktown-Eastover aquifers. Maps delineating the tops of the aquifers and confining units were developed from correlation of lithologic and geophysical logs, water-quality analyses, and water-level data.

Prior to 1940, ground-water withdrawals on the Eastern Shore were minimal, and the ground-water system was in a state of long-term dynamic equilibrium. Water from precipitation falling on the peninsula recharged the Columbia aquifer and flowed from the topographic highs near the center of the peninsula to discharge into streams, estuaries, the Chesapeake Bay, and the Atlantic Ocean. Some water flowed vertically through the upper Yorktown-Eastover confining unit to recharge the confined-aquifer system. Water-level measurements made after withdrawals began on the peninsula indicated lowering of water levels and creation of cones of depression around major pumping centers.

Annual ground-water-withdrawal data for the model area were compiled by aquifer for commercial, industrial, and municipal withdrawals. Prior to 1965, there were few large users of ground water on the Eastern Shore. By 1970, increased population along with commercial and industrial growth greatly increased the demand for the ground water. Ground-water use, excluding domestic and irrigation, was estimated to be about 5.04 Mgal/d in 1988. The upper, middle, and lower Yorktown-Eastover aquifers supplied 36, 42, and 22 percent of the 5.039 Mgal/d withdrawal, respectively. Major pumping centers on the Eastern Shore were located near the towns of Chincoteague, Hallwood, Accomac, Exmore, Oyster, Cheriton, and Cape Charles.

Data on chloride concentrations were compiled by aquifer to provide information on the distribution of chlorides in the study area. Chloride concentrations in each aquifer are typically lower in the middle of the peninsula than they are along the coast. Chloride concentrations increase with depth and are higher in the lower Yorktown-Eastover aquifer than in the middle and upper Yorktown-Eastover aquifers. The elevated chloride concentrations (greater than 250 mg/L) found in the lower Yorktown-Eastover aquifer across the peninsula near Exmore, Va., could be a result of different hydraulic properties related to the presence of an ancient Pleistocene river channel. Chloride concentrations in the lower Yorktown-Eastover aquifer are stratified, and concentrations are lower near the top than near the bottom of the aquifer.

A model was developed for the Eastern Shore to simulate changes in ground-water-flow conditions that result from changes in hydrologic stresses. Simulation included ground-water flow both prior to ground-water pumpage and throughout the history of pumpage. The maximum simulated water-level decline since prepumping conditions was 53 ft in the lower Yorktown-Eastover aquifer near the town of Accomac, Va. Simulated water-level gradients indicated a change in the direction of ground-water flow from prepumping conditions. Prepumping flow was from topographic highs in the center of the peninsula to the Chesapeake Bay and Atlantic Ocean. Simulated 1988 conditions show ground-water flow is being diverted toward the major pumping centers. Ground-water pumpage is supplied by an increase in vertical leakage to the confined-aquifer system from the unconfined aquifer and a decrease in vertical leakage from the confined-aquifer system to the unconfined aquifer. The simulated position of the interface between saltwater and freshwater did not change in response to historic pumpage.

Three scenarios predicted ground-water conditions that result from increasing withdrawals in southern Northampton County, in northeastern Accomack County, and throughout the peninsula at 1990 permitted rates. Simulation results indicate that water levels continue to decline as withdrawals increase and could result in well interference among major ground-water users and in a reduction in freshwater discharge to the Chesapeake Bay and Atlantic Ocean. The water-level declines associated with the increased withdrawals could cause slight movement of the saltwater-freshwater interface over a 50-year simulation period. The potential for induced vertical leakage of saltwater from overlying salty-surface-water sources into the freshwater parts of the upper Yorktown-Eastover aquifer is indicated by areas of reversed ground-water gradients caused by offshore water-level declines.

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