SIMULATION OF GROUND-WATER FLOW IN AQUIFERS IN CRETACEOUS ROCKS IN THE CENTRAL COASTAL PLAIN, NORTH CAROLINA

by Jo Leslie Eimers, William L. Lyke, and Allen R. Brockman

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by Jo Leslie Eimers[1], William L. Lyke[1], and Allen R. Brockman[2]

ABSTRACT

The principal sources of water-supply in Cretaceous rocks in the central Coastal Plain of North Carolina are the Peedee, Black Creek, and upper Cape Fear aquifers. Ground-water withdrawals from these aquifers have increased from about 0.25 million gallons per day in 1910 to over 29 million gallons per day in 1986, causing water-level declines as much as 160 feet. The maximum rate of water-level decline in 1986 is about 11 feet per year in the Black Creek aquifer.

A quasi-three dimensional ground-water flow model was constructed and calibrated for the period 1900 to 1986 to simulate past water-level declines and to estimate the effects of future pumpage. Comparisons of 1,867 observed and model-computed heads were made at 323 well sites. The average difference between computed and observed water levels is -1 foot. About 68 percent of all the differences between computed and observed water levels falls in the range from -21.0 to 21.0 feet.

Simulation indicates that the 29 million gallons per day of pumpage in 1986 was supplied by (1) increased recharge (net discharge of 2 million gallons per day in 1900 changed to net recharge of 18 million gallons per day in 1986), (2) increased lateral inflow to the aquifers of about 8 million gallons per day, and (3) depletion of ground-water storage of about 1 million gallons per day. Two pumping scenarios simulated head changes through 1991 and were based on (1) constant pumpage at the 1986 rates in each aquifer, and (2) continuing increases in pumping rates from 1986 through 1991 and rates varying from 10 to 19 percent per year for the three pumped aquifers. For scenario 1, water-level declines exceeded 5 feet locally; however, water-level rises of about 1 foot occurred in two areas. For scenario 2, water-level declines ranged from 1 foot to 30 feet in some pumping centers.

[1]U.S. Geological Survey.
[2]North Carolina Department of Environment, Health, and Natural Resources.

INTRODUCTION

Water derived from aquifers in Cretaceous rocks is the major source of freshwater in the central Coastal Plain of North Carolina. Total ground-water withdrawals from these aquifers have increased from about 0.25 million gallons per day (Mgal/d) in 1910 to over 29 Mgal/d in 1986. Ground-water levels in these aquifers have declined as a result of these withdrawals, creating public concern about the future effect of withdrawals on the ground-water resources of the area.

In 1983, the U.S. Geological Survey (Survey), in cooperation with the North Carolina Department of Environment, Health, and Natural Resources and various local agencies, began a hydrologic investigation of the central part of the North Carolina Coastal Plain. The 3,600 square-mile (mi^2) study area includes all or part of Beaufort, Craven, Duplin, Edgecombe, Greene, Jones, Lenoir, Onslow, Pender, Pitt, Wayne, and Wilson Counties. The study area (fig. 1) is about 14 percent of the 25,000 square-mile area of the North Carolina Coastal Plain.

Purpose and Scope

This report describes the design, calibration process, and results of a ground-water flow model for the central Coastal Plain water-supply aquifers and demonstrates the application of this model to the management of ground-water resources by simulating effects of two withdrawal scenarios through the year 1991. Limitations of the model, as well as the requirements needed to improve model accuracy for future simulations, are presented.

The objectives of the central Coastal Plain aquifer study are to evaluate the ground-water supply potential of the central Coastal Plain and to make quantitative evaluations of the effects of several regional ground-water development schemes on water levels and on maximum development potential. To accomplish these objectives, the study included the construction of a detailed hydrogeologic framework, documentation of historic records of ground-water withdrawals and water levels, and application of steady-state and transient digital ground-water models to analyze the ground-water flow system.

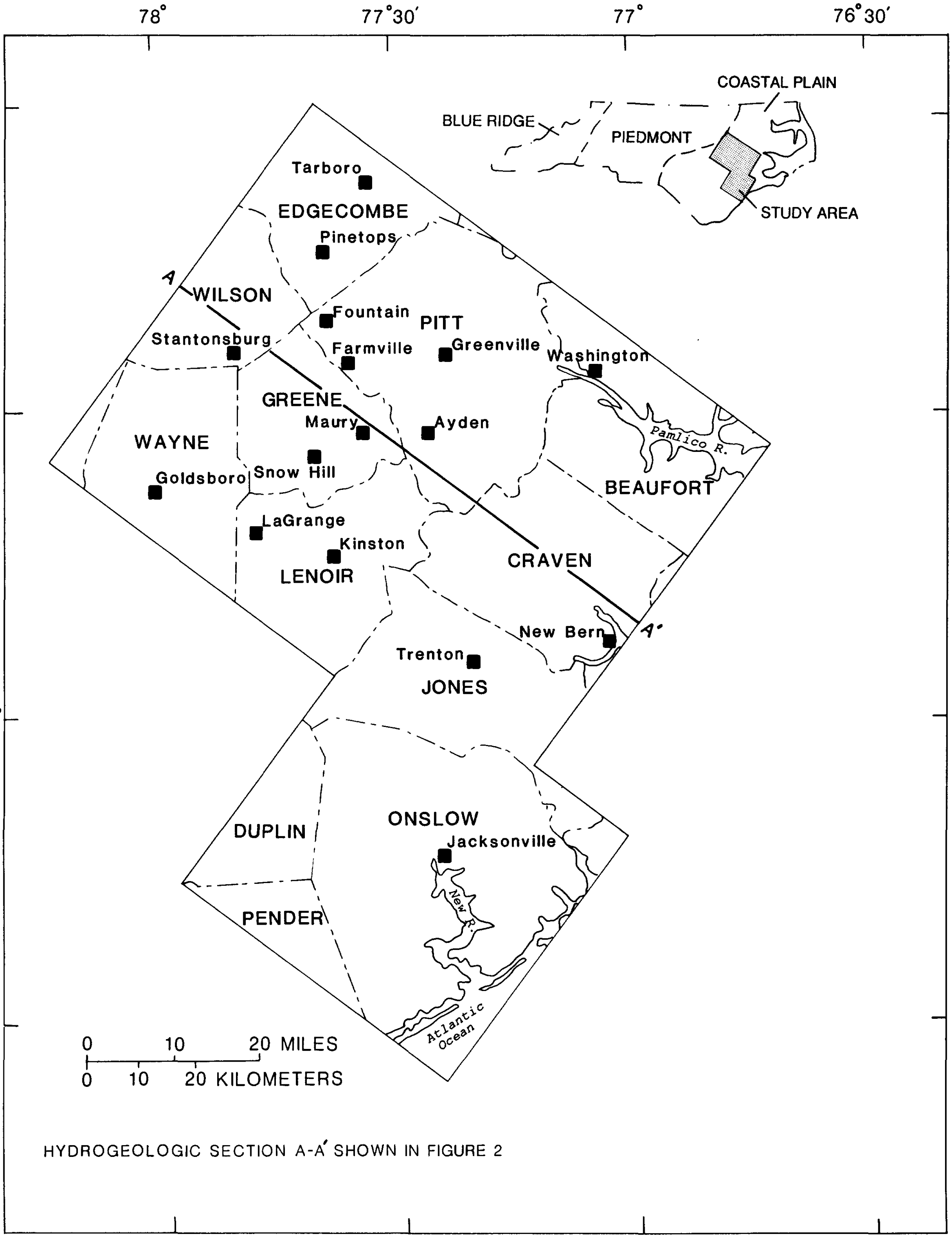

Figure 1.--The central Coastal Plain study area.

Hydrogeologic data, including altitudes of the tops and thicknesses of the hydrogeologic units used in model development, were available from an earlier investigation of the study area. Hydraulic parameters were estimated from published sources, a previous model study of the entire Coastal Plain, and from aquifer tests. Ground-water pumpage data used were for systems that withdrew at least 10,000 gal/d (gallons per day) from aquifers of Cretaceous age.

Previous Investigations

Modern hydrogeologic studies (since the 1940's) in the central Coastal Plain area of North Carolina include multi-county reconnaissances and detailed investigations of counties. A report by Brown and others (1972) described the geologic framework of the central Coastal Plain sediments as part of a multi-State investigation. Hydrogeologic reports covering multi-county areas in the central Coastal Plain include those by Mundorff (1946), Billingsley and others (1957), Brown (1959), LeGrand (1960), Pusey (1960), Narkunas (1980), and the North Carolina Department of Natural Resources and Community Development (1984). County studies include those for Craven County (Floyd, 1969; Floyd and Long, 1970), Pitt County (Sumsion, 1968), and Wilson County (Winner, 1976).

The central Coastal Plain aquifer study was developed from an earlier ground-water investigation that was completed for the entire North Carolina Coastal Plain as part of a Regional Aquifer Systems Analysis Study (RASA) conducted by the U.S. Geological Survey. The regional hydrogeologic units identified and described by the RASA study (Winner and Coble, 1989) for the North Carolina Coastal Plain were used in this study to characterize Coastal Plain sediments outside the central Coastal Plain. Hydraulic parameters resulting from the RASA analysis of the ground-water flow system (G.L. Giese, U.S. Geological Survey, written commun., 1989) were used as initial estimates for the central Coastal Plain flow model. Also, much of the conceptual ground-water flow model and model design used in the central Coastal Plain study were taken from the RASA project and are described in detail later in this report. A study of RASA model sensitivity to aquifer transmissivity and storage coefficient and confining-unit vertical leakance estimates (Eimers, 1986) was used as a guide in calibrating the central Coastal Plain flow model.

Publications resulting from the central Coastal Plain aquifer study have provided the basic data used in the modeling effort of this study. Lyke and Winner (1986) identified the location of the basement rocks in the study area. Winner and Lyke (1989) and Lyke and Winner (1989) refined previous estimates of the hydrogeologic characteristics of the aquifers and confining units in the study area. Winner and Lyke (1986) and Lyke and Brockman (1990) provide a detailed history of ground-water withdrawals and water-level decline in the study area. Potentiometric-surface maps for December 1986 were also prepared for the Peedee (Brockman and others, 1989), Black Creek (Lyke and others, 1989), upper Cape Fear (Winner and others, 1989a), and lower Cape Fear (Winner and others, 1989b) aquifers. Definitions of terms found in this report can be found in the glossary at the back.

Acknowledgments

This report is prepared in cooperation with the North Carolina Department of Environment, Health, and Natural Resources (DEHNR), Greene County, Jones County, Onslow County, City of Jacksonville, City of Kinston, City of New Bern, Town of Ayden, Town of Farmville, Town of La Grange, Town of Pinetops, Town of Snow Hill, Town of Stantonsburg, Greenville Utilities, and North Lenoir Water Corporation.

AQUIFERS IN CRETACEOUS ROCKS

Regional aquifers and confining units for the entire North Carolina Coastal Plain were first described as part of the RASA program. Ten aquifers and nine confining units (table 1) were identified (Winner and Coble, 1987) based upon geophysical log correlations and vertical differences in water-level and water-quality values throughout the North Carolina Coastal Plain. Of these hydrogeologic units, only the Lower Cretaceous aquifer and its overlying confining unit are not present in the central Coastal Plain study area.

Aquifers in the central Coastal Plain study area are composed of permeable sand and limestone beds itermixed with less permeable clay and silt beds and are the source of ground water to wells. Confining units are composed of relatively impermeable clay beds intermixed with some silt beds.

Table 1.--*Hydrogeologic units in the central Coastal Plain*

System	Series	North Carolina Coastal Plain hydrogeologic units	North Carolina central Coastal Plain hydrogeologic units
Quaternary	Holocene and Pleistocene	Surficial aquifer	Surficial aquifer
Tertiary	Pliocene and Miocene	Yorktown confining unit Yorktown aquifer	Yorktown confining unit Yorktown aquifer
	Miocene	Pungo River confining unit Pungo River aquifer	Pungo River confining unit Pungo River aquifer
	Oligocene and Eocene	Castle Hayne confining unit Castle Hayne aquifer	Castle Hayne confining unit Castle Hayne aquifer
	Paleocene	Beaufort confining unit Beaufort aquifer	Beaufort confining unit Beaufort aquifer
Cretaceous	Upper Cretaceous	Peedee confining unit Peedee aquifer	Peedee confining unit Peedee aquifer
		Black Creek confining unit Black Creek aquifer	Black Creek confining unit Black Creek aquifer
		Upper Cape Fear confining unit Upper Cape Fear aquifer	Upper Cape Fear confining unit Upper Cape Fear aquifer
		Lower Cape Fear confining unit Lower Cape Fear aquifer	Lower Cape Fear confining unit Lower Cape Fear aquifer
	Lower Cretaceous	Lower Cretaceous confining unit Lower Cretaceous aquifer	Not present
Precambrian to Paleozoic		Igneous and metamorphic rocks	

Confining units are located between adjacent aquifers, restricting the vertical flow of ground water between these aquifers. The sediments that compose the aquifers and confining units in the central Coastal Plain overlie igneous and metamorphic basement rocks (Lyke and Winner, 1986), which are the lower boundary of ground-water flow in the study area.

Aquifers in the central Coastal Plain have been divided into two aquifer systems, the aquifers in Quaternary and Tertiary rocks and the aquifers in Cretaceous rocks (Winner and Lyke, 1987; Lyke and Winner, 1989) (fig. 2). Aquifers in Quaternary and Tertiary rocks are composed of sand, clayey sand, clay, and limestone beds. From top to bottom, these aquifers are the surficial aquifer, the Yorktown aquifer, the Pungo River aquifer, the Castle Hayne aquifer, and the Beaufort aquifer. The most water productive of these aquifers is the Castle Hayne (Winner and Lyke, 1986), which is composed largely of limestone.

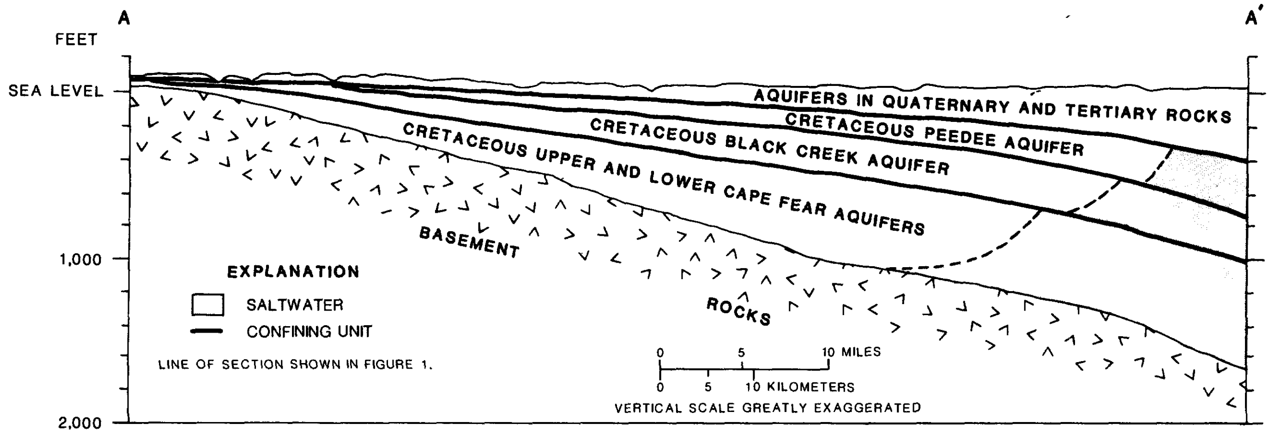

Figure 2.--Eastward-dipping Coastal Plain aquifers that overlie basement rocks (modified from Winner and Lyke, 1986).

Aquifers in Cretaceous rocks are composed of sand, silty and clayey sand, clay, and minor beds of limestone. From top to bottom, these aquifers are the Peedee aquifer, the Black Creek aquifer, the upper Cape Fear aquifer, and the lower Cape Fear aquifer. This system of aquifers and confining units thickens toward the east-southeast from less than 200 ft (feet) in the northwestern part of the study area to more than 1,800 ft in eastern Onslow County. As a group, these aquifers contain about 60 percent permeable sand and limestone; the remainder is less permeable clay and silt that occur as individual beds or intermixed with sand. The sedimentary volume of the aquifers in Cretaceous rocks is about 5 times that of the aquifers in Quaternary and Tertiary rocks. Aquifers in Cretaceous rocks are the major source of ground water for public and industrial water-supply systems in the central Coastal Plain (Winner and Lyke, 1986) and, therefore, are emphasized in this report.

This section discusses the hydrogeology, occurrence of saltwater, ground-water pumpage, and ground-water flow as related to aquifers in Cretaceous rocks of the study area. These following discussions are intended as a brief review of the hydrogeologic framework that served as the basis for the construction of the flow model described in this report.

Hydrogeology

Peedee Aquifer and Confining Unit

The Peedee aquifer in the Upper Cretaceous Peedee Formation is present southeast of a line that runs from La Grange, Lenoir County, to Greenville, Pitt County (fig. 3). The dip of the top of the aquifer is 15 ft/mi (feet per mile) toward the southeast from an altitude of more than 50 ft above sea level in western Lenoir County, to about 800 ft below sea level in eastern Onslow County.

The average thickness of the Peedee aquifer is 111 ft based on observations from 118 well logs. The aquifer is less than 10 ft thick near its northwestern margin and generally thickens to about 300 ft near New Bern, Craven County. Based on 114 well logs, the Peedee contains an average of about 65 percent sand and limestone, but this increases to about 85 percent along the northwestern boundary.

The Peedee confining unit overlies the Peedee aquifer everywhere. The confining unit averages about 28 ft thick based on observations from 130 well logs. However, it is less than 10 ft thick along its northwestern limit where the aquifer is thinnest and in scattered areas in Craven and Jones Counties. It is more than 50 ft thick in several areas in Craven, Jones, Lenoir, and Onslow Counties. The Peedee confining unit averages about 17 percent sand and limestone based on 128 well logs, but this increases to about 20 percent in Craven, Lenoir, and central Onslow Counties and in several smaller areas throughout the study area.

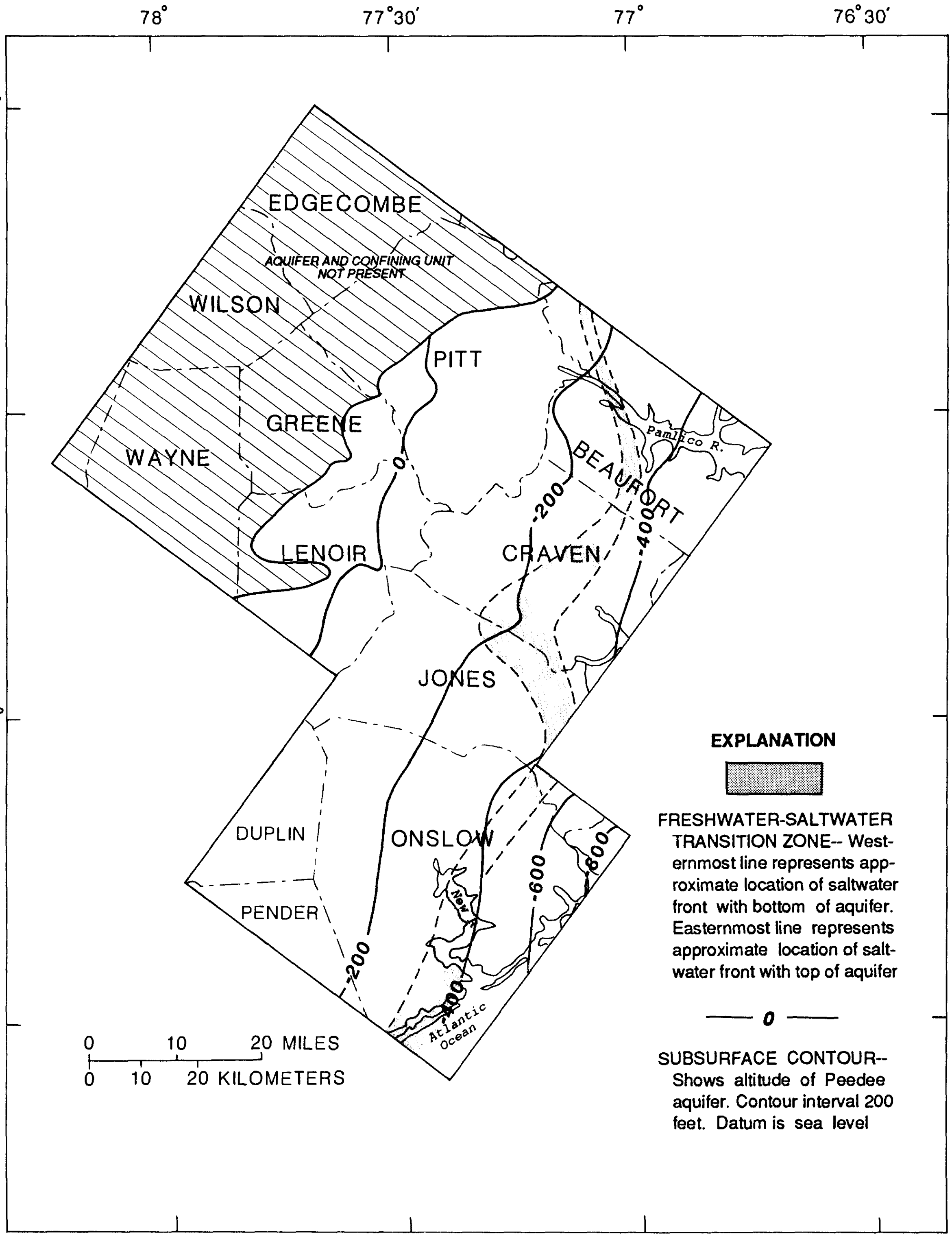

Figure 3.--Altitude of the top of the Peedee aquifer and location of freshwater-saltwater transition zone.

Black Creek Aquifer and Confining Unit

The Black Creek aquifer in the Upper Cretaceous Black Creek Formation extends southwest from a line that runs from near Tarboro in Edgecombe County to Goldsboro in Wayne County (fig. 4). The dip of the top of the aquifer increases from about 10 ft/mi in the northwestern part to about 30 ft/mi in the southeastern part of the study area. The altitude of the top of the aquifer ranges from more than 50 ft above sea level in eastern Wayne County to more than 1,000 ft below sea level in eastern Onslow County.

The Black Creek aquifer generally thickens toward the southeast from less than 10 ft at its northwestern boundary to about 500 ft in central Onslow County. The thickness of the aquifer averages 230 ft based on 91 well logs. Based on 90 well logs, the Black Creek aquifer is about 50 percent sand throughout the study area, but is as much as 68 percent sand along its northwestern boundary in Edgecombe, Greene, and Pitt Counties and in central Lenoir and Onslow Counties.

The Black Creek confining unit everywhere overlies the Black Creek aquifer. The average thickness for the unit is 49 ft based on 131 well logs, but the unit thickens toward the south and is more than 100 ft thick in Craven, Jones, and northern Onslow Counties. The maximum observed thickness is 145 ft in Craven County. Sand constitutes about 21 percent of the confining unit based on 139 well logs. The amount of sand is about 20 percent in the central part of the study area from central Pitt County to northern Onslow County.

Upper Cape Fear Aquifer and Confining Unit

The upper Cape Fear aquifer in the Upper Cretaceous Cape Fear Formation is present throughout the central Coastal Plain study area (fig. 5). The altitude of the top of the aquifer ranges from less than 200 ft below sea level in the western part of the study area to more than 1,400 ft below sea level in eastern Onslow County. The dip of the top of the aquifer is about 37 ft/mi in the eastern part of the study area.

The aquifer thickens toward the southeast from a minimum observed thickness of 8 ft in Wilson County to more than 400 ft in Beaufort County.

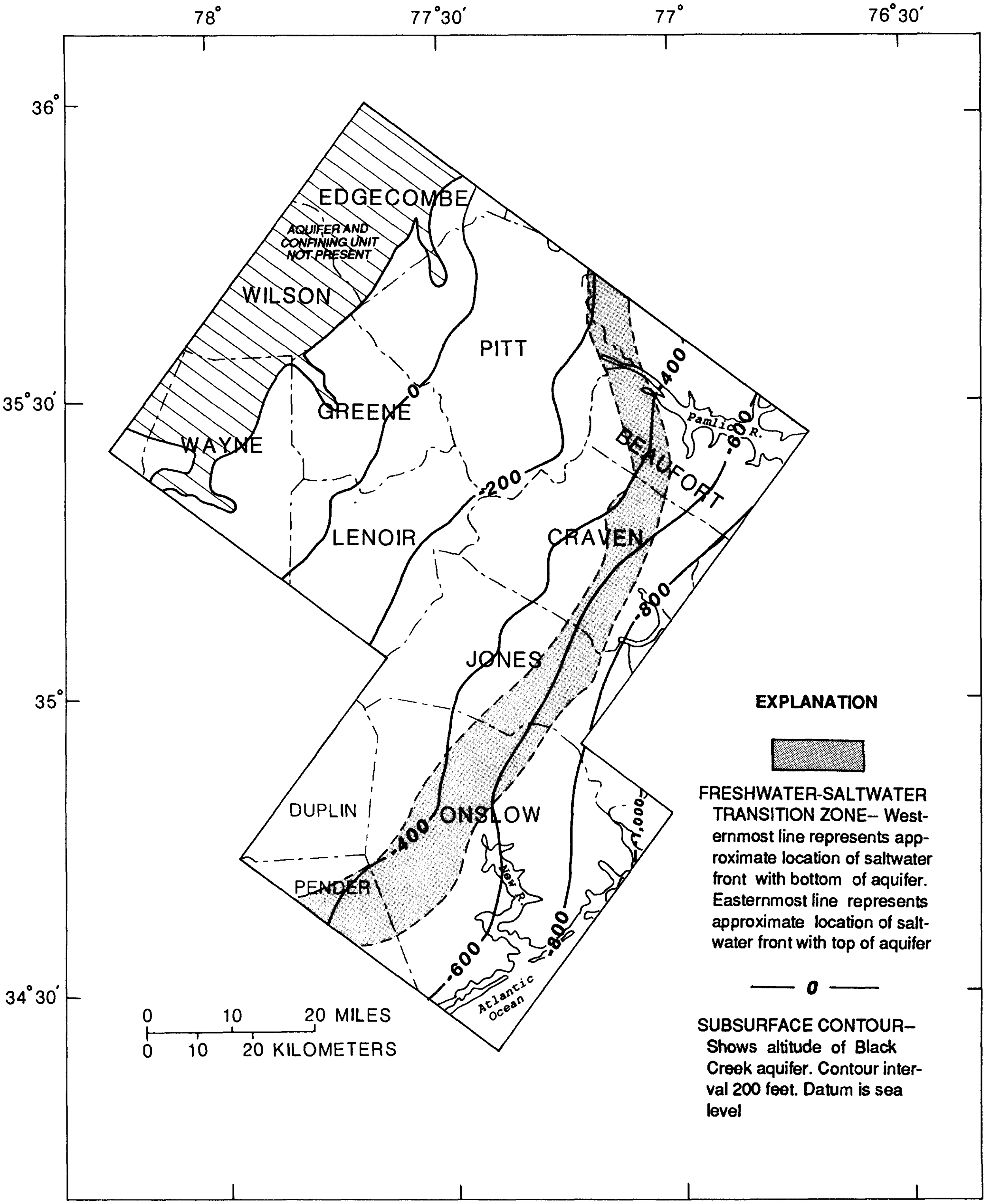

Figure 4.--Altitude of the top of the Black Creek aquifer and location of freshwater-saltwater transition zone.

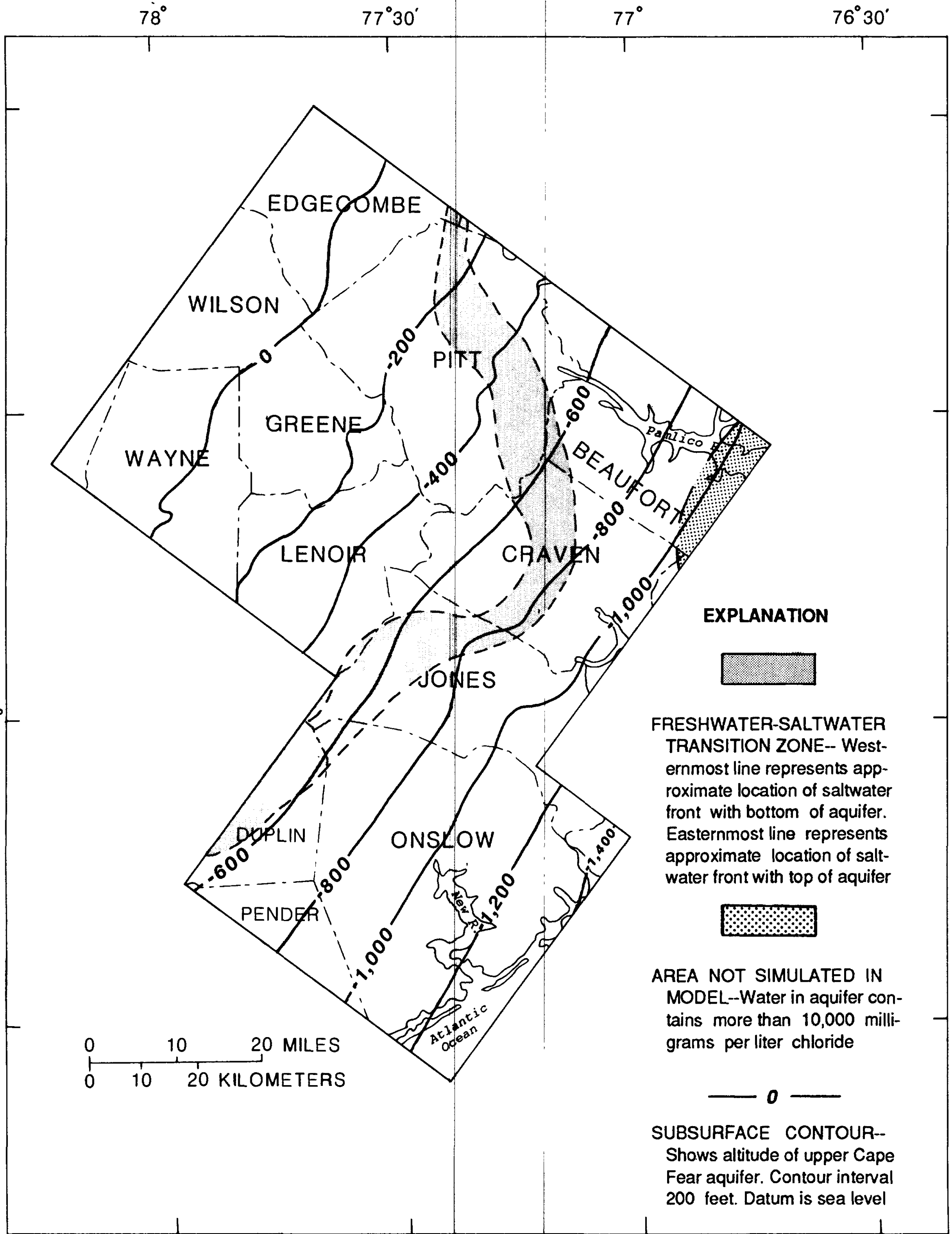

Figure 5.--Altitude of the top of the upper Cape Fear aquifer and location of freshwater-saltwater transition zone.

The average thickness is 134 ft based on 53 well logs. The percentage of sand and limestone in the aquifer averages 60 percent from 51 well-log observations, but may be as much as 79 percent in the northwest part of the study area from Edgecombe to Wayne Counties where the unit is thin and in southern Craven, Jones, and Onslow Counties where the aquifer generally is less than 100 ft thick.

The upper Cape Fear confining unit overlies the upper Cape Fear aquifer where the aquifer is present. Based on 96 well logs, the confining unit averages about 37 ft thick. This confining unit is more than 50 ft thick in Jones and Onslow Counties and at several other locations in the study area. It is less than 25 ft thick in the northwest part of the study area in Edgecombe, Wilson, and Wayne Counties and in parts of Craven, Lenoir, and Pitt Counties. The upper Cape Fear confining unit averages 18 percent sand based on 96 well logs, but may be as much as 32 percent sand in some areas. Areas where the confining unit contains 20 percent or more sand include part of Edgecombe, Greene, Lenoir, Onslow, Pitt, Wayne, and Wilson Counties.

Lower Cape Fear Aquifer and Confining Unit

The lower Cape Fear aquifer in the Cape Fear Formation is present south of a line from western Pitt County to central Lenoir County (fig. 6). The aquifer dips toward the east-southeast from about 16 ft/mi at its northwestern boundary to more than 50 ft/mi in the southeast part of the study area. The altitude of the top of the aquifer ranges from less than 400 ft below sea level in western Pitt County to more than 1,600 ft below sea level in eastern Beaufort and Onslow Counties.

The lower Cape Fear aquifer generally thickens downdip from its northwestern boundary, where it is 19 ft thick in Greene County to about 600 ft in Beaufort County. The average thickness based on 27 well logs, is 150 ft. The aquifer averages about 60 percent sand based on logs from 25 wells that completely penetrate the aquifer. The amount of permeable material in this aquifer is as much as 90 percent along the western boundary of the aquifer in Greene County and is as little as 48 percent near the Jones-Craven County border.

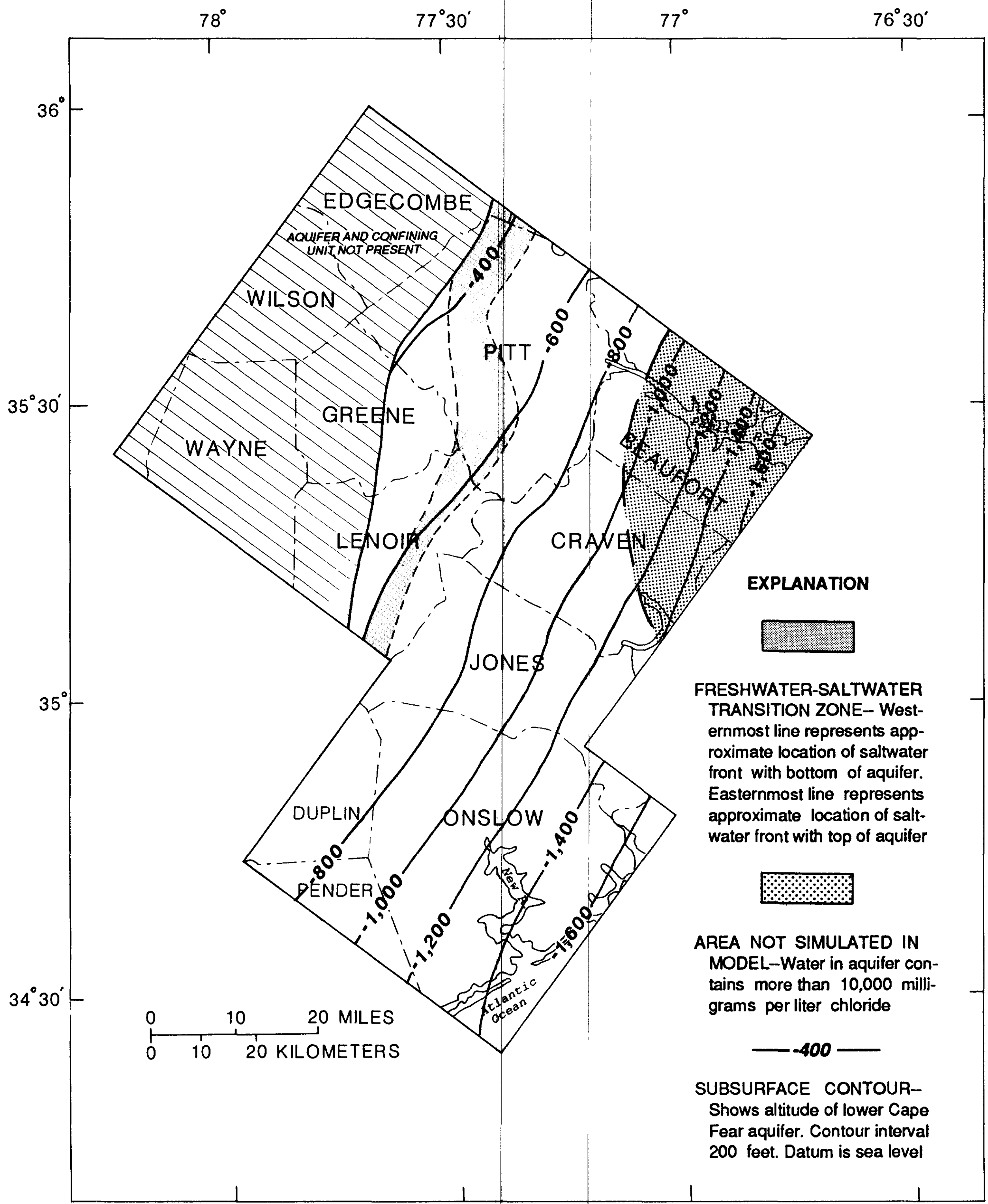

Figure 6.--Altitude of the top of the lower Cape Fear aquifer and location of freshwater-saltwater transition zone.

The lower Cape Fear confining unit overlies the lower Cape Fear aquifer everywhere the aquifer is present. The confining unit thickens to the east-southeast from an observed minimum of 7 ft near Farmville in Pitt County to a maximum of 74 ft near Jacksonville in Onslow County. Its average thickness is 38 ft based on 34 well logs. Locally, the confining unit is about 50 ft thick near Maury in Greene County and east of Jacksonville in Onslow County. The amount of sand in the unit averages about 19 percent based on 34 well logs but is locally about 20 percent in Onslow County and in a north-trending band through central Craven and Pitt Counties.

Occurrence of Saltwater

Saltwater, for purposes of this report, is defined as water with a chloride concentration equal to or greater than 250 mg/L (milligrams per liter), which is the upper limit for drinking water established by the U.S. Environmental Protection Agency (1984). Chloride concentration generally increases with depth and in the downdip (or seaward) direction in the aquifer system in Cretaceous rocks. Saltwater does not occur commonly in aquifers in the western part of the study area, although local occurrences of saltwater derived from seawater trapped in bedrock beneath the sediments have been documented in this area (Winner, 1976).

The 250 mg/L chloride concentration of water in an aquifer is represented in cross section as an upward concave line (fig. 2) called the freshwater-saltwater interface. In map view the interface is represented as an area or transition zone. The western-most line of the transition zone represents the presence of saltwater in the bottom of the aquifer, and the easternmost line indicates saltwater at the top of the aquifer (Winner and Lyke, 1989). The location of the freshwater-saltwater transition zones for aquifers in Cretaceous rocks in the study area are shown in figures 3-6.

Water with a chloride concentration equal to or greater than 10,000 mg/L is used in this report to define the location of the downdip no-flow boundary in the flow model as discussed in a following section. The Peedee and Black Creek aquifers of the study area do not contain saltwater of this concentration. In the upper and lower Cape Fear aquifers, however, water containing 10,000 mg/L chloride is present in the northeastern part of the study area (Winner and Coble, 1989).

Ground-Water Withdrawals

Significant withdrawals from aquifers in Cretaceous rocks of the central Coastal Plain began about the year 1900 when public water supplies were beginning to be constructed; Darton (1896) reported public water-supply systems in Kinston, New Bern, Washington, and Tarboro. For modeling purposes, ground-water flow conditions at about 1900 were assumed to represent prepumping conditions. Withdrawals from public and industrial water systems, which are included in this investigation and incorporated into the flow model, are those that exceed 10,000 gal/d.

Sources of ground water for municipal and industrial water-supply systems in the study area are the Peedee, Black Creek, and upper Cape Fear aquifers. The lower Cape Fear aquifer is not a source of potable ground water because the chloride concentration of the water exceeds 250 mg/L everywhere except possibly along the northwestern limit of the aquifer (Winner and Lyke, 1989). The area where the aquifers in the sediments of Cretaceous age are the major source of freshwater is shown in figure 7a. The locations of major public and industrial supply wells withdrawing from the Peedee, Black Creek, and upper Cape Fear aquifers in 1986 are shown in figures 7b, 7c, and 7d, respectively.

The principal source of ground water in the study area is the Black Creek aquifer, which produced about 19.50 Mgal/d in 1986 (fig. 8), or about 68 percent of the water withdrawn from the aquifer system in Cretaceous rocks. Withdrawals from other aquifers included about 8.30 Mgal/d (27 percent) from the upper Cape Fear aquifer and 1.55 Mgal/d (5 percent) from the Peedee aquifer.

Ground-water withdrawals in the study area increased from about 0.25 Mgal/d in 1910 to about 29 Mgal/d in 1986 (table 2). The number of water systems withdrawing more than 10,000 gal/d increased from 2 to 49 during this same period. During 1980-86, the amount of ground-water withdrawn increased at 25 of these systems, decreased at 12 systems, and remained unchanged at 12 water systems.

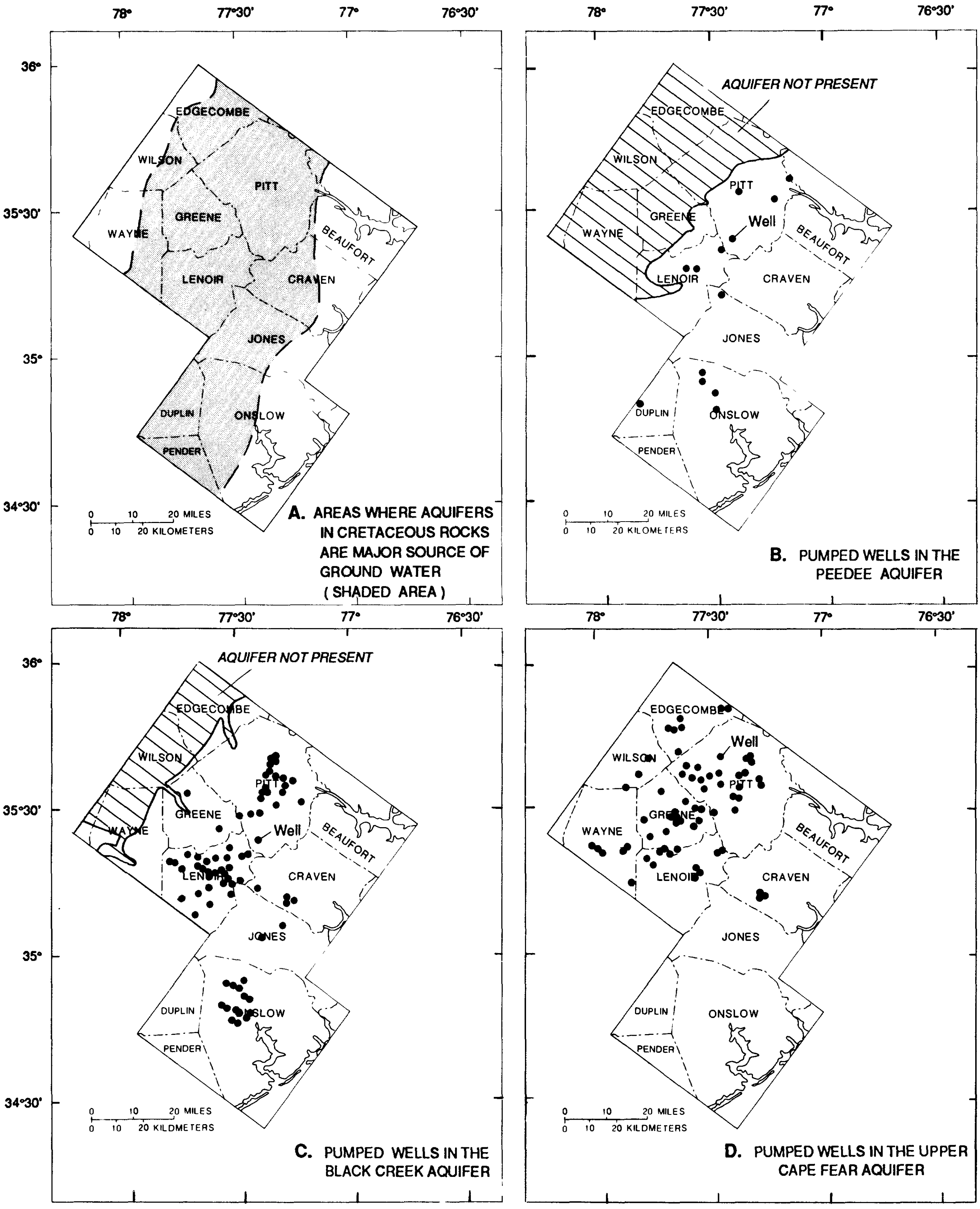

Figure 7.--Area where the aquifers in Cretaceous rocks are the major sources of ground water (a), and location of wells pumped in 1986 in (b) the Peedee aquifer, (c) the Black Creek aquifer, and (d) the upper Cape Fear aquifer.

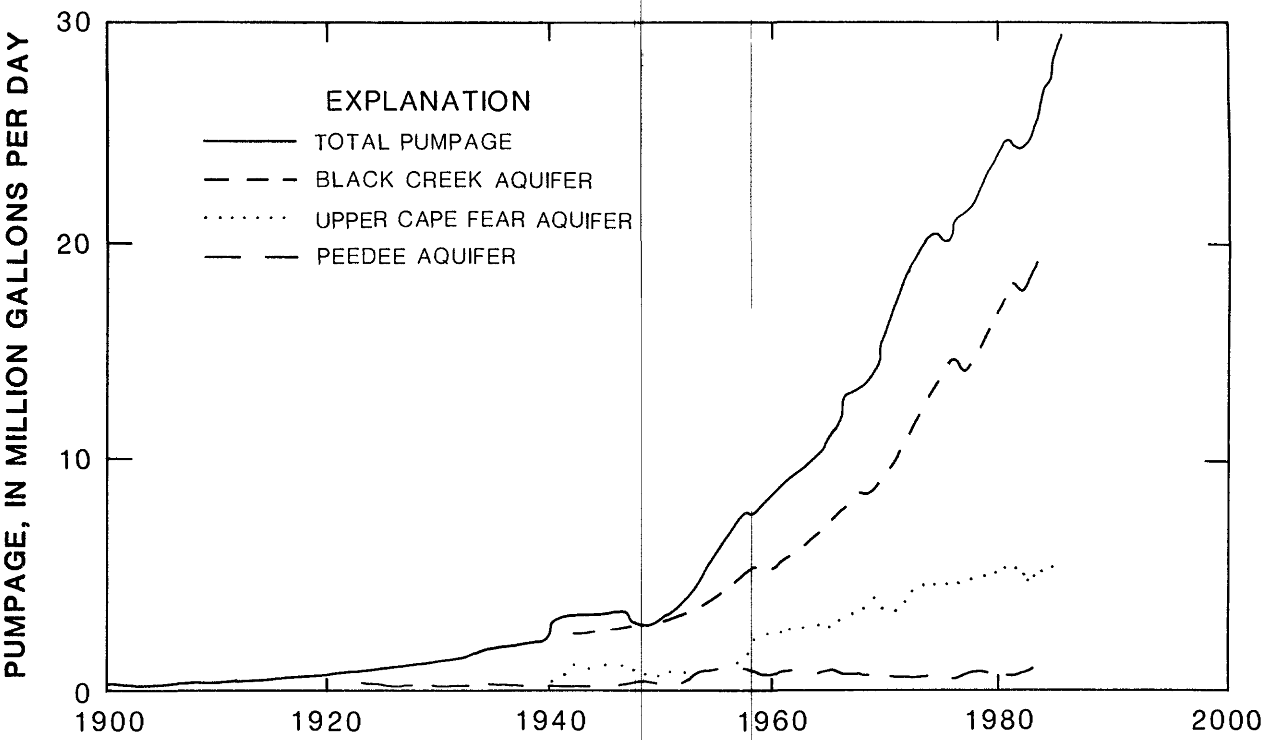

Figure 8.--Estimated ground-water pumpage from the Black Creek, upper Cape Fear, and Peedee aquifers.

Table 2.--*Ground-water pumpage by water systems tapping aquifers in Cretaceous rocks of the central Coastal Plain, 1910-86*
(modified from Winner and Lyke, 1986)
[Annual average pumpage in million gallons per day; --, system discontinued]

Water system	1910	1920	1930	1940	1950	1960	1970	1980	1986
Caswell School	0.13	0.13	0.16	0.19	0.22	0.26	0.30	--	--
Kinston	.12	.40	.80	1.35	1.95	2.66	3.47	5.37	4.65
Ayden		.04	.04	.07	.10	.17	.30	.39	.35
La Grange		.03	.04	.04	.08	.14	.20	.28	.42
Grifton		.01	.02	.02	.02	.08	.12	.15	.18
Hookerton			.07	.07	.07	.09	.10	.12	.20
Farmville			.05	.12	.37	.65	1.76	1.80	1.75
Bethel			.03	.04	.11	.20	.24	.28	.16
Snow Hill			.02	.04	.05	.08	.18	.47	1.06
Pinetops			.02	.04	.05	.07	.11	.16	.21
Stantonsburg			.01	.01	.04	.06	.10	.08	.12
Seymour Johnson AFB				1.00	1.08	1.16	.83	.92	.77
Winterville				.02	.05	.06	.10	.18	.38
Richlands				.01	.06	.06	.06	.23	.20
Fountain				.01	.02	.03	.04	.04	.04
Macclesfield					.02	.03	.06	.07	.06
Walstonburg					.01	.01	.02	.09	.07
DuPont Corporation						2.48	3.95	3.12	2.78
Greenville						.56	1.52	2.17	1.80
Smithfield Foods, Inc.						.30	.35	.40	.40
Saratoga						.02	.03	.04	.05
Grimesland						.02	.02	.10	.25
Eureka						.01	.01	.01	.02
Jacksonville							1.76	2.78	3.64
New Bern at Cove City							1.04	3.46	2.61
North Lenoir							.20	.40	.60
Eastern Pines							.14	.64	.78
Deep Run							.10	.40	.68
Crestview							.08	.09	.09
Maury							.04	.06	.06
Conetoe							.02	.06	.07
Dover							.02	.03	.03
Ormondsville							.02	.02	.02
Walnut Creek							.01	.05	.06
Saulston							.01	.03	.04
Arba							.01	.02	.02
Lizzie							.01	.01	.01
Hillview							.01	.01	.01
Bell Arthur								.25	.37
Jones County								.22	.45
Beulaville								.11	.13
Greene County								.05	.10
Falling Creek								.04	.05
Jason								.04	.05
Stokes								.03	.03
Northwest Onslow								.02	.06
Chinquapin								.02	.02
Seven Springs								.01	--
Onslow County									3.45
Totals	0.25	0.61	1.26	3.03	4.30	9.20	17.34	25.32	29.35

Conceptual Ground-Water Flow Model

The construction of a model to simulate ground-water flow must be based on a concept of how water moves into (recharge), out of (discharge), and is stored in the ground-water system. This section outlines the concept of ground-water flow used for this model.

Recharge and discharge are commonly expressed as components of a water budget that uses precipitation as the source of water. Water enters the ground-water system in recharge areas and leaves the system in discharge areas. The source of recharge to aquifers is precipitation entering and percolating through the various hydrogeologic units comprising the system.

In the Coastal Plain of North Carolina, all interstream areas are areas of recharge to the unconfined surficial aquifer. Stream valleys and their flood plains, low swamps, and estuaries are areas of discharge from the surficial aquifer. This areal pattern of recharge to an aquifer in interstream areas and discharge from an aquifer in stream valleys and other lowlands is most pronounced in the surficial aquifer. Under natural (non-pumped) conditions, this pattern also extends to the confined aquifers. However, in confined aquifers, the effect of localized recharge and discharge lessens with increasing depth of the aquifer. At depths where local variations in recharge and discharge no longer significantly affect the pattern of recharge and discharge, it is regional variations that determine recharge and discharge areas.

Wilder and others (1978) presented the components of a generalized annual water budget for a typical location in the eastern Coastal Plain of North Carolina under natural conditions (fig. 9). Precipitation there is about 50 in. (inches) per year. Of this amount, about 34 in. is lost to evapotranspiration; about 5 in. is overland runoff, and about 11 in. reaches the water table and, thus, recharges the unconfined surficial aquifer. Of this ground-water recharge, 10 in. moves mainly through the surficial aquifer and discharges to streams, and only about 1 in. moves downward as recharge to confined aquifers.

As shown in figure 10, recharge to aquifers in Cretaceous rocks occurs in interstream areas. Under natural prepumping conditions, water in the

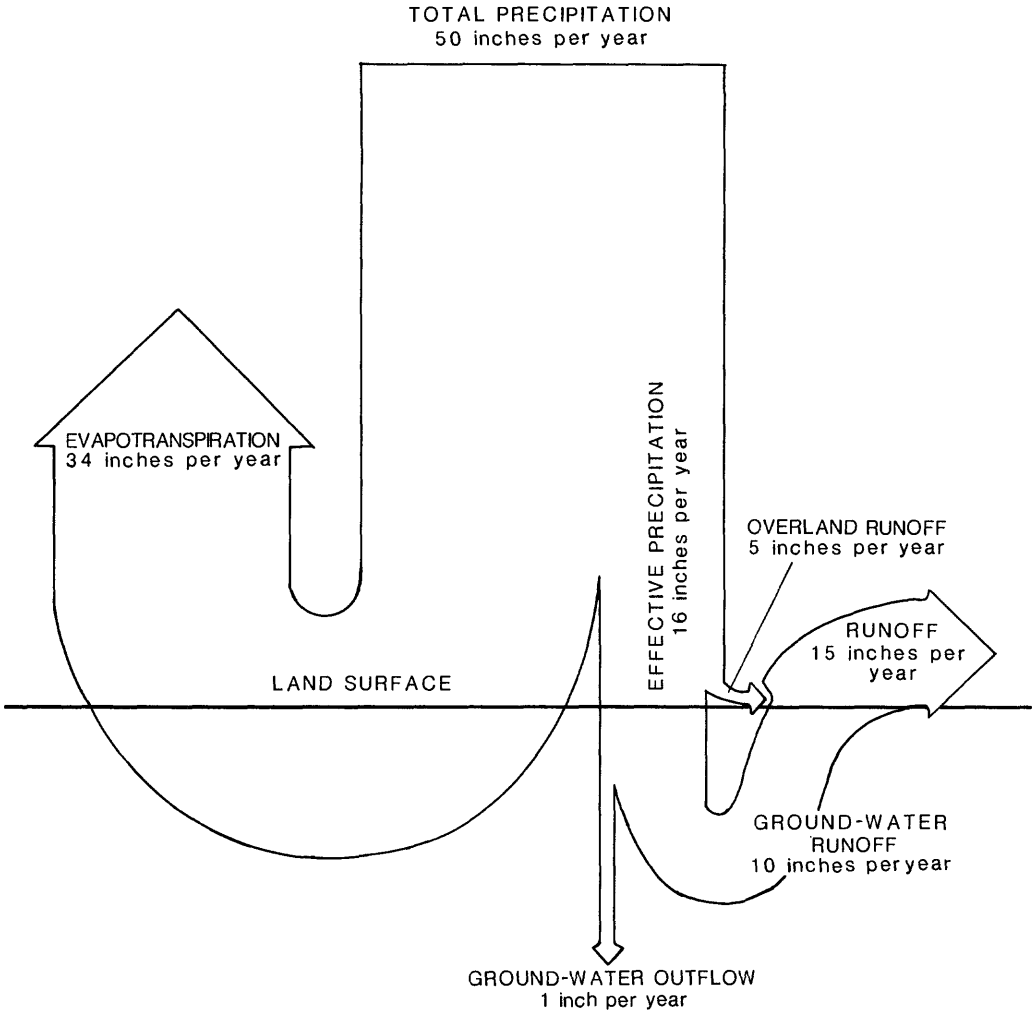

Figure 9.--Generalized water budget for a typical area in the North Carolina Coastal Plain (from Wilder and others, 1978, fig. 11).

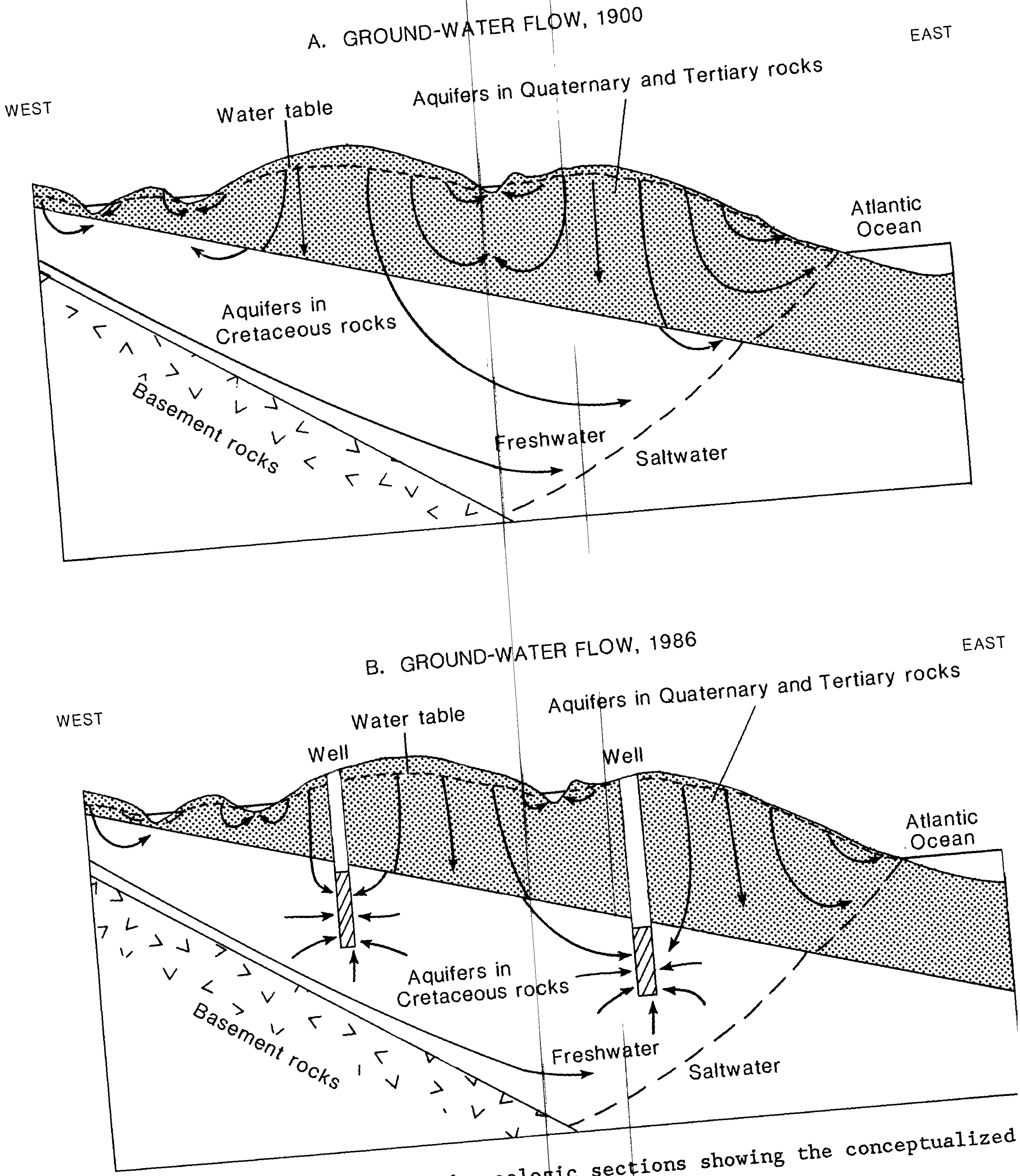

Figure 10.--Generalized hydrogeologic sections showing the conceptualized path of ground-water flow (a) before and (b) after ground-water pumpage began.

Cretaceous sediments is either discharged to streams where these sediments are near land surface in the western part of the study area, or is discharged upward through the Quaternary and Tertiary sediments to lowland swamps and estuaries in the eastern part of the area.

Under equilibrium conditions, which existed in the central Coastal Plain before the various pumping centers became established, recharge to the ground-water system was balanced by discharge, and there was no change in ground-water storage. This equilibrium has been disturbed in the study area by withdrawal of water from wells. The effect of ground-water pumpage on the regional flow pattern is illustrated in figure 10b. The ground-water system adjusts to this added discharge in five ways: (1) increased recharge occurs from the overlying aquifer system in Quaternary and Tertiary rocks; (2) decreased discharge occurs from the aquifer system in Cretaceous rocks to the overlying aquifer system in Quaternary and Tertiary rocks; (3) discharge to some streams is reduced; (4) ground water is released from aquifer storage, as indicated by declining water levels in the aquifer system in Cretaceous rocks; and (5) fresh ground water in aquifer storage is reduced by the inland movement of saltwater.

The flow model of the Coastal Plain ground-water system may be conceptualized in the form of a wedge. The bottom of the wedge is formed by the top of the crystalline basement rocks. These rocks are of low permeability, have no significant exchange of water with overlying hydrogeologic units, and, therefore, are assumed to be a no-flow boundary.

The eastern or seaward side of the sediment wedge, which is its thickest part, is also assumed to be a no-flow boundary. This no-flow boundary is represented by the 10,000 mg/L chloride contour as given by Meisler (1981) and is assumed to be stationary. The implications of this representation are discussed later in this report. The western side of the model is the thin edge of the wedge, where the hydrogeologic units pinch out updip and is also considered a no-flow boundary.

The upper boundary of the wedge is the water table with an assumed constant-head, where the net annual change in ground-water levels and ground-water storage of the surficial aquifer is assumed to be zero. The remaining boundaries are at the Statelines with Virginia and South Carolina, across which ground-water flows have been specified (G.L. Giese, U.S. Geological Survey, written commun., 1989). The nature of the flows across Statelines is discussed later in this report.

GROUND-WATER FLOW SIMULATION

Ground-water flow in the entire North Carolina Coastal Plain is simulated using the model constructed in this study, although model results discussed in this report are limited to the central Coastal Plain study area. Emphasis in the simulation is on the aquifers in Cretaceous rocks in the central Coastal Plain.

The simulation, as presented in this section, involves choosing a suitable model code for the physical system and selecting a grid size to represent discrete cells through which ground water flows. Time steps are selected to best represent changing conditions, and various physical parameters that characterize the system are determined. The last step in simulation involves calibration of the model to match as closely as possible observed water levels in each of the aquifers.

Model Code Selection

The model code selected for this study is a finite-difference, three-dimensional ground-water flow model (McDonald and Harbaugh, 1984). The model code is similar to the one used in the North Carolina RASA study (G.L. Giese, U.S. Geological Survey, written commun., 1989). The model used in the RASA study was described by Leahy (1982) and is a version of a three-dimensional finite-difference flow model program presented by Trescott (1975) and Trescott and Larson (1976). The model developed by McDonald and Harbaugh (1984) is modularized so that the model code may be more readily modified. It is easy to use and maintain and is relatively efficient with respect to computer memory and execution time (McDonald and Harbaugh, 1984, p. 2).

Grid Design

The finite-difference solution technique requires that the modeled area be discretized horizontally into a two-dimensional grid (fig. 11) and

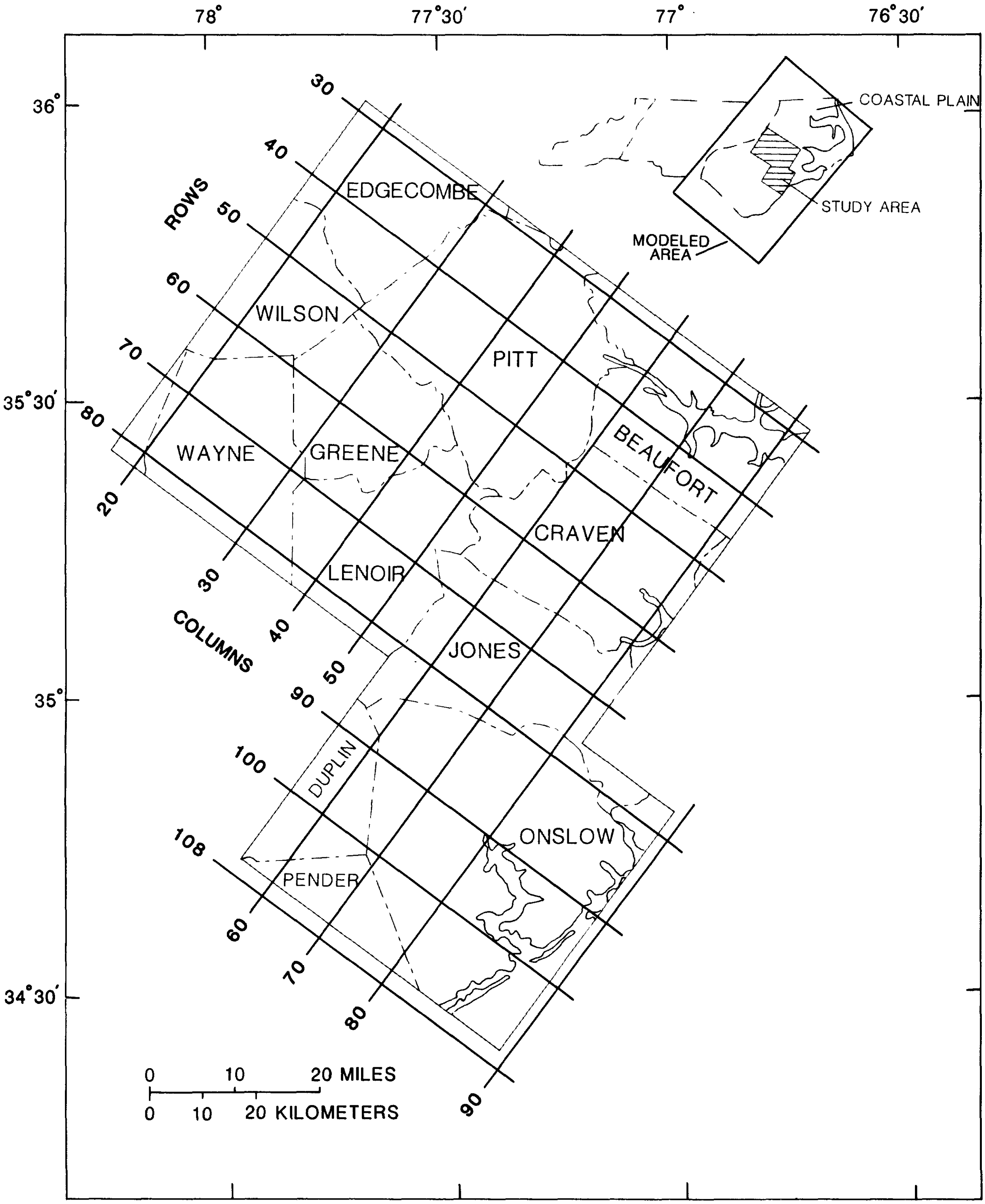

Figure 11.--The finite-difference model grid showing spatial discretization in the central Coastal Plain study area. (Grid spacing is variable)

vertically into layers. All 10 aquifers of the entire North Carolina Coastal Plain were modeled using 10 layers. However, only the Peedee, Black Creek, and upper and lower Cape Fear aquifers of the aquifer system in Cretaceous rocks in the central Coastal Plain are the aquifers of primary concern in this study.

Rows and columns for this model are parallel to rows and columns of the RASA model (G.L. Giese, U.S. Geological Survey, written commun., 1989). The central Coastal Plain model grid has 120 rows and 102 columns, which form 122,400 cells in the 10 layers of the model. In areas where a particular aquifer is not present, or in areas where the ground-water chloride concentration is greater than 10,000 mg/L, the cells are coded in such a way as to make them "inactive." Thirty percent of the nodes in this model application are inactive. The RASA model grid is coarse relative to the grid eventually selected for the central Coastal Plain model. Throughout about 60 percent of the central Coastal Plain area, 16 cells correspond to one RASA cell. In the remaining 40 percent of the central Coastal Plain area, one RASA cell corresponds to 3, 6, 9, or 12 cells.

Within the study area, cell size averages 0.98 mi^2. Fifty-five percent of the study area is discretized into the smallest cells in the model; these have linear dimensions of 0.875 mi by 0.875 mi, or 0.766 mi^2. Gradually, cell size, or grid spacing, was expanded away from the center of the study area. The largest cells in the modeled area are at the outer limits of the modeled area, well outside the central Coastal Plain, and are 56.25 mi^2.

Temporal Discretization

"Temporal discretization" means averaging data that change through time over discrete periods to represent changing conditions. Twelve time periods, ranging in length from 3 to 21 years (as shown on the following page), were used to simulate substantial changes in rates of pumpage or changes in location of pumpage from 1900 to 1986. Pumpage from a given well during each period is the average pumpage from that well during that period. Using the model to predict water levels after 1986 requires that time periods be added to the calibrated model. The predictive examples in this report included the period from 1987 through 1991.

Time period	Years	Time period	Years
1	1900-1920	7	1965-1967
2	1921-1939	8	1968-1972
3	1940-1945	9	1973-1977
4	1946-1952	10	1978-1980
5	1953-1957	11	1981-1983
6	1958-1964	12	1983-1986

Boundary fluxes also change with time. Flows across State-line boundaries, provided to this model by the RASA investigation, were calculated at the end of a time period. These are assumed to estimate the boundary flux for that entire period. Boundary fluxes after 1980 are also assumed to remain unchanged, because no estimates of later fluxes are available from RASA. Because these specified fluxes are distant from the study area, no significant error is believed to be introduced to the model by this assumption.

Model Parameters

Components of the conceptual model of ground-water flow are represented in the simulation by model parameters. In this report, model parameters are hydraulic properties, pumpage, boundary conditions, and initial hydraulic head conditions. Hydraulic properties are transmissivity and storage coefficients of the aquifers and vertical leakance of the confining units.

The center of each cell formed by layering the model grid is a point called a node at which hydraulic heads are calculated by the model. Each cell is assigned a set of input parameters--aquifer transmissivity, storage coefficient, confining-unit vertical leakance, and initial head. A head value is assigned to the node, but transmissivity and storage coefficients are average values for the volume of aquifer that a cell represents. Vertical leakance is the average value for that region of the confining unit that overlies the cell. Pumpage from a cell and fluxes across model boundaries also are assigned to some nodes and represent the net amount of water leaving or entering those cells due to pumping or boundary conditions.

The data values of all parameters were estimated for each active cell in the model grid and were derived from (1) the RASA ground-water flow model

(G.L. Giese, U.S. Geological Survey, written commun., 1989), (2) analyses of hydrogeologic data, such as well logs and aquifer tests, (3) water-supply system records, and (4) published reports. Changes were made to initial estimates during the calibration of the flow model; this process is discussed in the model calibration section of this report.

Hydraulic Coefficients

The prinicpal hydraulic coefficients used in the simulation of ground-water flow are transmissivity and vertical hydraulic conductivity. Horizontal flow in the ground-water system is expressed as the transmissivity of the aquifer, whereas vertical flow is governed by the vertical hydraulic conductivity of confining units between aquifers (see glossary). Field observations of transmissivity in the study area are available from aquifer tests and are presented in table 3, but vertical hydraulic conductivities are estimated from laboratory tests. The coefficient of storage is also briefly discussed in this section.

The Peedee aquifer has a median transmissivity of 2,170 ft^2/d (feet squared per day) in the study area (table 3). Median observed transmissivity values for this aquifer exceed 2,500 ft^2/d for two counties in the southern part of the study area--Jones and Onslow Counties. The median observed transmissivity values are less than 1,000 ft^2/d in the northwest part of the study area in Greene and Wayne Counties.

Median transmissivity of the Black Creek aquifer is 2,330 ft^2/d in the study area (table 3). Median observed transmissivity values for this aquifer exceed 2,500 ft^2/d in four counties in the eastern part of the study area--Beaufort, Craven, Lenoir, and Pitt Counties. Only in Wayne County are the median observed transmissivity values less than 1,000 ft^2/d .

The upper Cape Fear aquifer has a median transmissivity of 1,770 ft^2/d in the study area (table 3). Median observed transmissivity values for this aquifer exceed 2,500 ft^2/d in three counties in the eastern part of the study area--Beaufort, Craven, and Onslow Counties. The lowest median observed transmissivity value is 1,080 ft^2/d in Wilson County.

Table 3.--*Transmissivity estimates derived from aquifer tests in the central Coastal Plain study area*

[Values in feet squared per day; number in parentheses indicates number of aquifer tests; --, no data]

County	Peedee aquifer				Black Creek aquifer				Upper Cape Fear aquifer			
	Average	Median	Maximum	Minimum	Average	Median	Maximum	Minimum	Average	Median	Maximum	Minimum
Beaufort	1,790 (4)	1,740	2,560	1,130	3,240 (3)	3,060	4,340	2,320	3,050 (1)	3,050	3,050	3,050
Craven	2,180 (8)	2,130	2,700	1,630	5,890 (5)	5,850	6,960	4,800	4,570 (2)	4,570	6,390	2,750
Edgecombe	--	--	--	--	--	--	--	--	1,250 (1)	1,250	1,250	1,250
Greene	450 (1)	450	450	450	1,470 (2)	1,470	2,220	710	2,300 (5)	1,920	3,450	1,380
Jones	2,620 (2)	2,620	3,030	2,210	2,340 (4)	2,300	3,420	1,360	--	--	--	--
Lenoir	1,700 (5)	1,840	2,800	600	3,200 (6)	3,540	4,350	1,770	1,940 (2)	1,940	2,200	1,680
Onslow	5,250 (5)	5,250	7,090	3,750	2,900 (11)	1,520	7,590	1,060	3,220 (3)	3,740	4,150	1,770
Pitt	--	--	--	--	2,980 (2)	2,980	3,900	2,060	2,010 (3)	2,220	2,600	1,210
Wayne	430 (1)	430	430	430	1,110 (5)	810	2,730	520	1,230 (6)	1,440	1,900	270
Wilson	--	--	--	--	--	--	--	--	1,080 (2)	1,080	1,750	400
Aquifer summary	2,520 (26)	2,170	7,090	430	3,000 (38)	2,330	7,590	520	2,160 (25)	1,770	6,390	270

There are no aquifer tests available for the lower Cape Fear aquifer in the study area. Estimated values for this aquifer were based on model simulated values derived from the RASA ground-water flow model (G.L. Giese, U.S. Geological Survey, written commun., 1989).

Values of transmissivity determined from aquifer tests are used to estimate average transmissivity for each cell in the model. Any given transmissivity value input to a cell may differ from an aquifer test value by as much as 100 percent.

The vertical movement of water between aquifers through a confining unit is a function of vertical leakance. Vertical hydraulic conductivity of individual units tends to decrease toward the coast and with depth because the material comprising the confining units is compacted with depth of burial. A common range for vertical hydraulic conductivity values for clay-size material is 4×10^{-6} to 1×10^{-3} ft/d; a common range for silt-size material is 3×10^{-5} to 2 ft/d (Morris and Johnson, 1967).

The storage coefficient value selected for use in confined aquifers was 1×10^{-4} (dimensionless). For the unconfined aquifer, a storage coefficient value of 0.15 (dimensionless) was used. These values are identical to the storage coefficients used in the RASA model.

Pumpage

To simulate the effect of ground-water pumpage on aquifers in Cretaceous rocks, the history of pumpage by major ground-water users was constructed (Winner and Lyke, 1986; Lyke and Brockman, 1990). Pumpages greater than 10,000 gal/d from these aquifers within the central Coastal Plain were inventoried for the period from 1900 to 1986; those greater than 100,000 gal/d were inventoried for all aquifers outside the central Coastal Plain for the period from 1980 to 1986. Data from the RASA study provided pre-1980 pumpages for the modeled area outside the study area (G.L. Giese, U.S. Geological Survey, written commun., 1989).

Pumpage values used in the model were annual averages recorded by the user. However, some values were estimated from user records. A few water-system records include water pumped by each well in the system, whereas most users record only the total pumpage for a well field or for the entire system. For water systems where pumpage was not recorded for each well, the withdrawal from each well was estimated by multiplying the system's total pumpage by the ratio of the yield of each well to the total yield of all wells. Some wells withdraw water from more than one aquifer. In these instances, withdrawals from each aquifer were estimated by multiplying the total pumpage recorded or estimated for each well by the ratio of the vertical length of screen in the aquifer to the total length of screen in the well.

Annual pumpage values for some water systems were not available, particularly for earlier years. Pumpage for these years were estimated based on well yields, well history, and other methods described in Winner and Lyke (1986).

About 200 pumping wells were inventoried for water use in the study area. Well yields recorded for 166 of these wells (table 4) indicate an average yield per well for all aquifers in Cretaceous rocks is 365 gpm (gallons per minute). Well yields are highest for the Black Creek aquifer. Wells screened in only that aquifer have average yields of about 515 gpm. Wells with the highest average yield are those in which the Black Creek aquifer is screened in conjunction with the upper Cape Fear aquifer. The average yield for these wells is 655 gpm.

Table 4.--*Average well yields in the aquifers of the central Coastal Plain*

[Numbers in parentheses are numbers of observations]

	Well yields, in gallons per minute			
Aquifers	Minimum	Maximum	Average	
Peedee	35	460	232	(7)
Black Creek	100	1,100	515	(53)
Upper Cape Fear	40	700	270	(66)
Peedee and Black Creek	200	610	392	(9)
Black Creek and upper Cape Fear	100	1,400	655	(30)
Peedee, Black Creek, and upper Cape Fear	605	605	605	(1)
Summary for all aquifers	35	1,400	365	(166)

Boundary Conditions

The simulated boundary conditions represent the conceptualization of the limits of the ground-water flow system. Boundary conditions include the configuration of the boundary and specification of values of hydraulic head at a boundary or ground-water flow across the boundary. Three types of ground-water flow boundaries are used in this model: specified-flux, no-flow (specified flux of zero), and specified-head boundaries.

Specified-flux boundaries are those at which the amount of water flowing into or out of cells along the boundary is specified and changes with respect to time. No-flow boundaries are those at which no water flows across the boundary. Specified-head boundaries exist where constant values of hydraulic head are specified and also change with respect to time. These boundary conditions are described in detail by Franke and others (1984).

Water flows into and out of the North Carolina Coastal Plain aquifers across the State boundaries with Virginia and with South Carolina. These are specified-flux boundaries in the North Carolina RASA model and as used in this study. Estimates of fluxes across boundaries were calculated from the northern Atlantic Coastal Plain RASA simulations (table 5). Because of the great distance between Virginia and South Carolina and the central Coastal Plain study area, the effect of possible errors in these specified fluxes on model results in the central area is assumed to be negligible. Less than 1.5 Mgal/d crossed the statelines prior to ground-water withdrawals, except in the Peedee and Black Creek aquifers where simulated flow from North Carolina to South Carolina was 2.55 to 3.47 Mgal/d.

Specified boundary fluxes changed with each time period. Pumpage from aquifers in Cretaceous rocks in Virginia increased from 1900 to 1980, resulting in simulated flow from North Carolina of about 2.71 and 5.12 Mgal/d in the upper and lower Cape Fear aquifers in 1980, respectively. Pumpages also increased in South Carolina, resulting in simulated ground-water flow from North Carolina's Peedee, Black Creek, and upper Cape Fear aquifers of about 2.44, 3.29, and 1.12 Mgal/d, respectively, across the South Carolina Stateline. Water from the lower Cape Fear aquifer flowed from South Carolina to North Carolina at the rate of 1.79 Mgal/d. Because estimates of boundary fluxes through 1986 were unavailable, the 1986 Stateline boundary fluxes were assumed to be the same as those determined for 1980.

Table 5.--*Net simulated flux across Virginia and South Carolina boundaries in 1900 and 1980*

[Negative numbers indicate water leaving North Carolina; --, aquifer not present]

Aquifer	Net flux, in million gallons per day	
	Virginia boundary	South Carolina boundary
	1900	
Peedee	--	-2.55
Black Creek	-0.02	-3.47
Upper Cape Fear	.50	-1.36
Lower Cape Fear	-.26	1.17
	1980	
Peedee	--	-2.44
Black Creek	-.01	-3.29
Upper Cape Fear	-2.71	-1.12
Lower Cape Fear	-5.12	1.79

Because of large withdrawals from the ground-water system throughout the Coastal Plain, the use of specified fluxes at the boundaries of the study area could have introduced significant inaccuracy into the model results. An analysis was performed to determine the magnitude of water-level decline at the central Coastal Plain study area boundaries from (1) pumpage only north of the study area, (2) pumpage only south of the study area, and (3) pumpage only within the central Coastal Plain. In each model run, there was at least 20 ft of simulated drawdown somewhere along the study area boundary. About 50 ft of water-level decline was simulated along part of the study area boundary where pumpage only in the central Coastal Plain was used. The analysis indicated that future pumpages within or outside the central Coastal Plain study area could cause the introduction of unacceptably large errors, and the area modeled was extended to deal with withdrawals outside the study area.

Three no-flow boundaries exist in the North Carolina Coastal Plain aquifers. The western limit of the Coastal Plain (fig. 1) where the Coastal Plain sediments thin to extinction against igneous and metamorphic rocks is one such boundary. These relatively impermeable crystalline rocks also underlie the aquifer system in Cretaceous rocks throughout the Coastal Plain, constituting a second no-flow boundary.

The third no-flow boundary is wherever ground water contains more than 10,000 mg/L chloride in the eastern part of each aquifer. It is assumed that ground-water flow across this boundary is negligible (Meisler, 1981). This boundary is generally east of the central Coastal Plain study area in all aquifers except the upper and lower Cape Fear aquifers, where it occurs in Beaufort and Craven Counties (figs. 5 and 6).

In this model, the 10,000 mg/L chloride boundary is assumed to be stationary; however, it could move in response to increased withdrawal of ground water. To illustrate the significance of a moving 10,000 mg/L chloride boundary, consider a hypothetical aquifer where the 10,000 mg/L chloride boundary is 100 miles long, and the aquifer is 200 ft thick and has a porosity of 0.1 (dimensionless). The amount of ground water released in a 1 ft landward advance of the boundary is 10.5 million cubic feet, or about 80 million gallons. However, no pumpage from aquifers in Cretaceous rocks occurs near the 10,000 mg/L chloride boundary in the central Coastal Plain that might cause measurable movement of this boundary.

The upper model boundary is a specified-head boundary, defined by the water table in the surficial aquifer and assigned temporally constant, areally variable water levels. The amount of flux from the unconfined surficial aquifer to the first confined aquifer is estimated by the RASA model to average 1 in. per year; but at some locations, the flux can be as much as 13 in. per year.

Care must be exercised when using this model to predict water levels. If the model were used to predict the effects of large pumpages located near the specified-head boundary, the amount of simulated recharge to the underlying aquifers could be unrealistically large in areas overlain by the specified-head boundary. Under historical pumpage conditions, heads in aquifers in Cretaceous rocks have been found to be insensitive to specified head in the water table (Eimers, 1988a).

Initial Hydraulic Heads

Estimates of initial hydraulic head were provided by a model simulation of steady-state conditions prior to ground-water development. The calibrated aquifer and confining unit parameters were used to generate water levels for 1900. These computer-generated water levels are shown in figures 12, 13, 14, and 15 with some observed predevelopment water levels measured between 1900 and 1950. Therefore, these measured water levels were used as guides to develop simulated water levels for 1900. Because of the range in time in which the water levels were measured, they may not match the simulated water levels for 1900 in some areas. However, the simulated contours for the Black Creek (fig. 13) and upper Cape Fear (fig. 14) aquifers match well with predevelopment water-level contours presented in Winner and Lyke (1986).

In the Peedee aquifer, initial heads ranged from more than 120 ft above sea level in parts of Greene and Lenoir Counties to less than 20 ft above sea level in parts of Beaufort, Craven, Onslow, and Pitt Counties (fig. 12). Early recorded heads in the Peedee aquifer ranged from 14 to 80 ft above sea level. In general, initial heads were highest and gradients steepest (up to 15 ft/mi) along the western boundary of the aquifer. Minimum hydraulic gradients were estimated to be about 0.7 ft/mi in Beaufort and Craven Counties.

Initial heads in the Black Creek aquifer ranged from more than 120 ft above sea level in parts of Wayne County to less than 40 ft above sea level in Beaufort, Craven, Jones, Onslow, and Pitt Counties (fig. 13). Around 1900, a few observed heads ranged from 116 to 35 ft above sea level. Maximum hydraulic gradient was about 8 ft/mi in western Wayne County; minimum was less than 0.6 ft/mi in Beaufort and Pitt Counties.

Simulated initial heads in the upper Cape Fear aquifer ranged from more than 140 ft above sea level in Wayne County to less than 60 ft above sea level in the eastern half of the study area (fig. 14). Several observed heads in this aquifer for the predevelopment period ranged from 92 to 52 ft above sea level. The steepest hydraulic gradient was about 7 ft/mi in western Wayne County, and the flattest was less than 0.5 ft/mi in Beaufort and Pitt Counties.

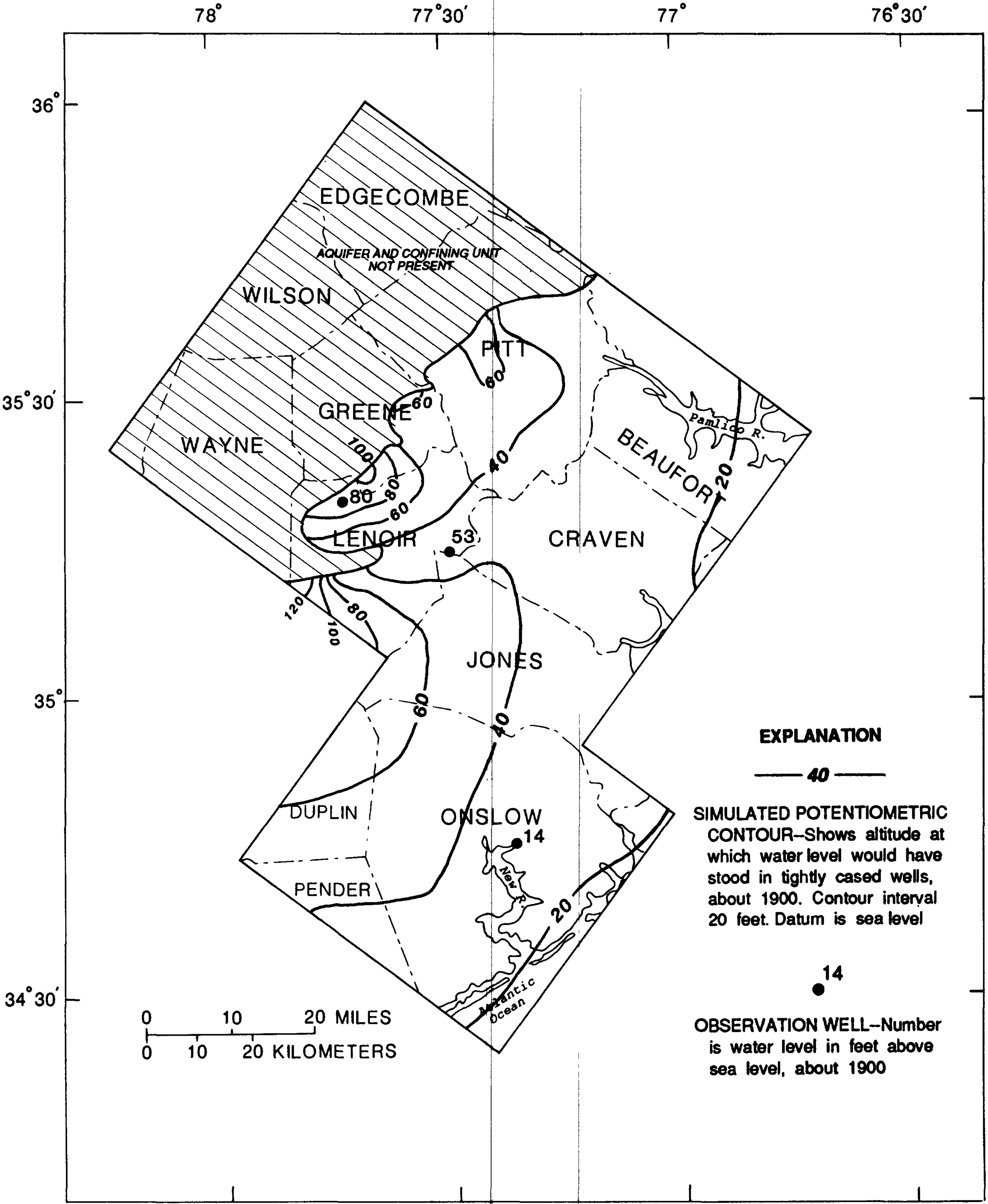

Figure 12.--Simulated water levels in the Peedee aquifer in 1900.

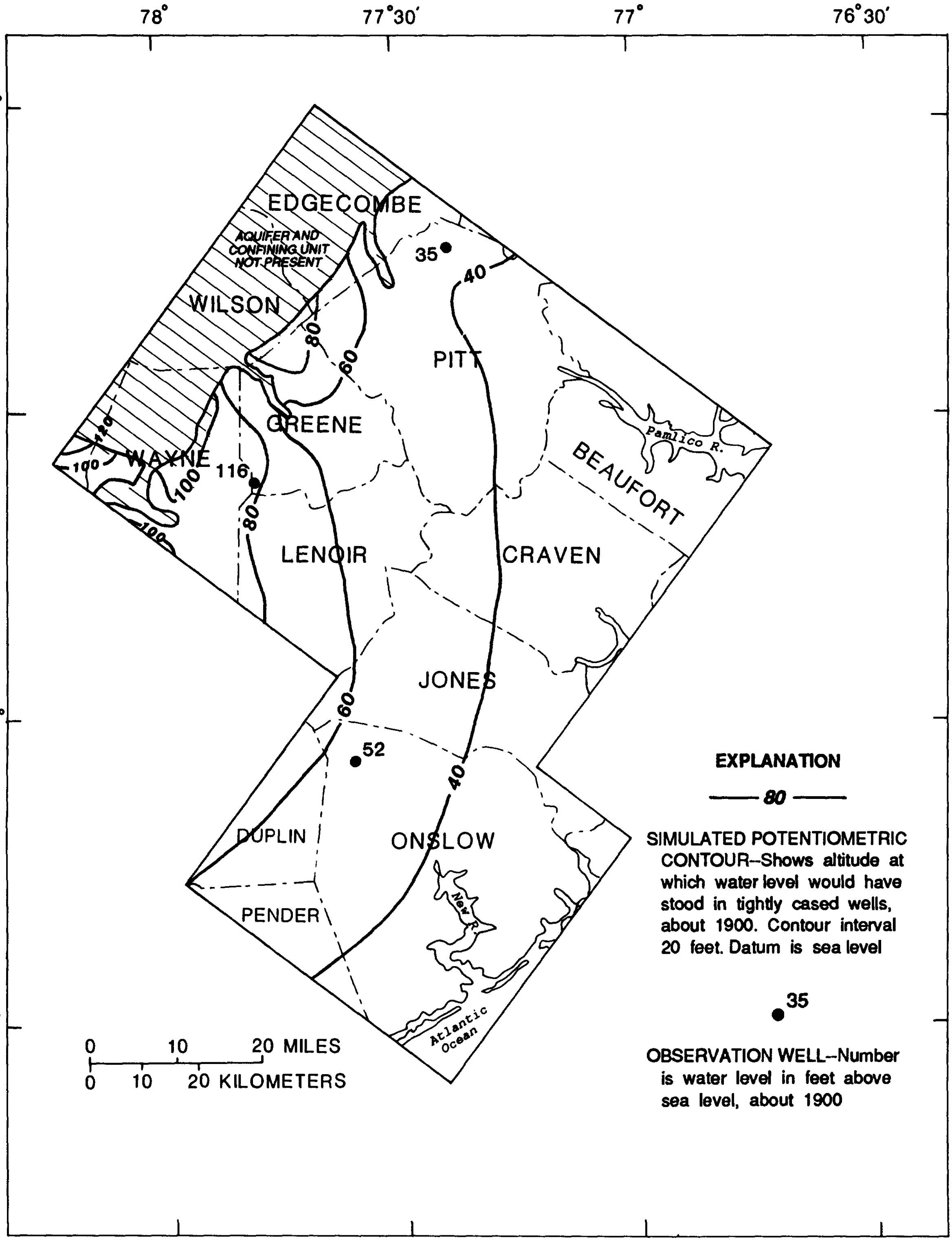

Figure 13.--Simulated water levels in the Black Creek aquifer in 1900.

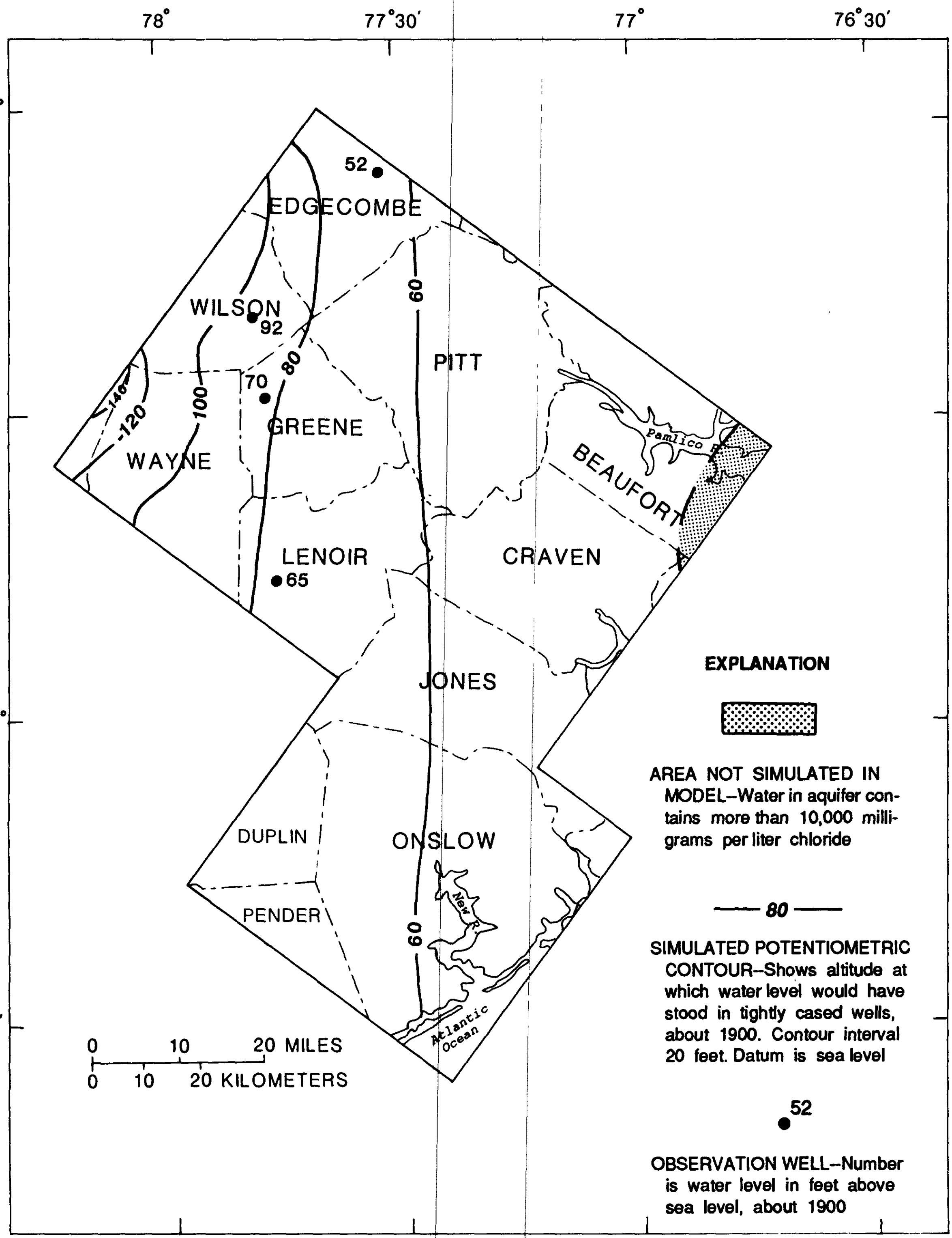

Figure 14.--Simulated water levels in the upper Cape Fear aquifer in 1900.

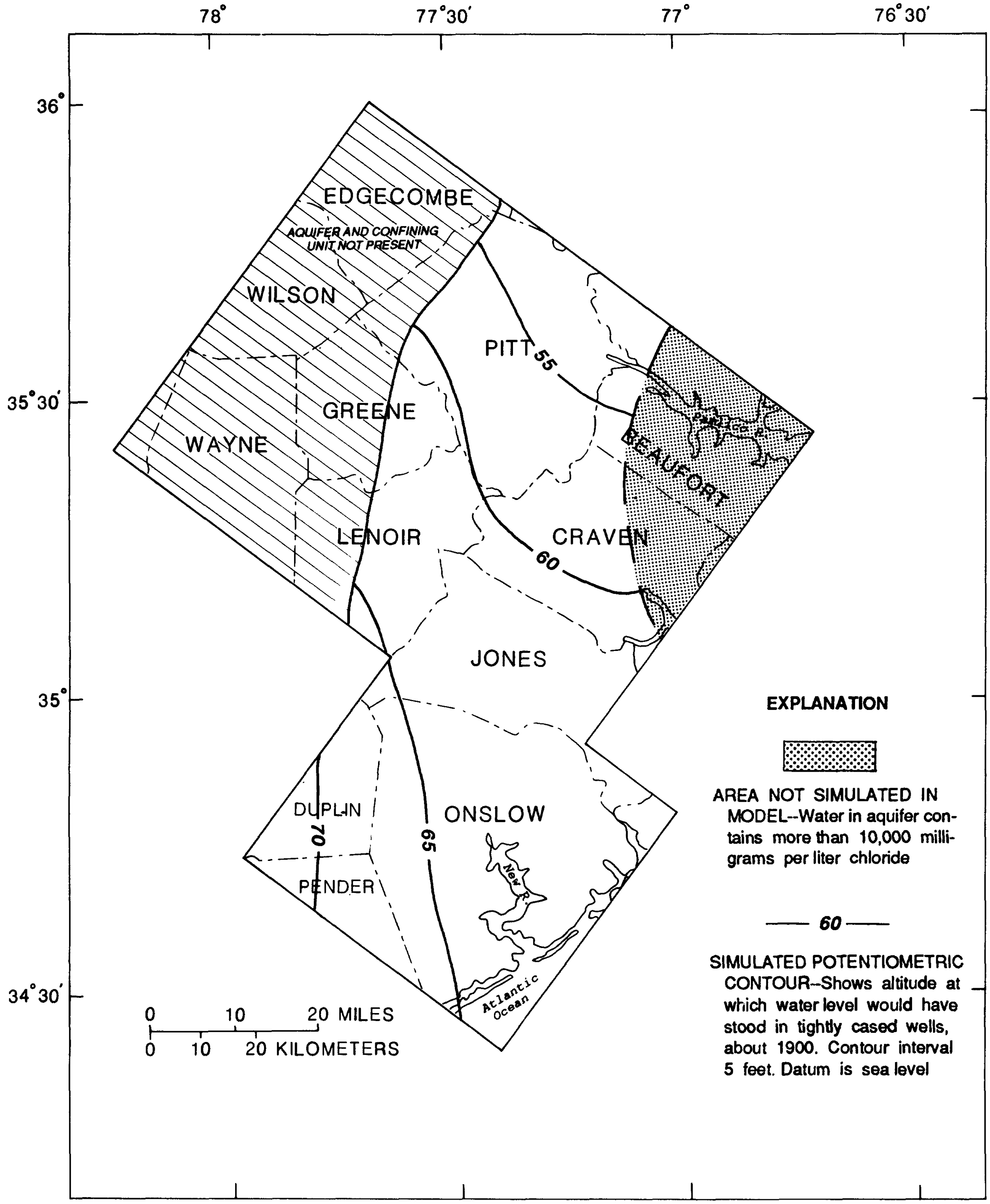

Figure 15.--Simulated water levels in the lower Cape Fear aquifer in 1900.

In the lower Cape Fear aquifer, initial simulated heads ranged from more than 70 ft above sea level in Duplin and Pender Counties to less than 55 ft above sea level in Beaufort and Pitt Counties (fig. 15). There are no predevelopment observed heads for this aquifer. In contrast to the generally eastward flow of ground water in overlying aquifers in Cretaceous rocks, predevelopment gradients in the lower Cape Fear aquifer indicate a northeasterly flow. Hydraulic gradients also were flatter and ranged from about 0.1 to 0.4 ft/mi.

Model Calibration

The model-calibration process consists of modifying initial parameter estimates within their probable ranges to obtain a better match of computed heads with observed hydraulic heads. The calibrated parameter set presented in this report is not the only set that can be used to match model-computed heads with observed heads. A way of ensuring that the final calibrated-data set is the best one possible is to include as much information about the ground-water flow system as possible in the calibration process (Emsellem and deMarsily, 1971). To include as much information as possible, parameter estimation was performed using an approach combining subjective and objective techniques; namely, parameters were adjusted within probable limits according to available water-budget information, well-log data, and aquifer-test data.

Steps taken in calibration include: (1) analyzing model sensitivity to input parameters, (2) optimizing the goodness-of-fit between observed and computed heads, and (3) analyzing errors in the model calibration. These procedures are not necessarily undertaken in the above order, nor are they used only once, but they are used interactively within the iterative calibration process. The following sections present model-derived estimates of parameters and hydraulic heads and discussions of sensitivity analysis, calibration error, and hydrologic analysis.

Model-Derived Estimates

The results of model calibration are model-derived parameter estimates, transmissivity and vertical leakance, and computed hydraulic heads. The distribution of model-derived transmissivity for each aquifer and vertical leakance for each confining unit are shown in figures 16, 18, 20, and 22 and 17, 19, 21, and 23, respectively.

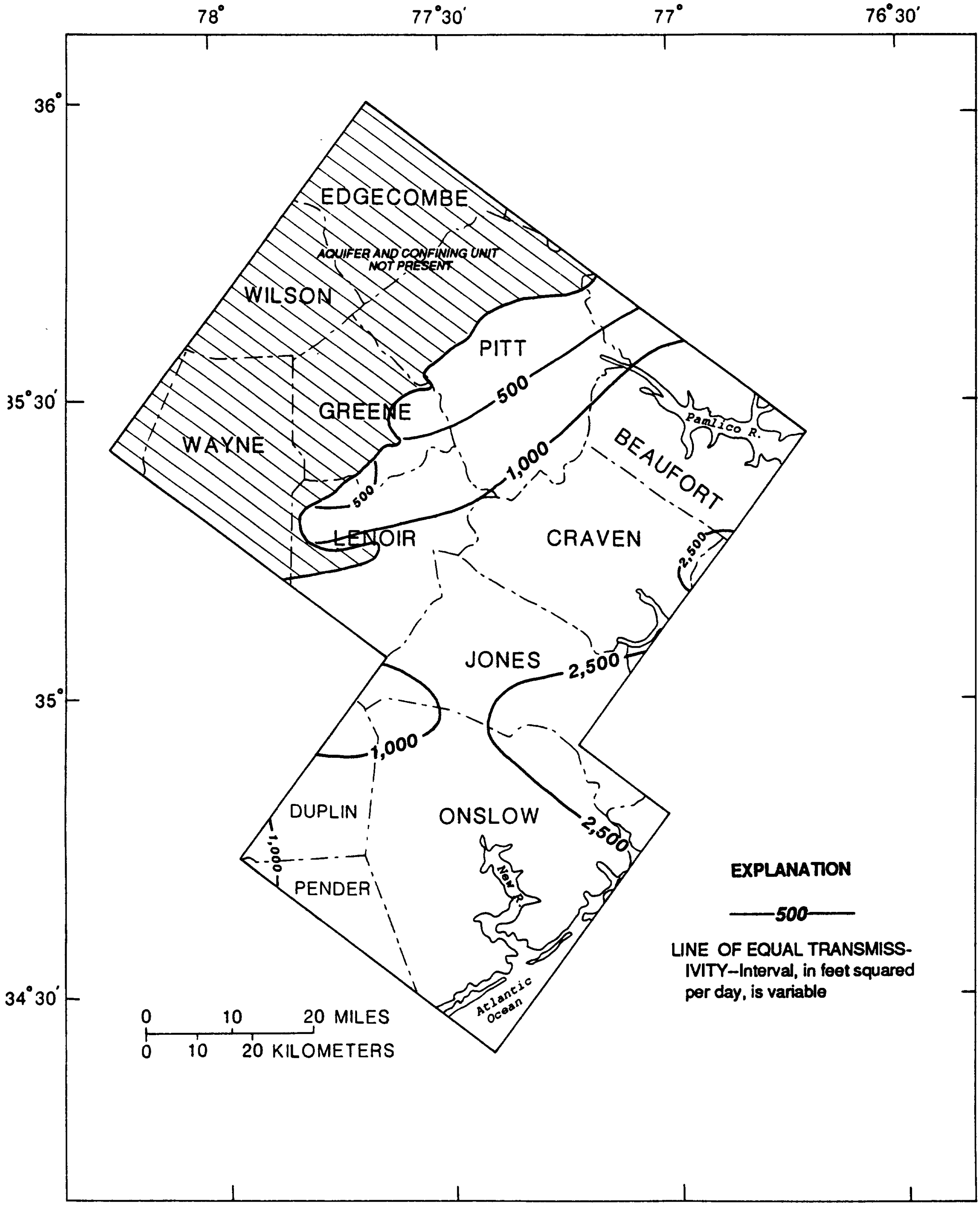

Figure 16.--Model-derived transmissivity of the Peedee aquifer.

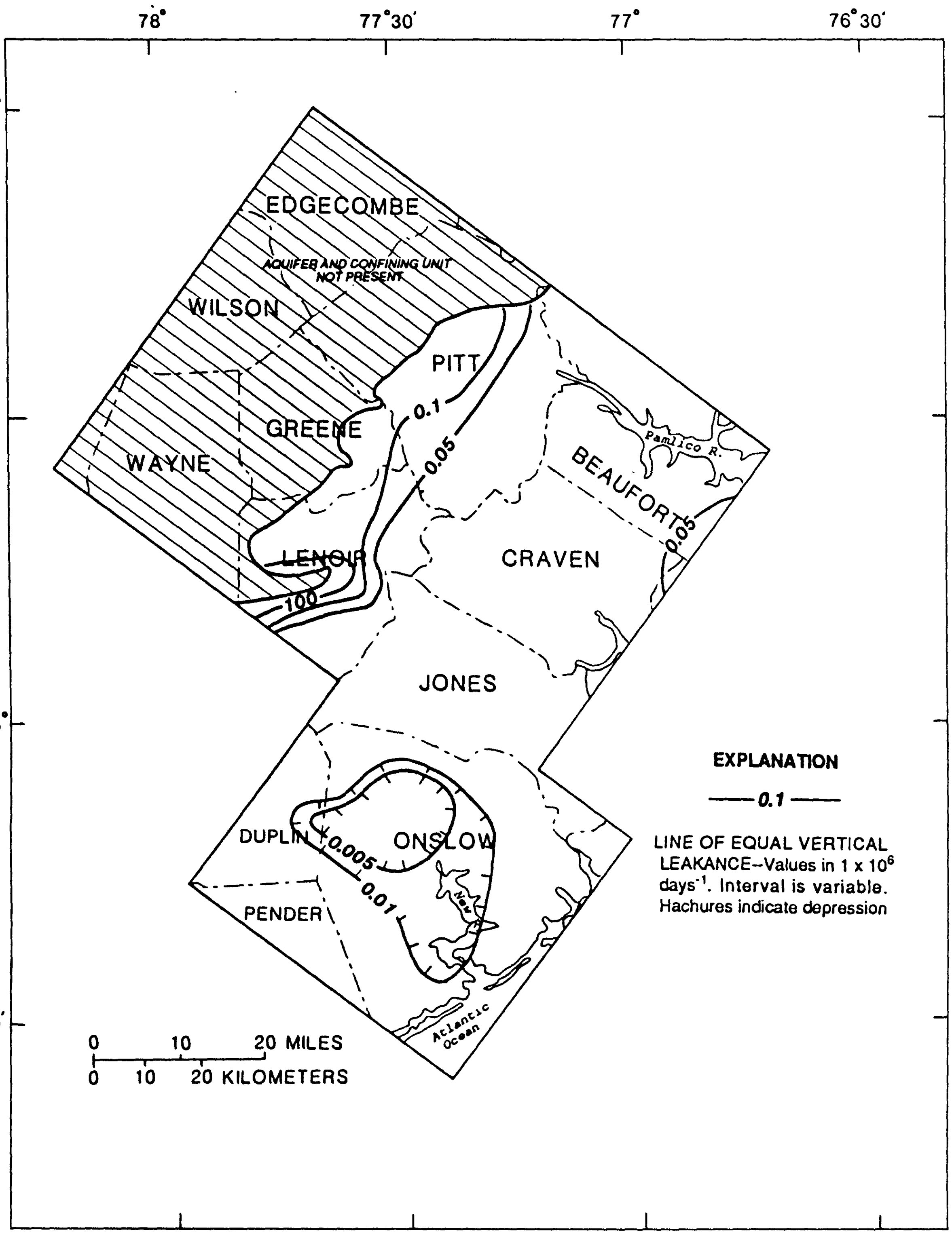

Figure 17.--Model-derived vertical leakance of the Peedee confining unit.

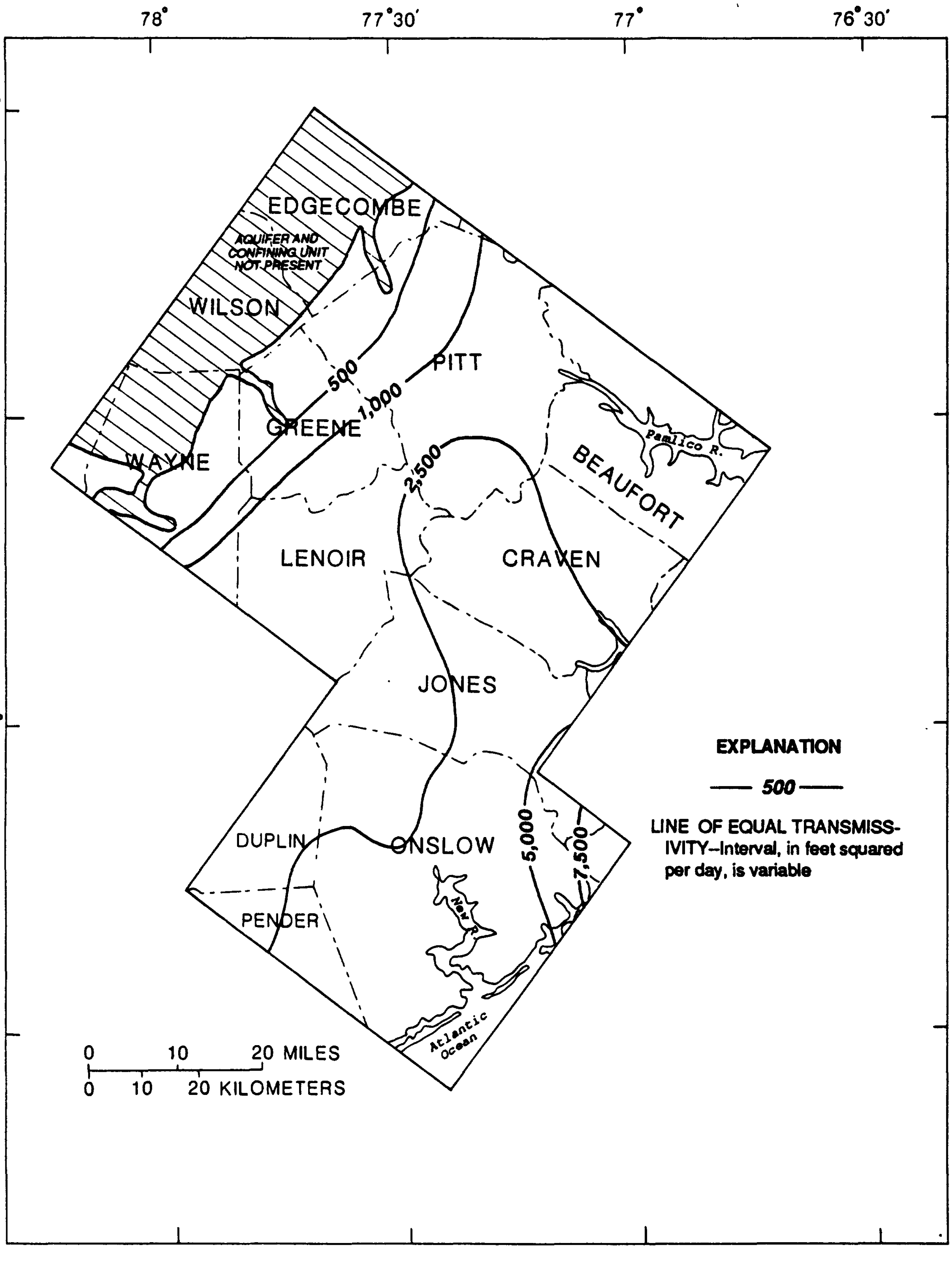

Figure 18.--Model-derived transmissivity of the Black Creek aquifer.

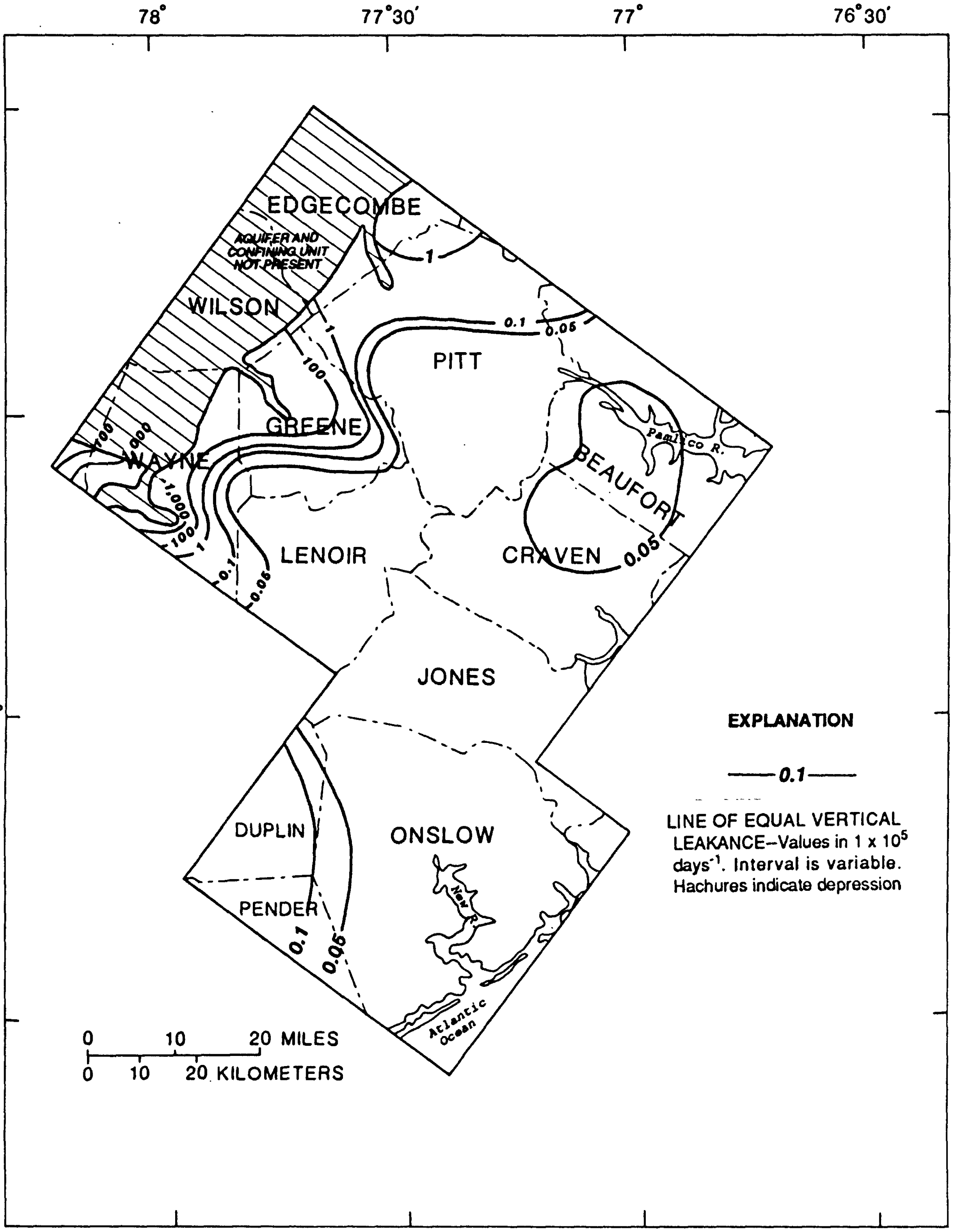

Figure 19.--Model-derived vertical leakance of the Black Creek confining unit.

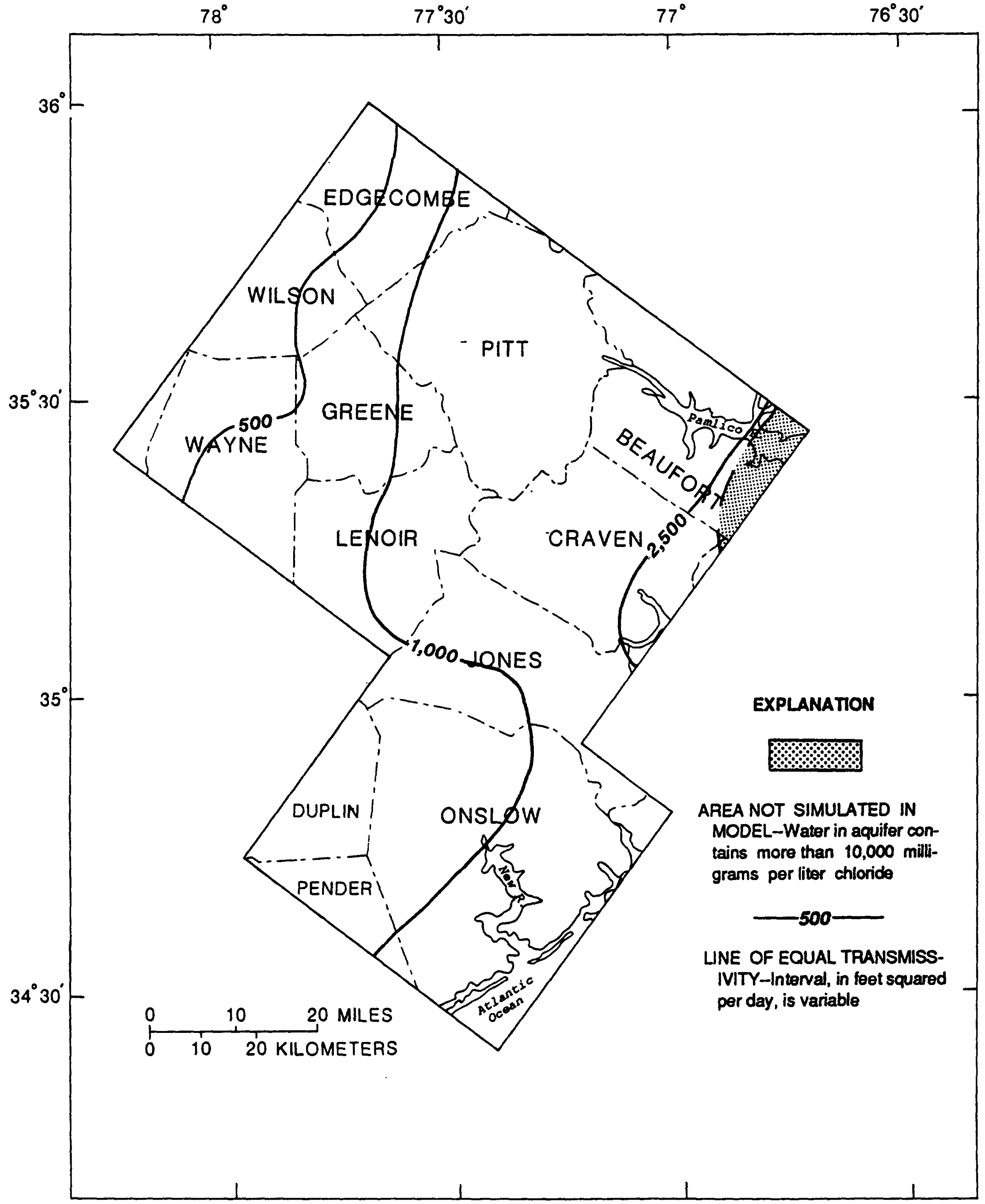

Figure 20.--Model-derived transmissivity of the upper Cape Fear aquifer.

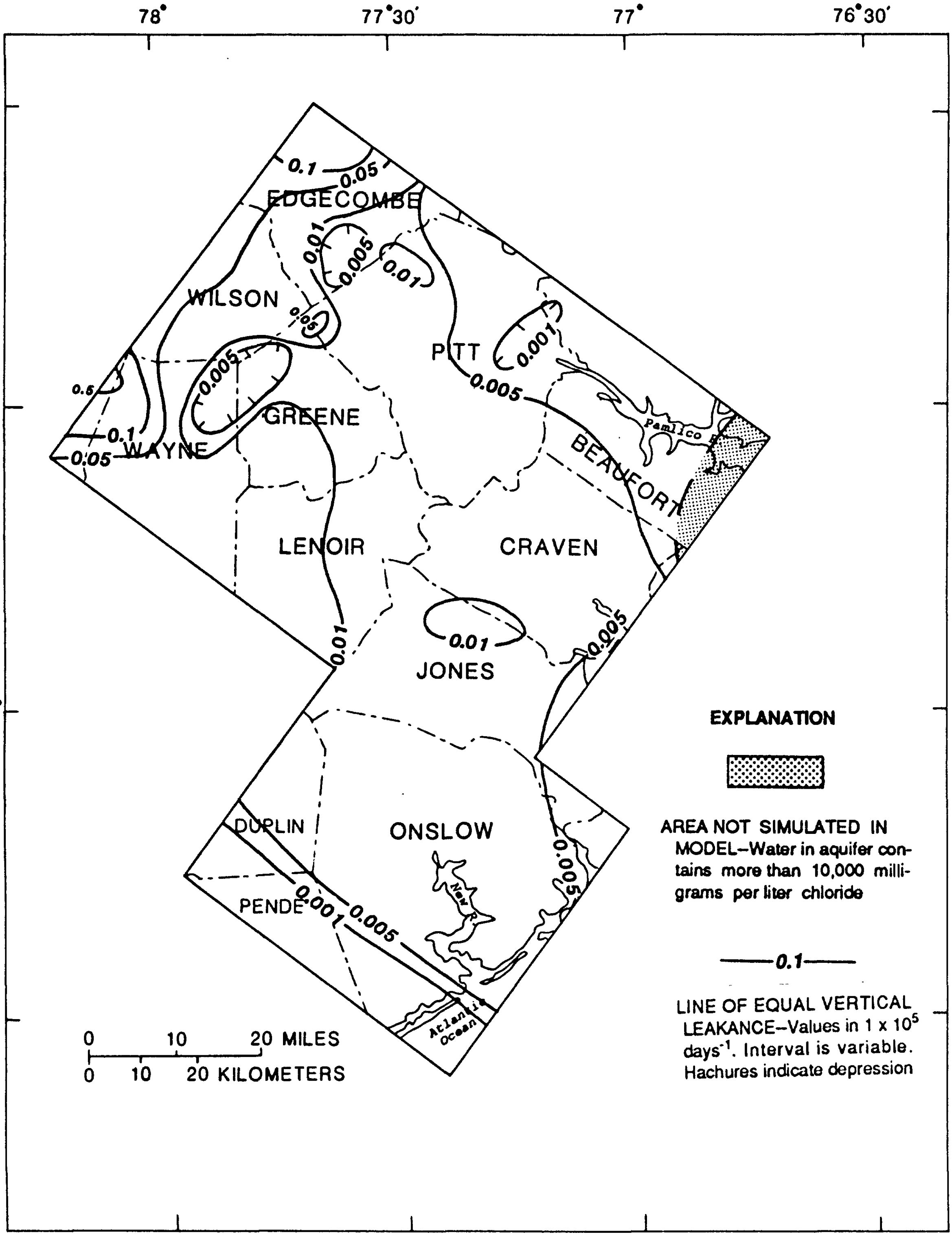

Figure 21.--Model-derived vertical leakance of the upper Cape Fear confining unit.

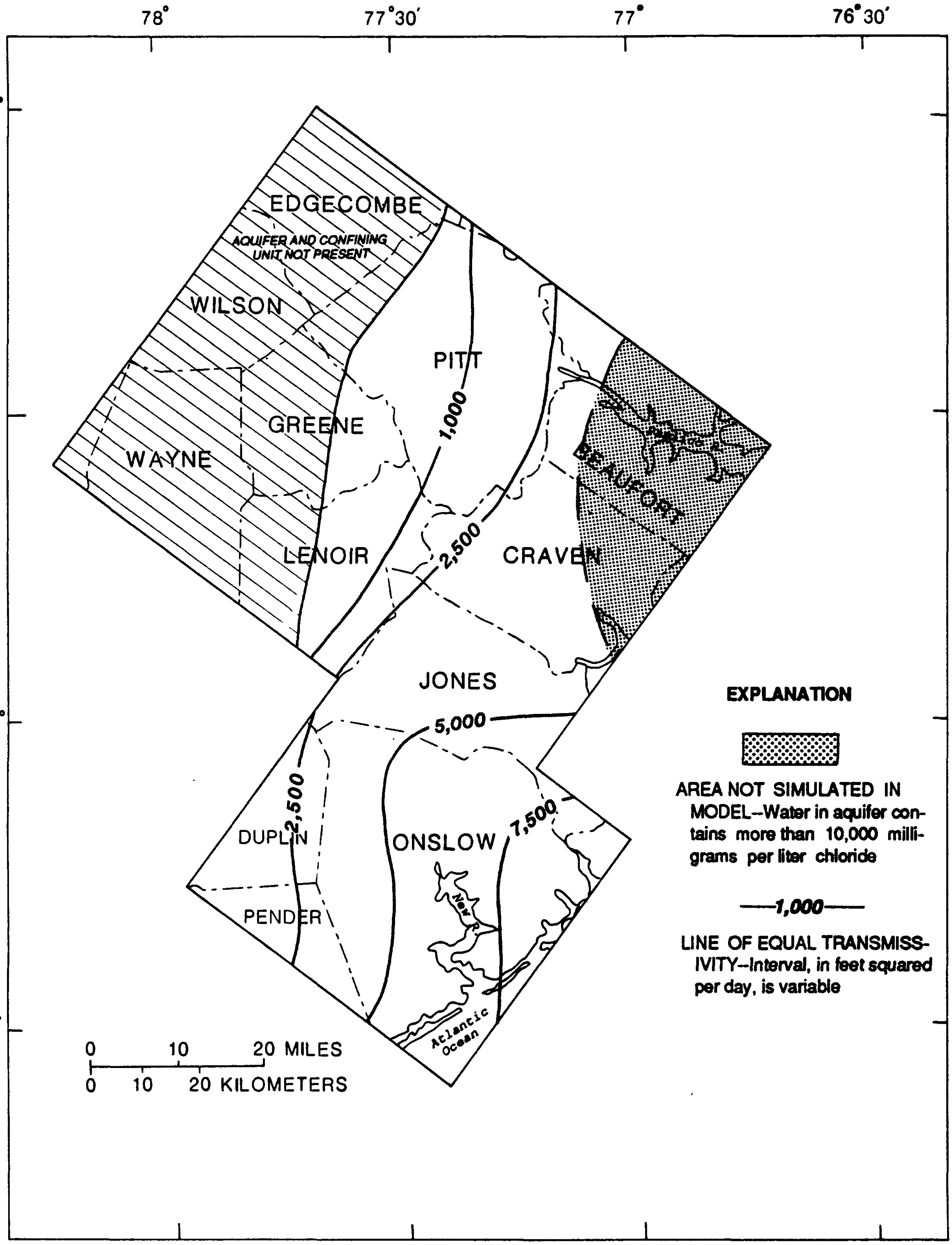

Figure 22.--Model-derived transmissivity of the lower Cape Fear aquifer.

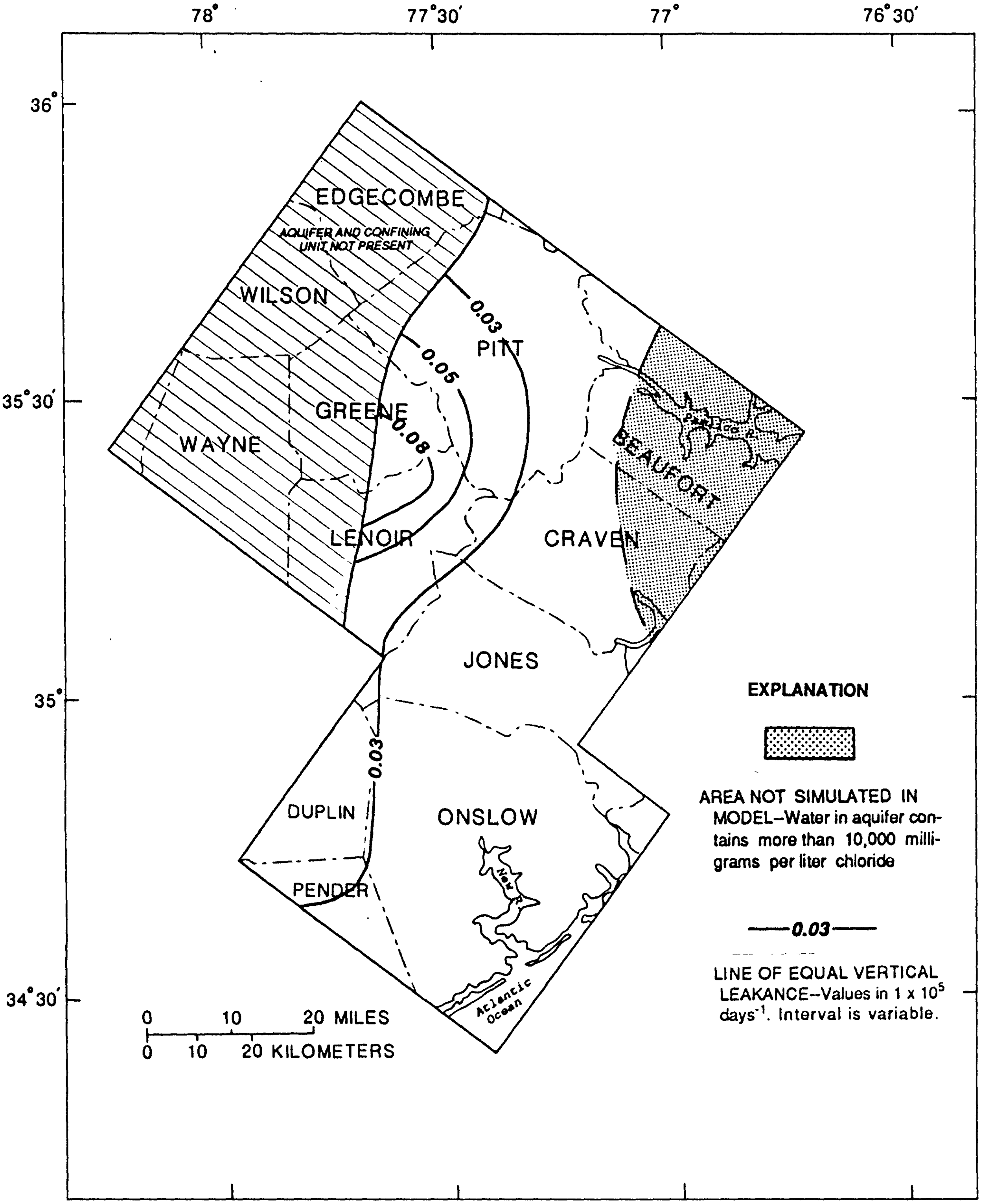

Figure 23.--Model-derived vertical leakance of the lower Cape Fear confining unit.

Calibrated estimates of transmissivity and vertical leakance for aquifers and confining units in the aquifer system in Cretaceous rocks of the central Coastal Plain are summarized in table 6. Median transmissivity values for these aquifers range from about 1,200 to 3,400 ft^2/d (table 6) and tend to increase toward the coast due to increasing aquifer thickness. Values of transmissivity determined from aquifer tests (table 3) are within about 100 percent of the model-derived values.

Table 6.--*Summary of model-derived transmissivity and vertical leakance values for Cretaceous units of the central Coastal Plain*

Unit	Median	Maximum	Minimum
Transmissivity, in feet squared per day			
Peedee	1,380	5,550	60
Black Creek	2,140	8,520	50
Upper Cape Fear	1,200	3,810	150
Lower Cape Fear	3,400	8,500	520
Vertical leakance of confining unit, per day			
Peedee	1.74×10^{-6}	3.89×10^{-2}	1.63×10^{-7}
Black Creek	2.63×10^{-7}	1.66×10^{-2}	8.02×10^{-8}
Upper Cape Fear	2.99×10^{-7}	2.10×10^{-5}	1.94×10^{-8}
Lower Cape Fear	1.97×10^{-7}	9.07×10^{-7}	1.12×10^{-7}

Model-derived transmissivity values for the Peedee aquifer have a median value of 1,380 ft^2/d. The maximum value, 5,550 ft^2/d, occurred in Onslow County, whereas the minimum value was 60 ft^2/d in Pitt County. Values exceed 2,500 ft^2/d in parts of Craven, Jones, and Onslow Counties (fig. 16) and are less than 1,000 ft^2/d in parts of Beaufort, Greene, Lenoir, and Pitt Counties.

The maximum model-derived transmissivity value for the Black Creek aquifer, 8,500 ft^2/d, was at a node in Jones County, and the minimum value was 50 ft^2/d in Edgecombe County. The median value for this unit is 2,100

ft^2/d. Model-derived transmissivity values exceed 2,500 ft^2/d in Craven, Jones, Lenoir, Onslow, and Pitt Counties; model-derived transmissivity values are less than 1,000 ft^2/d in Edgecombe, Greene, Pitt, Wayne, and Wilson Counties (fig. 18).

For the upper Cape Fear aquifer, transmissivities generated by the model have a median value of 1,200 ft^2/d. The maximum, 3,800 ft^2/d, occurred in Beaufort County, whereas the minimum value was 150 ft^2/d in Wilson County. Model-derived transmissivity values exceed 2,500 ft^2/d in parts of Beaufort, Craven, and Jones Counties. Transmissivity values are less than 1,000 ft^2/d in Edgecombe, Greene, Jones, Lenoir, Onslow, Pitt, Wayne, and Wilson Counties (fig. 20).

Transmissivity values for the lower Cape Fear aquifer, as calculated by the model, have a median value of 3,400 ft^2/d. The values ranged from 8,500 ft^2/d in Jones County to 520 ft^2/d in Edgecombe County. Transmissivity values exceed 2,500 ft^2/d in Beaufort, Craven, Jones, and Onslow Counties, whereas values are generally less than 1,000 ft^2/d in Greene, Lenoir, and Pitt Counties (fig. 22).

Median confining unit vertical leakances for the four Cretaceous units range from 2×10^{-7} to 1.7×10^{-6} per day (1/d). Vertical leakance values also tend to decrease downdip toward the southeast because of sediment compaction.

Model-derived vertical leakance values for the Peedee confining unit have a median value of 1.74×10^{-6} 1/d. The maximum value, 3.89×10^{-2} 1/d, occurred in Greene County, whereas the minimum value was 1.63×10^{-7} 1/d in Onslow County. Values exceed 1.00×10^{-5} 1/d in parts of Greene, Lenoir, Pitt, and Wayne Counties (fig. 17).

The median value of vertical leakance for the Black Creek confining unit is 2.63×10^{-7} 1/d. The maximum vertical leakance value of 1.66×10^{-2} 1/d occurred in Wayne County. The minimum value was 8.02×10^{-8} 1/d in Pitt County. Model-derived vertical leakance values exceed 1.00×10^{-5} 1/d in parts of Edgecombe, Greene, Pitt, and Wayne Counties (fig. 19).

Model-derived vertical leakance values for the upper Cape Fear confining unit range from 2.10×10^{-5} 1/d in Wayne County to 1.94×10^{-8} 1/d in Duplin County. The median value is 2.99×10^{-7} 1/d. Vertical leakance values exceed 5.00×10^{-7} 1/d in parts of Edgecombe, Greene, Pitt, Wayne, and Wilson Counties (fig. 21).

Model-derived vertical leakance values for the lower Cape Fear confining unit exhibit the closest range from 9.07×10^{-7} 1/d in Greene County to 1.12×10^{-7} 1/d in Jones County. Values exceed 5.00×10^{-7} 1/d in Greene, Lenoir, and Pitt Counties (fig. 23). The median value of vertical leakance is 1.97×10^{-7} 1/d.

Estimates of 1986 hydraulic head were provided by a model simulation of transient conditons beginning at predevelopment and continuing through 1986. In the Peedee aquifer, simulated heads ranged from more than 120 ft above sea level in parts of Lenoir County to slightly below sea level in parts of Onslow and Beaufort Counties (fig. 24). Maximum heads occur along the western limit of the aquifer where head gradients are about 15 ft/mi. Minimum hydraulic gradients were estimated to be about 1 ft/mi in Beaufort and Craven Counties. Minimum heads (below sea level) occur in the center of Onslow County in response to pumpage from the Peedee and Black Creek aquifers. Heads less than 0 ft sea level also occur in Beaufort County.

In the Black Creek aquifer, simulated heads ranged from more than 120 ft above sea level in parts of Wayne County to more than 80 ft below sea level in parts of Craven, Jones, Lenoir, and Onslow Counties (fig. 25). Maximum heads occur along the western limit of the aquifer. Minimum hydraulic heads occur in the center of pumpage areas of the Black Creek aquifer, which are also the areas of steepest hydraulic gradient.

In the upper Cape Fear aquifer, heads ranged from more than 120 ft above sea level in parts of Wayne and Wilson Counties to more than 60 ft below sea level in Greene and Lenoir Counties (fig. 26). Maximum heads of more than 120 ft above sea level occur along the northwest boundary of the study area. Minimum heads occur at pumpage centers in Greene and Lenoir Counties.

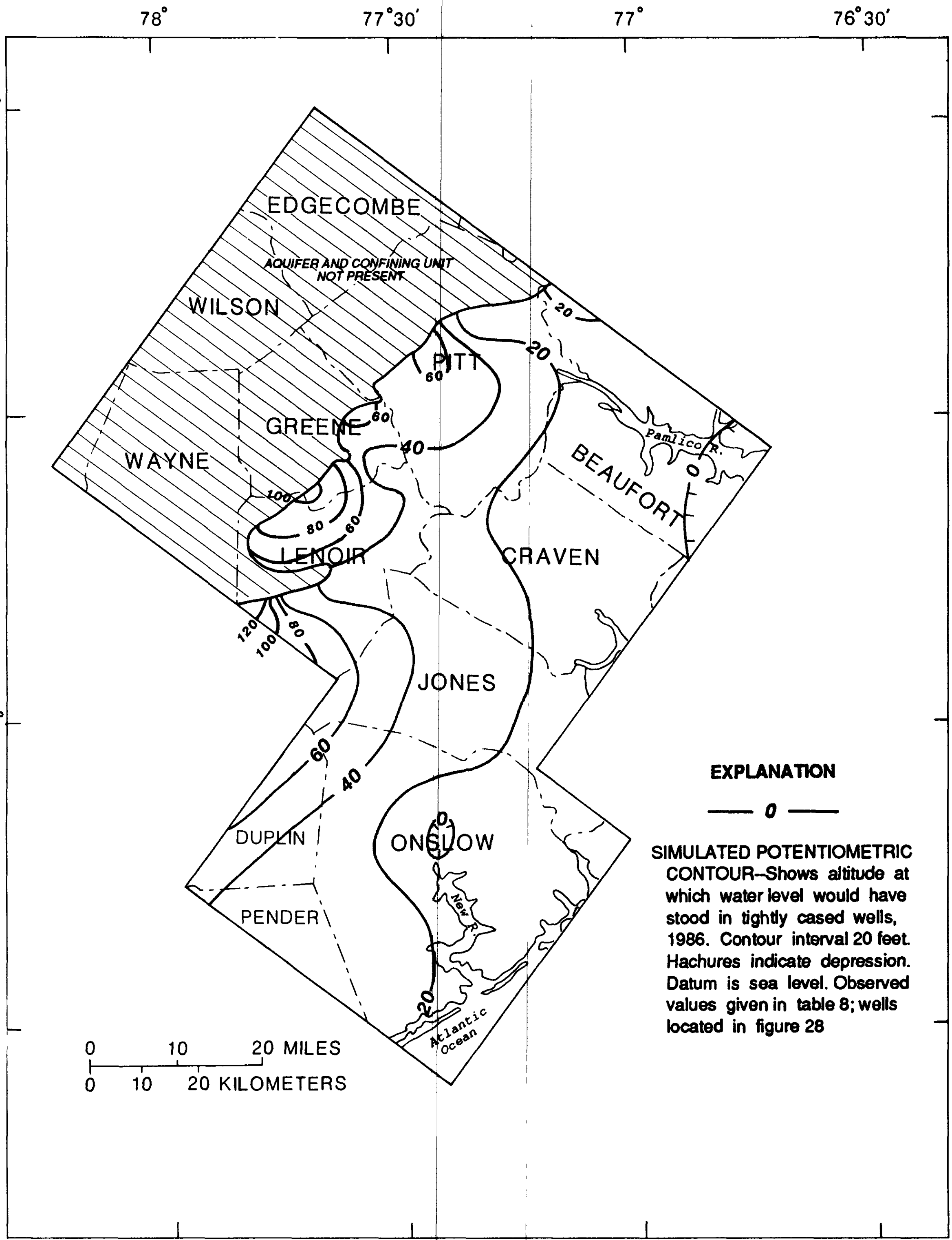

Figure 24.--Simulated water levels in the Peedee aquifer in 1986.

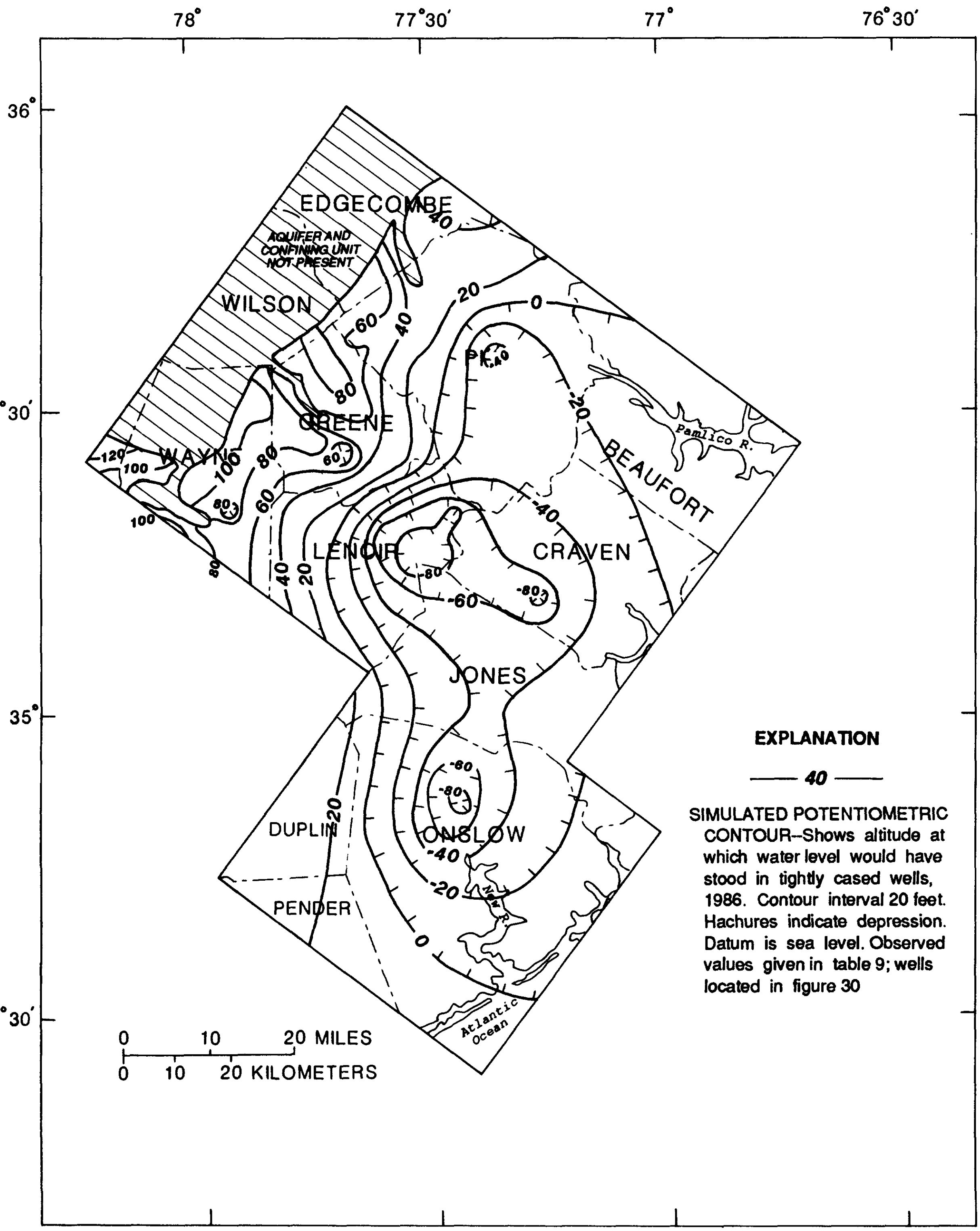

Figure 25.--Simulated water levels in the Black Creek aquifer in 1986.

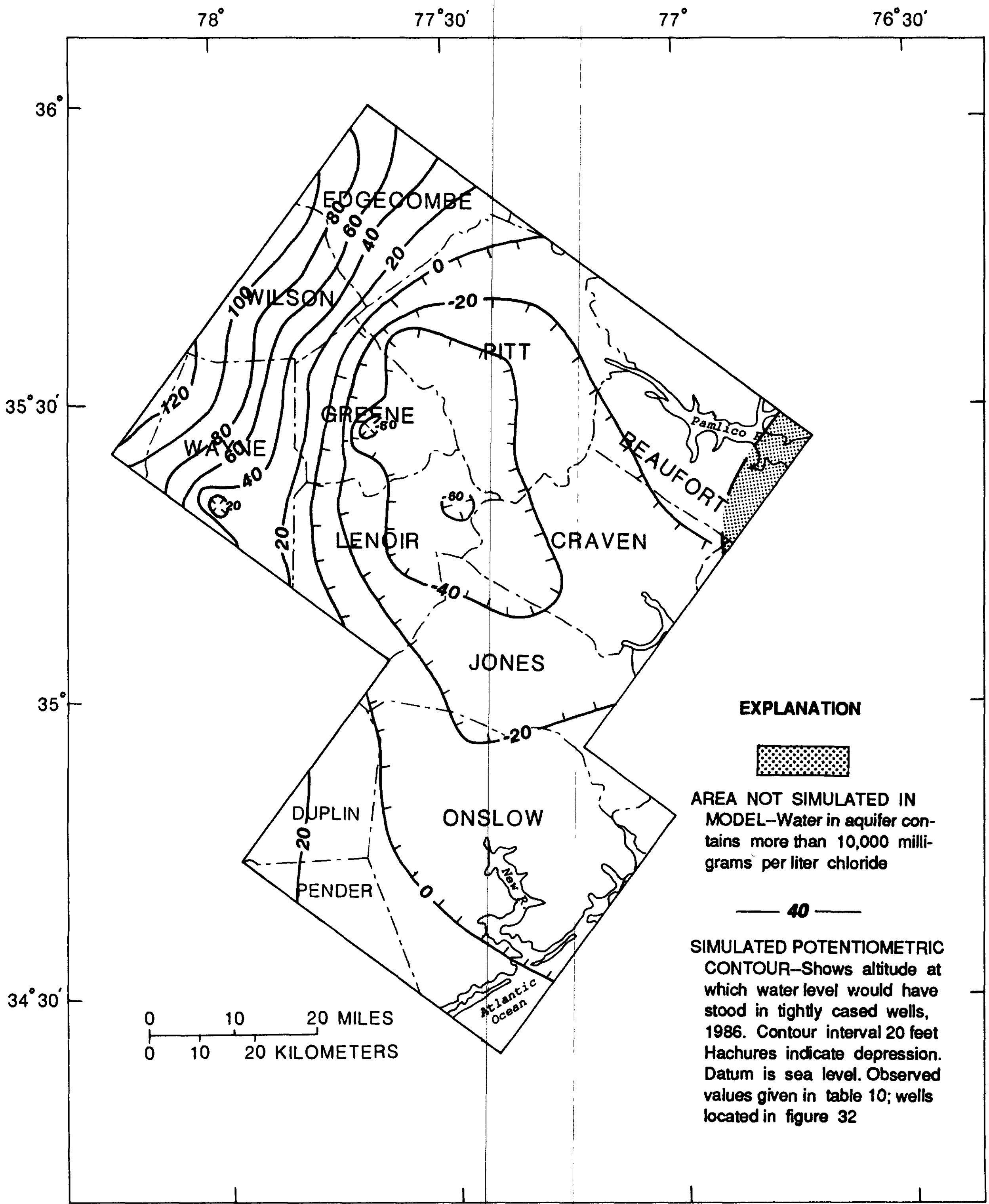

Figure 26.--Simulated water levels in the upper Cape Fear aquifer in 1986.

In the lower Cape Fear aquifer, heads ranged from more than 20 ft above sea level in Duplin and Pender Counties to more than 20 ft below sea level in parts of Craven, Greene, Lenoir, and Pitt Counties (fig. 27). Maximum heads occur along the southwestern boundary of the study area; minimum heads occur along the western boundary of the aquifer.

Sensitivity Analysis

During the model calibration process, it is helpful to have an understanding of the sensitivity of model output to changes in flow parameters. Such an assessment of the model's response to these changes is used to determine the type of parameter modifications required to bring about the desired calibration. Model response to parameter change was analyzed during the initial stage of calibration of the central Coastal Plain ground-water flow model using a technique known as node categorization (Eimers, 1986; Eimers, 1988b).

Results from sensitivity analysis of the initial model indicate that the ground-water flow model of the North Carolina Coastal Plain was 100 to 1,000 times more sensitive to changes in transmissivity and vertical leakance in the aquifers and confining units of Cretaceous rocks than in Tertiary and Quaternary hydrogeologic units. The model was 10 to 100 times more sensitive to changes in transmissivity and vertical leakance in areas where aquifers are pumped than in unpumped areas (Eimers, 1986). Computed hydraulic head was insensitive to estimates of storage coefficient everywhere; that is, computed heads changes no more than a few feet in response to a wide range of storage coefficient values. Results of this sensitivity analysis pertaining to aquifers in Cretaceous rocks are presented in table 7.

In interpreting the results of this sensitivity analysis, the difference in the initial and final cell size must be considered. Cells in the central Coatal Plain can be grouped into sets of 3, 6, 9, 12, or 16 cells. Any such cluster of cells can then be viewed as one cell, which allows for the direct application of the sensitivity analysis to the finer grid central Coastal Plain model. Hydraulic head varies throughout a cluster of 16 cells. Within a cluster of cells, model response to parameter variation will depend on the location of pumpage within the cluster.

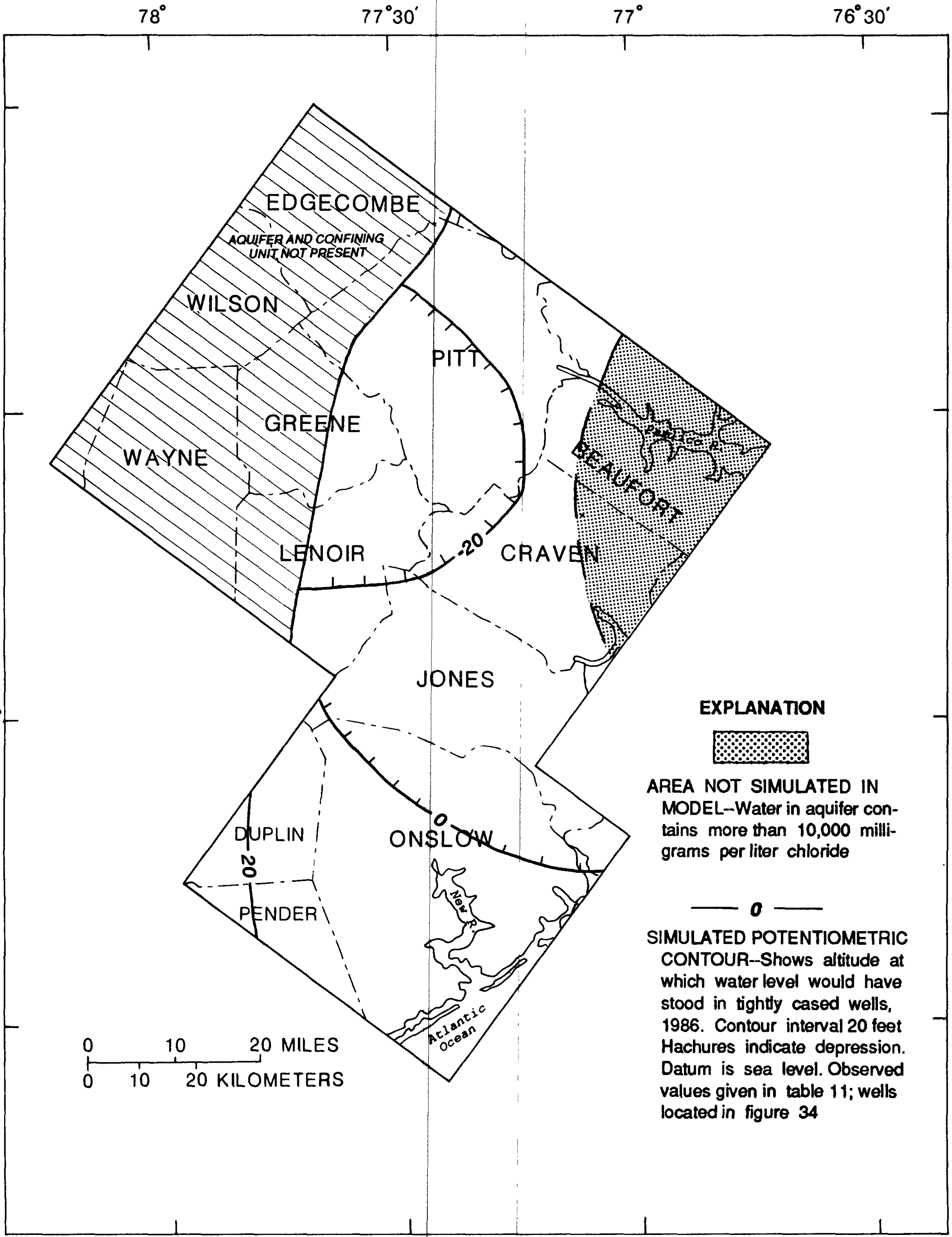

Figure 27.--Simulated water levels in the lower Cape Fear aquifer in 1986.

Table 7.--*Model sensitivity to vertical leakance and transmissivity parameters*
[Max., maximum; min., minimum]

Node category	Value	Vertical leakance (Head change, in feet) Percent change in parameter -90	-50	+50	+90	Transmissivity (Head change, in feet) Percent change in parameter -90	-50	+50	+90
All active	Max.	37.2	13.2	22.6	32.9	105.0	18.1	53.3	77.6
	Median	-65.2	-8.44	2.80	4.0	-3.2	-2.87	2.56	4.3
	Min.	-361	-57.3	-6.80	-10.2	-907	-.01	-1.20	-19.2
Pumping	Max.	.19	.08	18	27	6.01	2.74	53.3	77.6
	Median	-75.5	-13	4.96	7.5	-38.8	-8.96	4.77	7.4
	Min.	-284	-44.9	-.03	-.06	-907	-138	-2.07	-3.17
No flow	Max.	16.7	5.70	22.6	32.9	71.9	18.1	22.1	32.2
	Median	-54.2	-6.47	1.9	2.6	-.68	-2.05	2.23	3.8
	Min.	-361	-57.2	-4.05	-7.25	-415	-59.5	-12.1	-19.2

Calibration Error

Evaluation of the model calibration error made use of a computed measure called the objective function. This function measures the goodness-of-fit between observed and computer-generated heads through time at all locations. The object of calibration was to minimize the value of the objective function. A second measure, the well objective function (see glossary), was used to evaluate the goodness-of-fit between observed and computer-generated heads through time at a particular observation well.

The objective function reflects the greater importance of recent observations of hydraulic head in aquifers in Cretaceous rocks, although flow in these sediments is simulated over a period of 87 years. This is accomplished by applying weighting factors in the objective function. These weighting factors are arbitrary and are selected to (1) reduce the importance of data outside the study area and (2) reduce the importance of data from before 1940. The calibration outside the study area is not as important in this model as is the calibration within the study area and there are few reliable measurements among data before about 1940.

The average weighted difference between computed and observed hydraulic head is not sufficient to characterize the calibration. For instance, the individual differences between computed and observed hydraulic head could be quite large, indicating the calibration is not good, but the average difference might be zero, leading one to believe the calibration is quite good. For this reason, the objective function is a function of the absolute value of the difference between computed and observed heads.

Uncertainty in the model calibration is reflected in the differences between computed and observed data. Although it is desirable to attempt to calibrate so that differences between computed heads (h_c) and observed heads (h_o) are at a minimum, there are several reasons why some differences between h_c and h_o are acceptable. First, calibration errors result from natural variability of the input parameters, errors associated with making parameter estimates, and observations of hydraulic head. For instance, hydraulic heads in wells screened in shallow confined aquifers may vary by several feet over the course of a year due to variations in precipitation and possibly some withdrawals. However, this variability is not simulated in the model because the water table altitudes are assumed constant through time. Also, estimates of transmissivity and vertical leakance are characterized by natural variability, particularly just downdip from aquifer outcrops, as well as by substantial measurement and estimation error. Although variability in aquifer characteristics can be simulated in the model, variability within each cell or in areas without measured data cannot be accounted for in the model. Statistics for transmissivity derived from aquifer tests in table 3 show a narrow to moderately wide range of variability within each aquifer.

A second reason that some differences between h_c and h_o are acceptable is that some calibration error will not adversely affect the accuracy of the simulations of flow within aquifers in Cretaceous rocks. The importance of older observations (h_o before 1940) is reduced (by making the temporal weighting factor less than 1) in part because these measurements have less effect on model predictions than current data.

The importance of measurements (h_o) outside the study area is also reduced because this model does not simulate flow outside the study area as accurately as within the study area. The model calibration outside the study area is important only to the extent that it influences accuracy of simulated heads and flows at the limits of the study area. No observed heads after 1980 were available for model calibration outside the study area.

The third reason for accepting differences between h_c and h_o is that some error in the calibration is expected. The model simulates a uniform value for the potentiometric surface in the cell; any given measured head value is not likely to represent the average head in cells where head varies spatially and seasonally. Therefore, the purpose of calibration becomes to minimize the objective function, constrained by estimable differences in computed and observed heads in cells with variable potentiometric surfaces.

Because of this spatial and temporal averaging and because of random error in the calibration, potentiometric surfaces simulated by this model will differ from potentiometric surfaces made by contouring observed head values (Brockman and others, 1989; Lyke and others, 1989; Winner and others, 1989a and 1989b). These simulated and observed potentiometric surfaces may differ markedly in pumped areas and in other areas where observed water levels are affected by short-term pumping not simulated by the model.

The final value of the objective function for all computer-generated heads is 10.9 ft for 1,867 data values for 323 observation wells; standard deviation is 10.7 ft. The difference between computed and observed heads, $h_c - h_o$, is assumed to have an underlying normal probability distribution with zero mean. For this sample of 1,867 points, the mean value of $h_c - h_o$ is -1 ft. About 68 percent of the values of $h_c - h_o$ lie within the range of -21.6 ft to 21.6 ft, one standard deviation about the zero mean.

Among the 28 observations at the 15 wells that are pumped, the objective function is 22.4 ft; standard deviation is 9.4 ft. About 68 percent of the values of $h_c - h_o$ lie between -31.8 ft and 31.8 ft. This model does not define all of the variations of a potentiometric surface characterized by steep or rapidly changing hydraulic gradients, such as at or near a pumped well.

The objective function is 10.4 ft for the 295 observed wells that were not pumped; the standard deviation is 10.6 ft. About 68 percent of the values of $h_c - h_o$ for nonpumped wells lie between -21.0 ft to 21.0 ft. Some of these observation wells may be influenced by nearby pumping.

In the Peedee aquifer, values for $h_c - h_o$ in 1986 (table 8) lie within the range from -21.0 to 21.0 ft everywhere except (1) at wells pumped or known to be near pumping in Onslow County (well nos. 24 and 25) and (2) at well number 20 in an area characterized by steep hydraulic gradients near the western limit of the Peedee aquifer in Lenoir County (fig. 28).

Table 8.--*Well objective functions for observed heads in the Peedee aquifer, 1986*

[Well objective function is defined in the glossary; (ft), feet above or below sea level; N_w, number of observations at well; h_c, computed hydraulic head; h_o, observed hydraulic head; --, no observations were made]

Well number (fig. 28)	Well objective function (ft)	N_w	Hydraulic head (ft) h_c	h_o	$h_c - h_o$	Comments
1	3	1	-2	-4	2	
2	9	2	42	49	-7	
3	13	12	7	--	--	1968-81 measurements
4	11	19	12	--	--	1962-81 measurements
5	22	1	51	--	--	1981 measurement
6	9	1	25	16	9	
7	14	1	27	13	14	
8	4	3	13	17	-4	
9	10	2	35	40	-5	
10	4	2	33	29	4	
11	19	1	17	8	19	
12	4	2	22	26	-4	
13	38	10	52	--	--	1948-58 measurements
14	17	10	42	24	18	
15	5	2	31	25	6	
16	7	1	60	66	-6	
17	3	1	31	34	-3	
18	5	1	33	38	-5	
19	2	1	40	42	-2	
20	33	10	70	103	-33	
21	11	2	46	55	-9	airline measurement
22	10	3	31	36	-5	
23	16	3	13	29	-16	
24	33	2	0	-31	31	well is pumped
25	26	1	-10	-35	25	
26	5	1	12	16	-4	
27	10	3	42	31	11	
28	15	1	20	--	--	1981 measurement

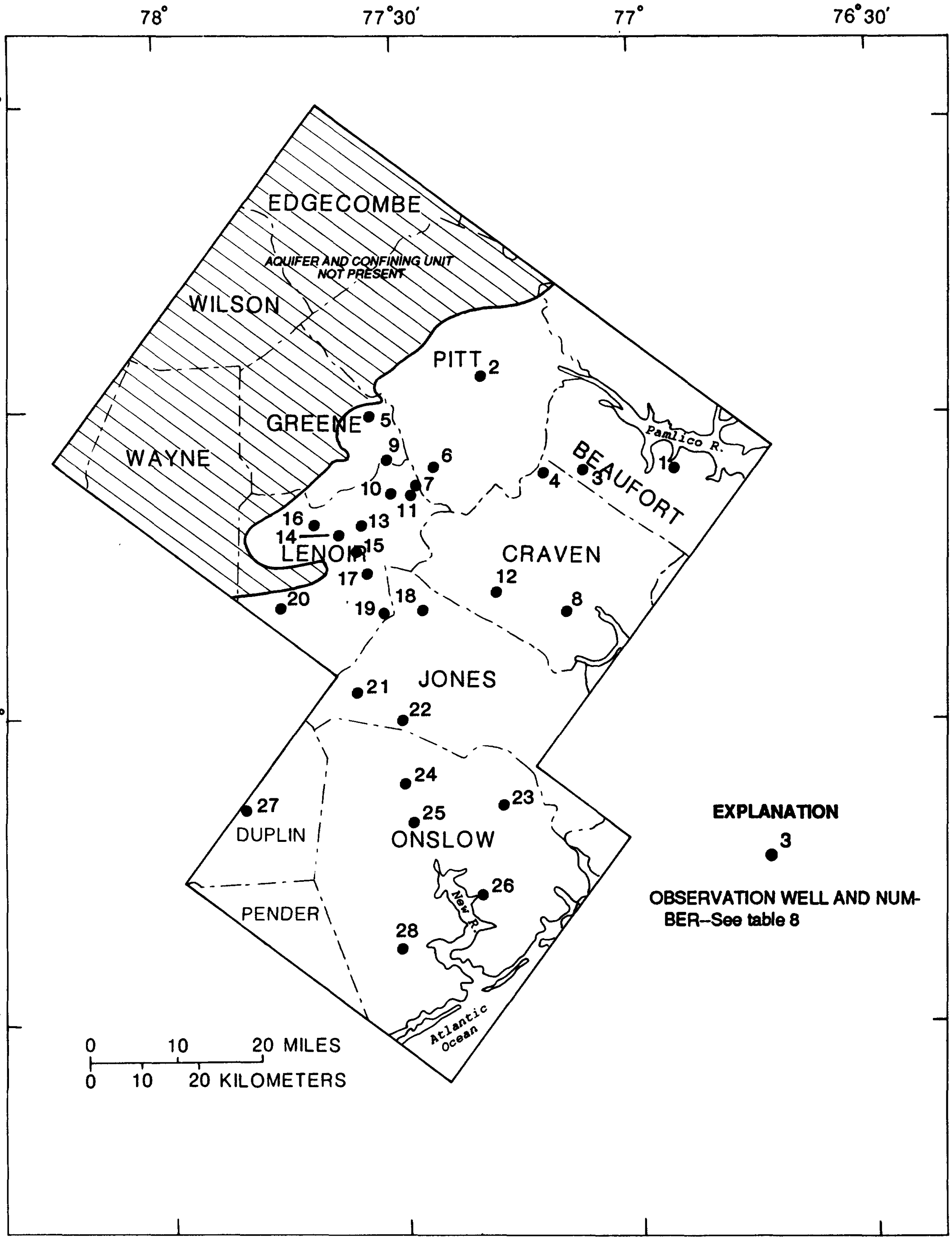

Figure 28.--Observation well locations in the Peedee aquifer.

The computed and observed hydrographs for well number 4 (fig. 29a) indicate a steady decline in water levels of about 0.5 ft/yr (foot per year) in Craven County from 1950 to 1986. The slopes of the computed and observed hydrographs for this well are well matched, but the observed head is consistently about 11 ft greater than the computed head. The computed hydrograph for the pumped well, well number 24 (fig. 29b), indicates a decline of about 1 ft/yr in water levels in Onslow County after about 1950. Slopes of the computed and observed hydrographs also show a good match, but the observed head in this pumped well is about 33 ft less than the computed head. This disparity occurs because the computed head is an average value for the cell, whereas the observed head is affected to a greater extent by pumping this elsewhere in the cell.

Values for $h_c - h_o$ in the Black Creek aquifer for 1986 lie within the range of -21.0 to 21.0 ft at all but the following locations: (1) at pumped wells 4 and 5 in Pitt County; (2) at well number 3 in Beaufort County, where depth interval of the well screen is uncertain; (3) at several pumped wells or wells near pumping in Onslow County (well nos. 29 through 35 and 37); (4) at well number 41 in southern Onslow County; and (5) at some wells pumped or near pumping in Lenoir County (well nos. 19, 20, and 24). These wells are located in figure 30, and the objective functions are listed in table 9.

The computed hydrograph for well number 28 (fig. 31a) indicates water levels in Jones County decreasing less than 1 ft/yr until 1965 and then decreasing nearly 4 ft/yr to 1986; h_c and h_o are well matched at this location. The computed hydrograph for pumped well number 30 in Onslow County (fig. 31b) indicates water levels decreasing at a rate of nearly 1.5 ft/yr from 1950 to 1970 and decreasing over 6 ft/yr from 1970 to 1986. The well objective function for this well is 20 ft (table 9); however, the 1986 value for $h_c - h_o$ is 42 ft due to steep and rapidly changing heads near this well in response to pumping.

In the upper Cape Fear aquifer, 1986 values for $h_c - h_o$ for most wells range from -21.0 to 21.0 ft (table 10). Exceptions are: (1) at wells 24 and 28 (fig. 32) in an area characterized by steep and rapidly changing hydraulic gradients near the western limit of the aquifer in Wilson County; (2) at well number 31 near pumping in Greene County; (3) at wells 44 and 45

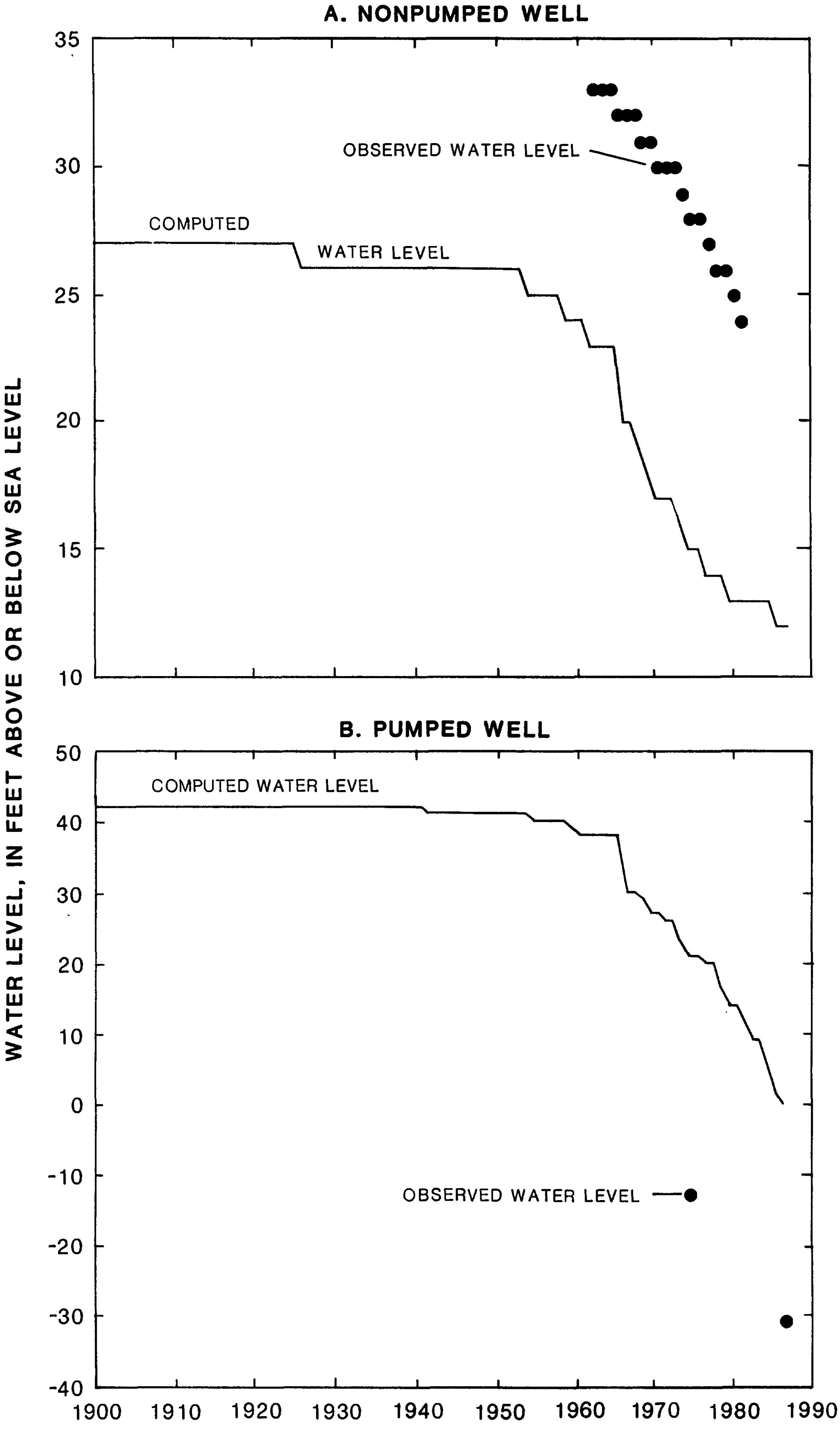

Figure 29.--Computed and observed water levels for the Peedee aquifer: (a) nonpumping well number 4 and (b) pumping well number 24.

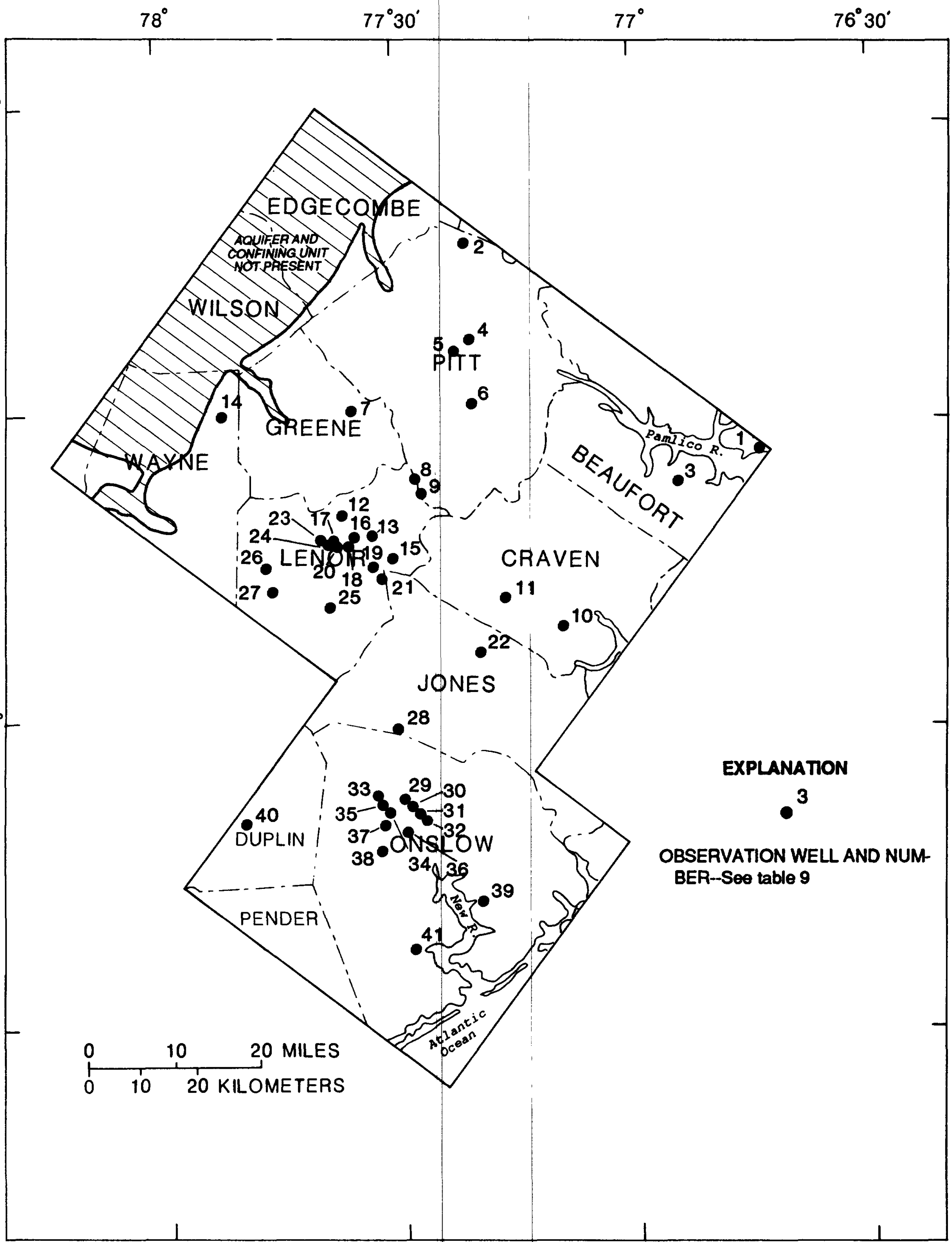

Figure 30.--Observation well locations in the Black Creek aquifer.

Table 9.--*Well objective functions for observed heads in the Black Creek aquifer, 1986*

[Well objective function is defined in the glossary; (ft), feet above or below sea level; N_w, number of observations at well; h_c, computed hydraulic head; h_o, observed hydraulic head; --, no observations were made]

Well number (fig. 30)	Well objective function (ft)	N_w	Hydraulic head (ft) h_c	h_o	$h_c - h_o$	Comments
1	12	8	-5	7	-12	
2	14	3	34	55	-21	
3	19	16	-9	17	-26	screen depth uncertain
4	26	2	-44	-92	48	well is pumped
5	24	2	-55	-94	39	well is pumped
6	13	1	-33	-46	13	well is pumped
7	11	3	36	45	-9	
8	6	8	-37	--	--	1953-62 measurements
9	4	8	-59	-70	11	
10	15	3	-30	-13	-17	
11	14	18	-71	-66	-5	
12	12	1	-69	-57	-12	well is pumped
13	22	2	-93	-80	-13	well is pumped
14	6	1	89	83	6	
15	26	2	-97	-78	-19	well is pumped
16	20	1	-94	-74	-20	
17	18	2	-85	-67	-18	well is pumped
18	10	4	-88	-73	-15	well influenced by near-by pumping
19	22	2	-93	-67	-26	well is pumped
20	34	5	-75	-46	-29	well influenced by near-by pumping
21	18	2	-77	-58	-19	
22	4	2	-47	-46	-1	airline measurement
23	9	1	-51	-42	-9	well is pumped
24	19	2	-60	-38	-22	well influenced by near-by pumping
25	15	2	-30	-15	-15	
26	22	1	13	34	-21	
27	13	1	4	25	-21	
28	6	8	-45	-53	8	
29	21	2	-104	-127	23	well is pumped
30	20	3	-91	-133	42	well is pumped
31	28	3	-80	-132	52	well is pumped
32	38	1	-65	-102	37	well influenced by near-by pumping
33	33	1	-59	-91	32	well influenced by near-by pumping
34	34	1	-74	-107	33	well influenced by near-by pumping
35	39	1	-65	-104	39	well influenced by near-by pumping
36	19	1	-64	-82	18	well influenced by near-by pumping
37	39	3	-72	-122	50	well is pumped
38	7	1	-46	-52	6	
39	6	1	-13	-18	5	
40	4	3	32	33	-1	
41	25	3	-3	27	-30	

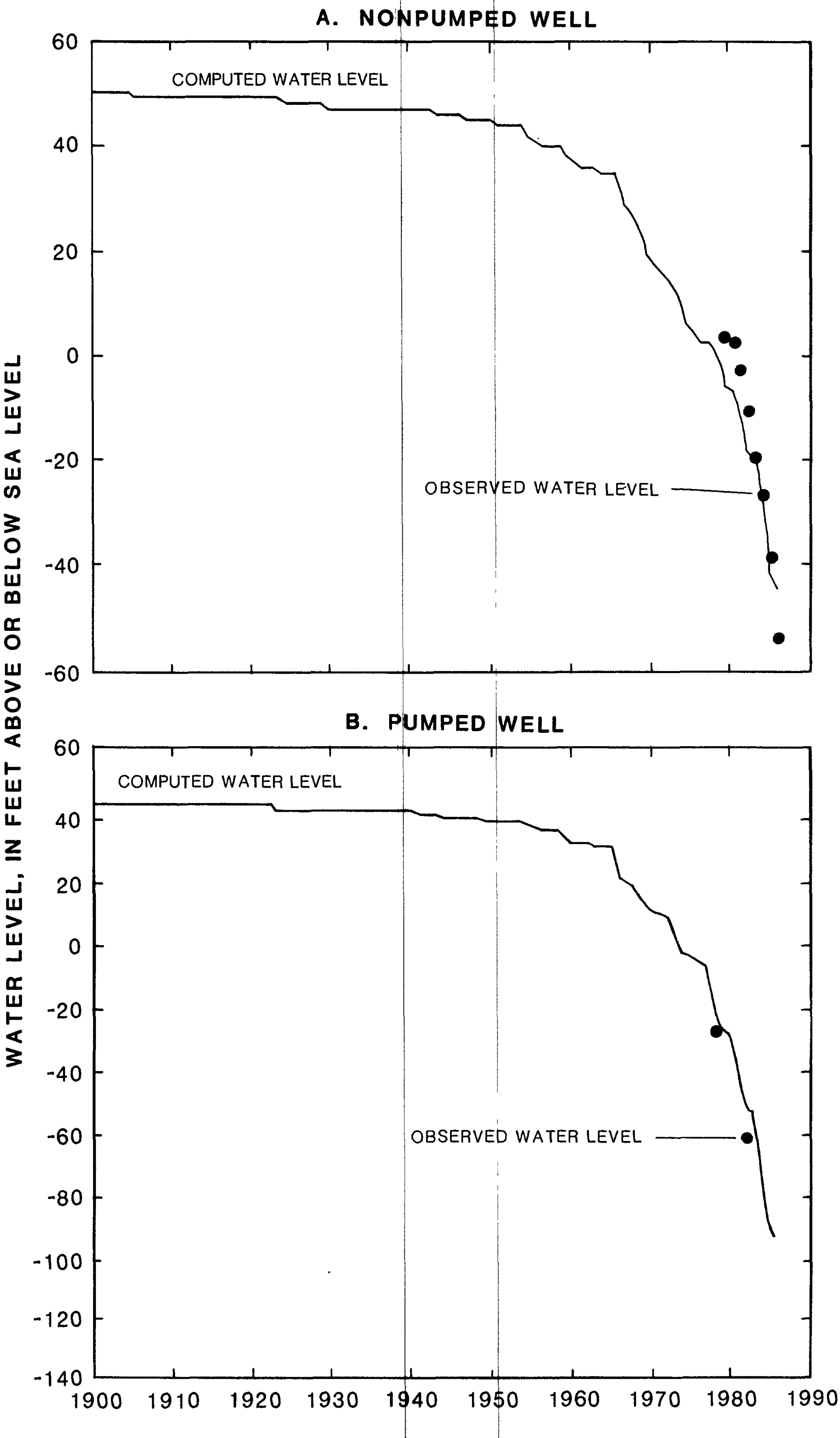

Figure 31.--Computed and observed water levels for the Black Creek aquifer: (a) nonpumping well number 28 and (b) pumping well number 30.

Table 10.--*Well objective functions for observed heads in the upper Cape Fear aquifer, 1986*

[Well objective function is defined in the glossary; (ft), feet above or below sea level; N_w, number of observations at well; h_c, computed hydraulic head; h_o, observed hydraulic head; --, no observations were made]

Well number (fig. 32)	Well objective function (ft)	N_w	Hydraulic head (ft) h_c	h_o	$h_c - h_o$	Comments
1	21	1	53	32	21	may be influenced by pumping not in model
2	13	1	33	20	13	
3	8	2	1	-11	12	
4	38	7	32	--	--	1968-74 measurements
5	2	9	65	--	--	
6	1	1	-1	0	-1	
7	23	1	-3	--	--	1981 measurement
8	1	1	31	30	1	
9	28	1	-35	-63	28	may be influenced by pumping not in model
10	13	13	-18	-9	-9	
11	15	1	68	43	15	well is pumped
12	3	1	-30	-32	2	
13	6	2	9	11	-2	
14	8	1	-43	-50	7	well is pumped
15	9	2	-45	-36	-9	
16	11	2	-52	-62	10	well is pumped
17	8	2	-44	-31	-13	
18	11	51	-53	-47	-6	
19	7	2	-60	-50	-10	
20	9	2	-63	-48	-15	
21	11	2	-58	-50	-8	
22	5	10	94	--	--	
23	11	5	78	91	-13	well is pumped
24	29	1	55	26	29	well is pumped
25	10	1	0	-10	10	well depth uncertain
26	13	13	37	--	--	
27	2	4	-47	-47	0	
28	29	3	54	18	36	
29	11	2	-65	-44	-21	
30	2	2	-23	-25	2	
31	33	2	-79	-38	-41	
32	8	1	-55	-47	-8	
33	22	2	-61	-83	22	may be influenced by pumping not in model
34	7	2	-50	-38	-12	
35	42	1	47	5	42	screen extends into upper Cape Fear confining unit
36	11	1	-28	-17	-11	
37	10	4	-43	-49	6	
38	3	1	-33	-35	2	
39	2	1	14	16	-2	well depth uncertain
40	6	1	24	38	6	
41	5	1	26	21	5	
42	41	1	21	62	-41	hydraulic connection with nearby river
43	37	2	23	114	-41	well is pumped
44	61	1	-13	48	-61	overlying aquifer pumped
45	38	1	-4	34	-38	overlying aquifer pumped

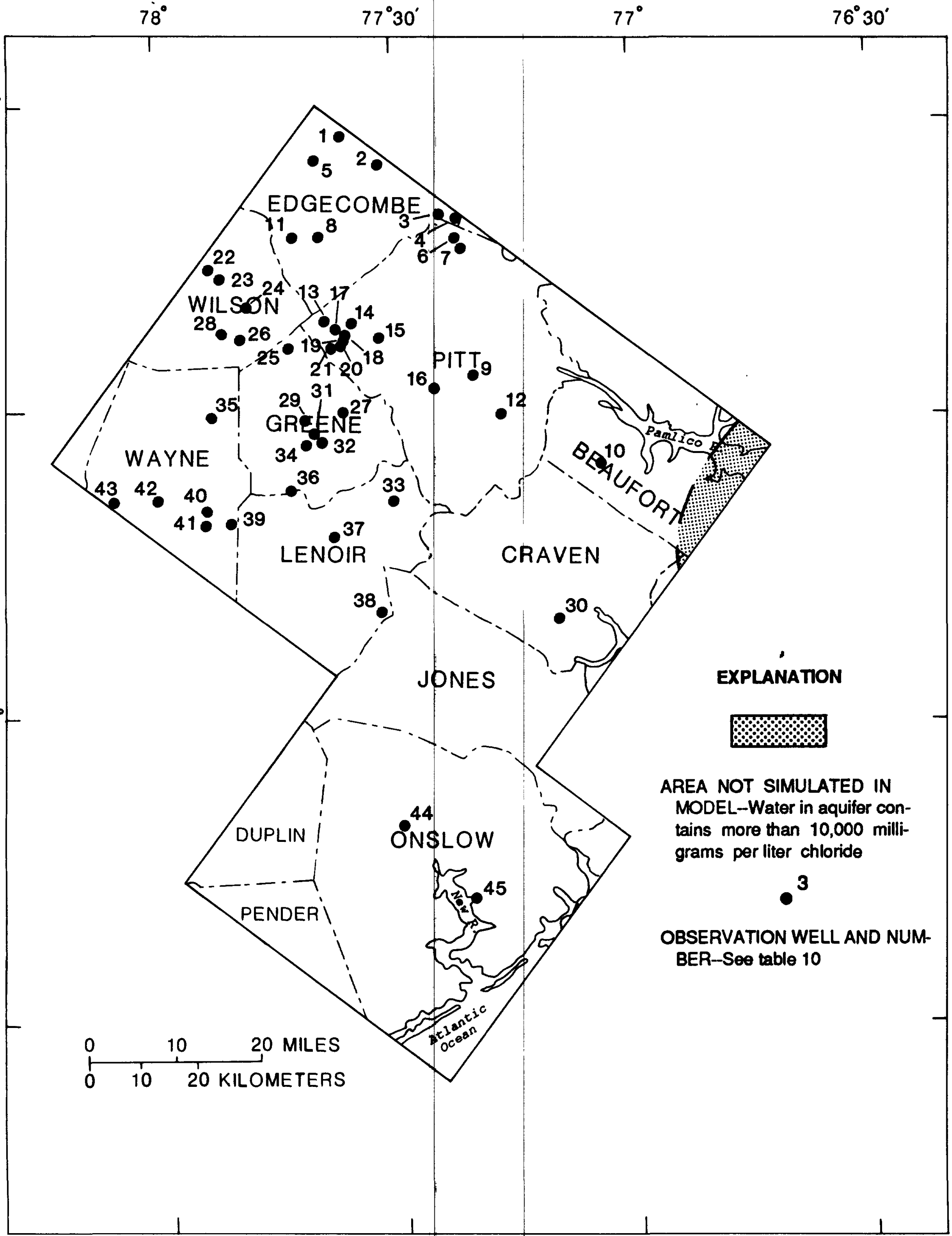

Figure 32.--Observation well locations in the upper Cape Fear aquifer.

in Onslow County, water levels of which are influenced by pumping from the Black Creek aquifer; (4) at well number 9 in Pitt County that may be influenced by pumping not simulated; (5) at well number 33 in Lenoir County, which also may be influenced by unsimulated pumping; and (6) and at wells 35, 42, and 43 in Wayne County where water levels may be influenced, respectively, by multi-aquifer screens, hydraulic connection with a nearby stream, and local pumping.

The computed hydrograph for well number 27 (fig. 33a) indicates water levels in Greene County declining about 1 ft/yr from 1940 to 1965 and about 3.5 ft/yr from 1965 to 1986; h_c and h_o show a good match at this location. The computed hydrograph for a pumped well in Pitt County, well number 16 (fig. 33b), indicates only a very slight decline in water levels up to about 1940; the decline then averages about 2 ft/yr to 1986. Observed heads are about 11 ft less than computed heads in this location.

Relatively few water level data were available for the lower Cape Fear aquifer (table 11). Values for $h_c - h_o$ that do not occur within the range of -21.0 to 21.0 ft are the following areas: (1) in well number 1 in Pitt County near the western limit of the aquifer; (2) in well number 3 near the eastern boundary of the 10,000 mg/L chloride water in Pitt County; and (3) in well number 7 in Onslow County where the screen probably extends into the lower Cape Fear confining unit (fig. 34).

The computed hydrograph for well number 5 (fig. 35) indicates water levels in the lower Cape Fear aquifer in Craven County declined less than 1 ft/yr between 1940 and 1965 but declined more than 2 ft/yr from 1965 to 1986. The computed head and two observed heads are well matched in 1985 and 1986 at this location. Water-level decline in this well is believed to be caused by the discharge of ground water from the lower Cape Fear aquifer to the overlying upper Cape Fear aquifer in response to pumpages from that aquifer.

ANALYSIS OF GROUND-WATER FLOW SYSTEM BASED ON SIMULATION

The horizontal and vertical movement of ground water in the aquifer system in Cretaceous rocks has been affected by increasing ground-water withdrawals since about 1900. The regional movement of water in 1900 was

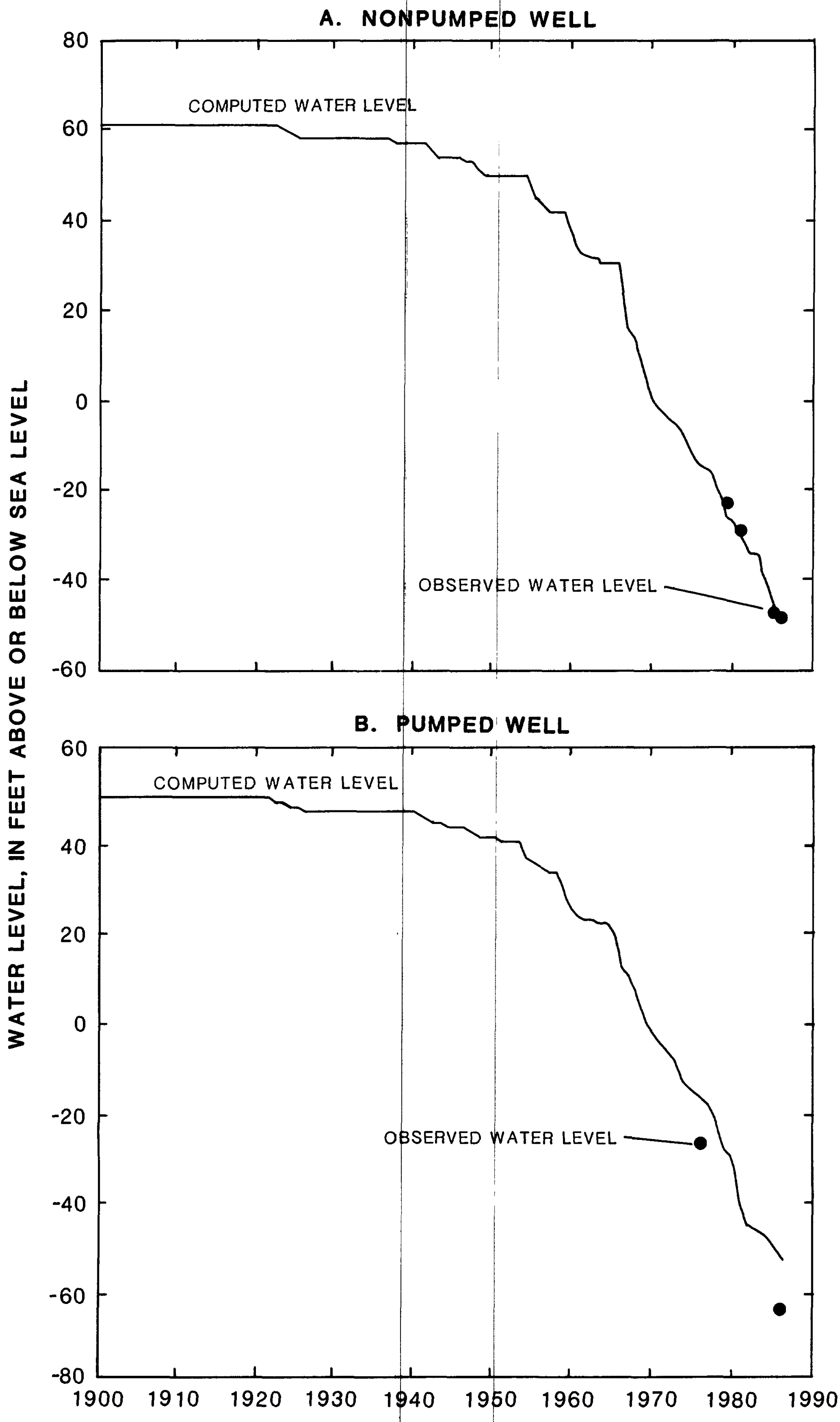

Figure 33.--Computed and observed water levels for the upper Cape Fear aquifer: (a) nonpumping well number 27 and (b) pumping well number 16.

Table 11.--*Well objective functions for observed heads in the lower Cape Fear aquifer, 1986*

[Well objective function is defined in the glossary; (ft), feet above or below sea level; N_w, number of observations at well; h_c, computed hydraulic head; h_o, observed hydraulic head; --, no observations were made]

Well number (fig. 34)	Well objective function (ft)	N_w	Hydraulic head (ft)			Comments
			h_c	h_o	$h_c - h_o$	
1	38	2	65	27	38	screened in lower and upper Cape Fear aquifers
2	33	1	-21	--	--	
3	40	1	-20	20	-40	
4	3	1	-32	--	--	
5	7	2	-14	-6	-8	
6	3	1	-13	-10	-3	
7	40	1	2	42	-40	screen probably extends into lower Cape Fear confining unit

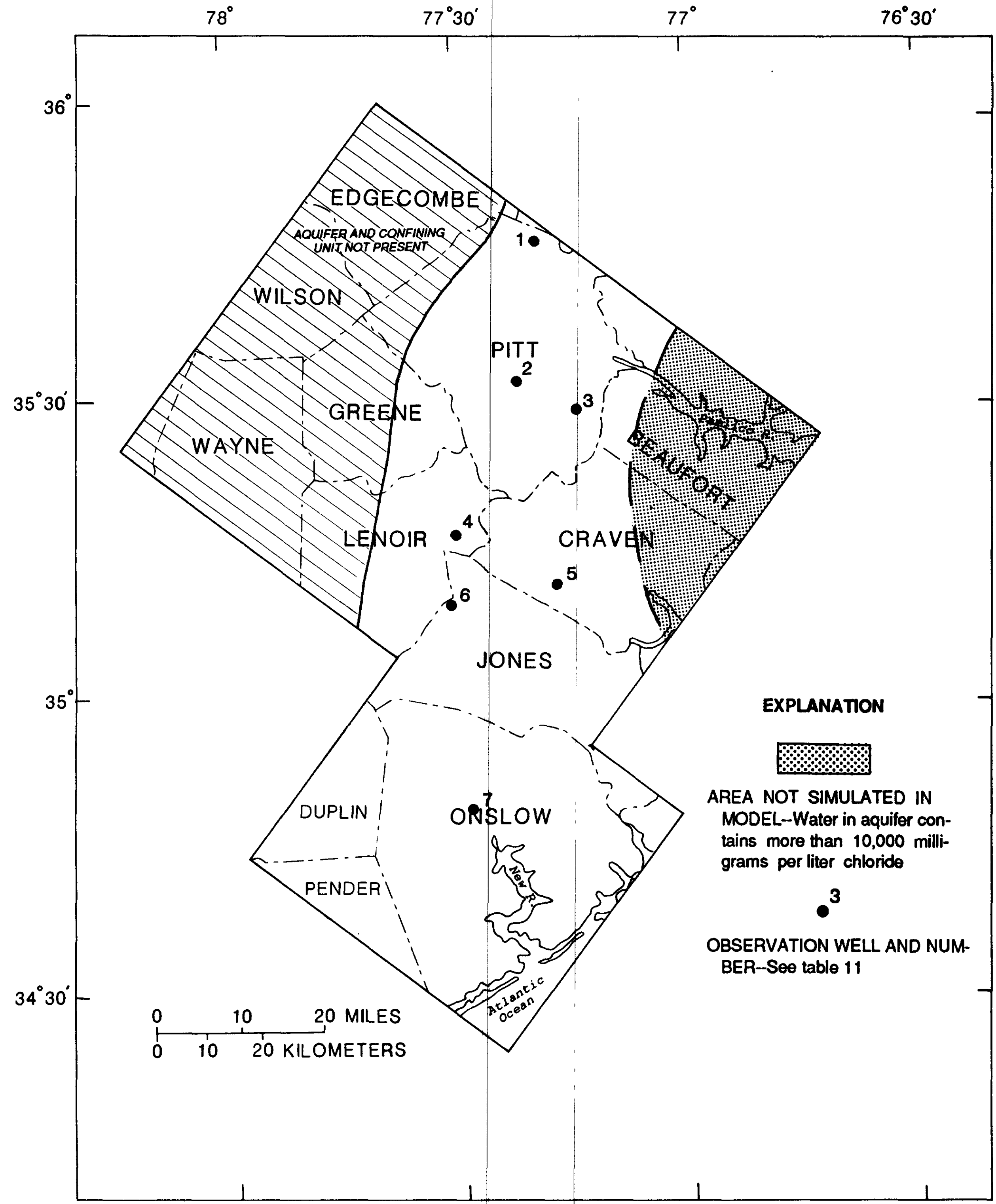

Figure 34.--Observation well locations in the lower Cape Fear aquifer.

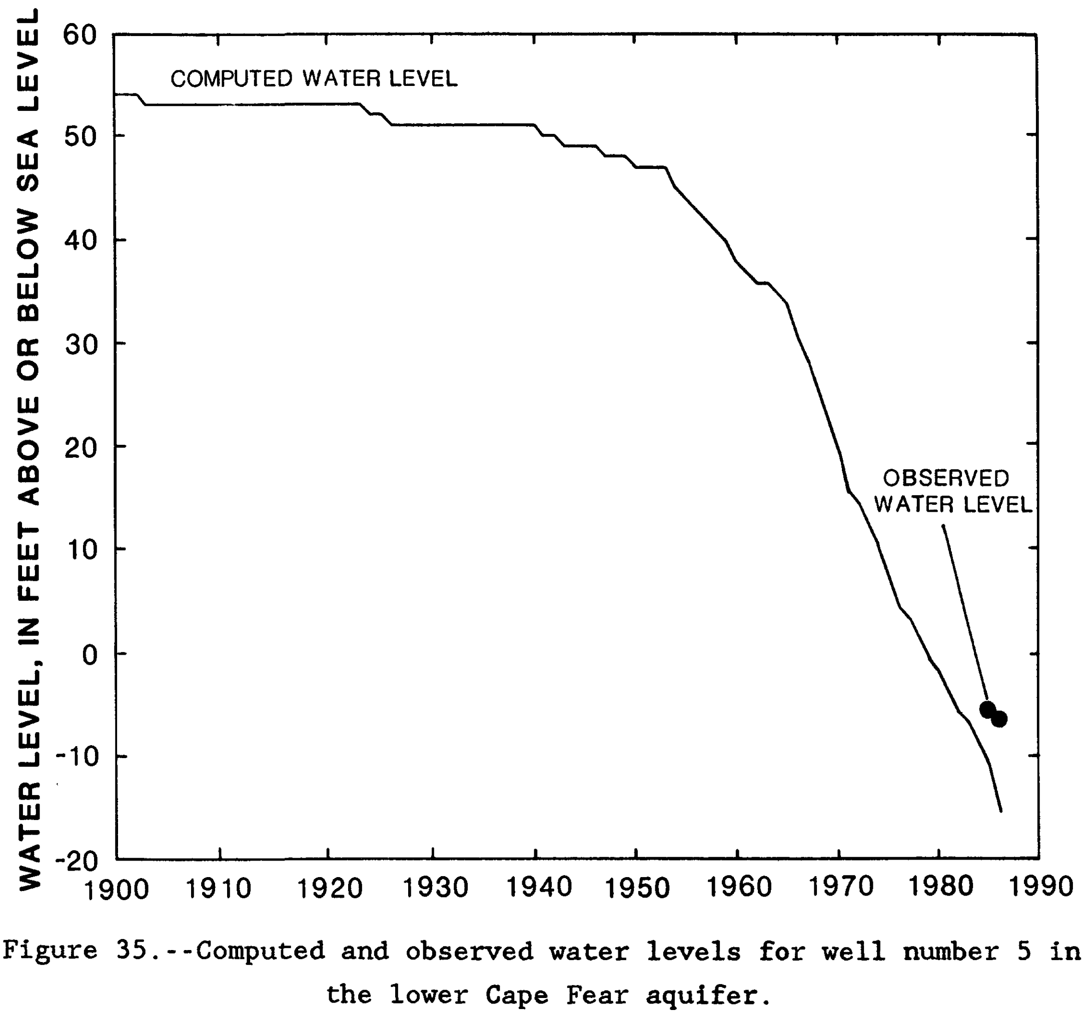

Figure 35.--Computed and observed water levels for well number 5 in the lower Cape Fear aquifer.

generally from northwest to southeast; in 1986, flow was generally toward pumping centers. Cones of depression around individual pumping centers coalesced to form larger areas of water-level declines. Pumping not only altered the regional flow within aquifers (compare figs. 13 and 25, for example), but also affected the vertical movement of water between aquifers. The effect of pumping on vertical flow is shown by changes in recharge and discharge areas for each aquifer from 1900 to 1986 (figs. 36-39).

The model indicates that at the beginning of pumping, about 1900, recharge areas in the Peedee (fig. 36a), Black Creek (fig. 37a), and upper Cape Fear (fig. 38a) aquifers were in interstream areas generally in the western or central parts of the study area. Water was discharged from these aquifers to streams in the western part of the study area and to large areas in the eastern part of the study area. The lower Cape Fear aquifer is the only aquifer that does not crop out near its western limit. Recharge to the lower Cape Fear aquifer occurred all along the aquifer's western boundary and discharge occurred all along its eastern boundary (fig. 39a).

When heads in an aquifer are lowered by pumping, this can increase the amount of vertical flow from aquifers above and below the pumped aquifer, or cause a reversal in the direction of ground water flow toward the pumped aquifer. Hence, ground-water withdrawals tend to cause recharge areas to increase in size in aquifers that are pumped or in aquifers that overlie pumped aquifers. Ground-water withdrawals tend to cause discharge areas to increase in size in aquifers that underlie pumped aquifers.

By 1986, the area of recharge to the Peedee (fig. 36b) and Black Creek (fig. 37b) aquifers increased so that almost the entire upper surface of both aquifers is receiving recharge. Because the amount of pumpage from the Peedee is small compared to withdrawals from the Black Creek, much of the recharge to the Peedee is in response to withdrawals from the underlying Black Creek aquifer. Total simulated amounts of recharge to and discharge from the Peedee aquifer for the end of 1986 are 39 and 22 Mgal/d, respectively. Both the maximum recharge and the maximum discharge in one model cell occur in Greene County (0.8 and 0.6 Mgal/d, respectively); both the minimum recharge and the minimum discharge occur in Pitt County (1×10^{-6} and 1×10^{-5} Mgal/d, respectively).

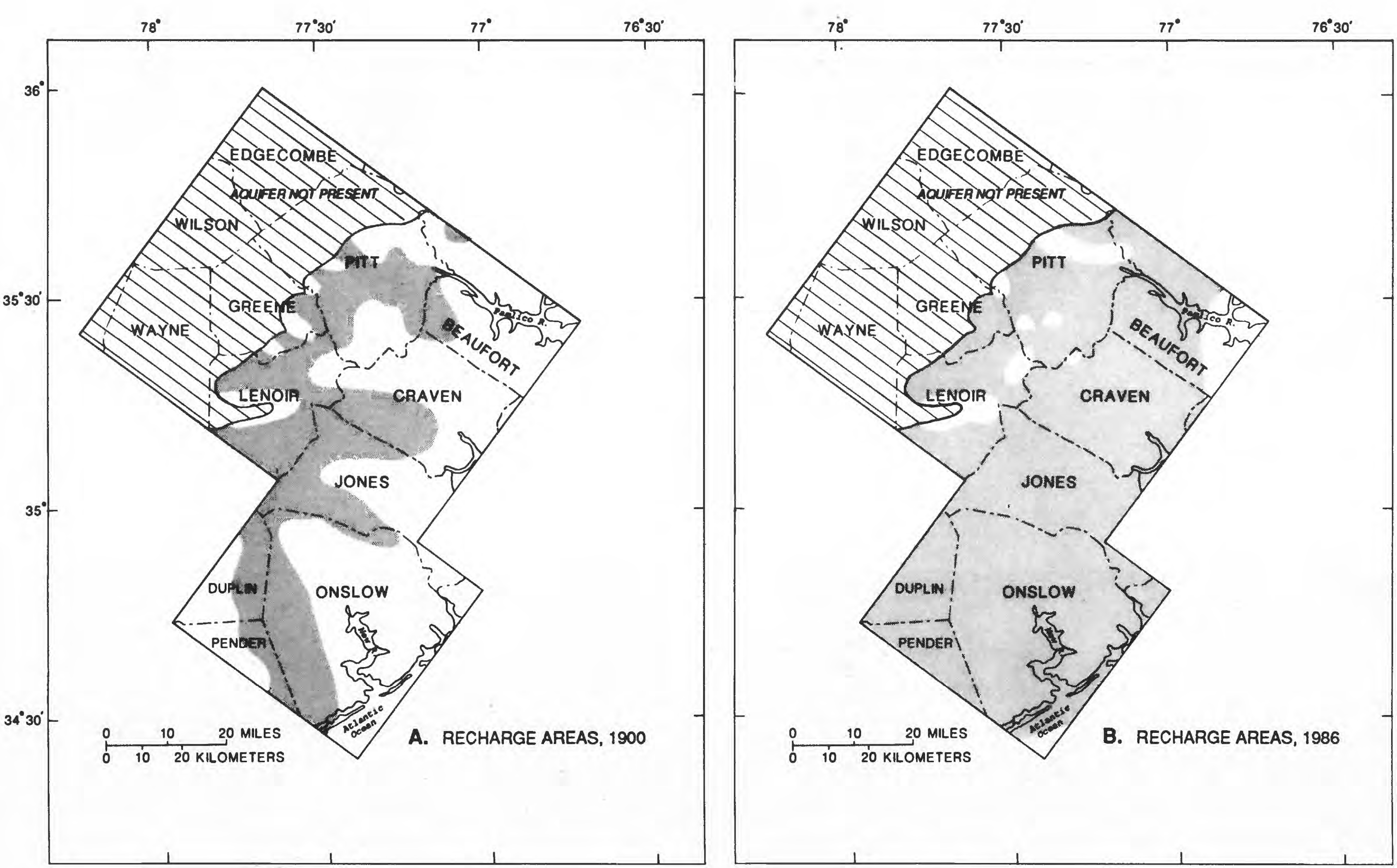

Figure 36.--Model-derived recharge areas for the Peedee aquifer from overlying sediments in (a) 1900, prior to withdrawals, and (b) 1986, under stressed conditions. (Shaded area indicates recharge areas.)

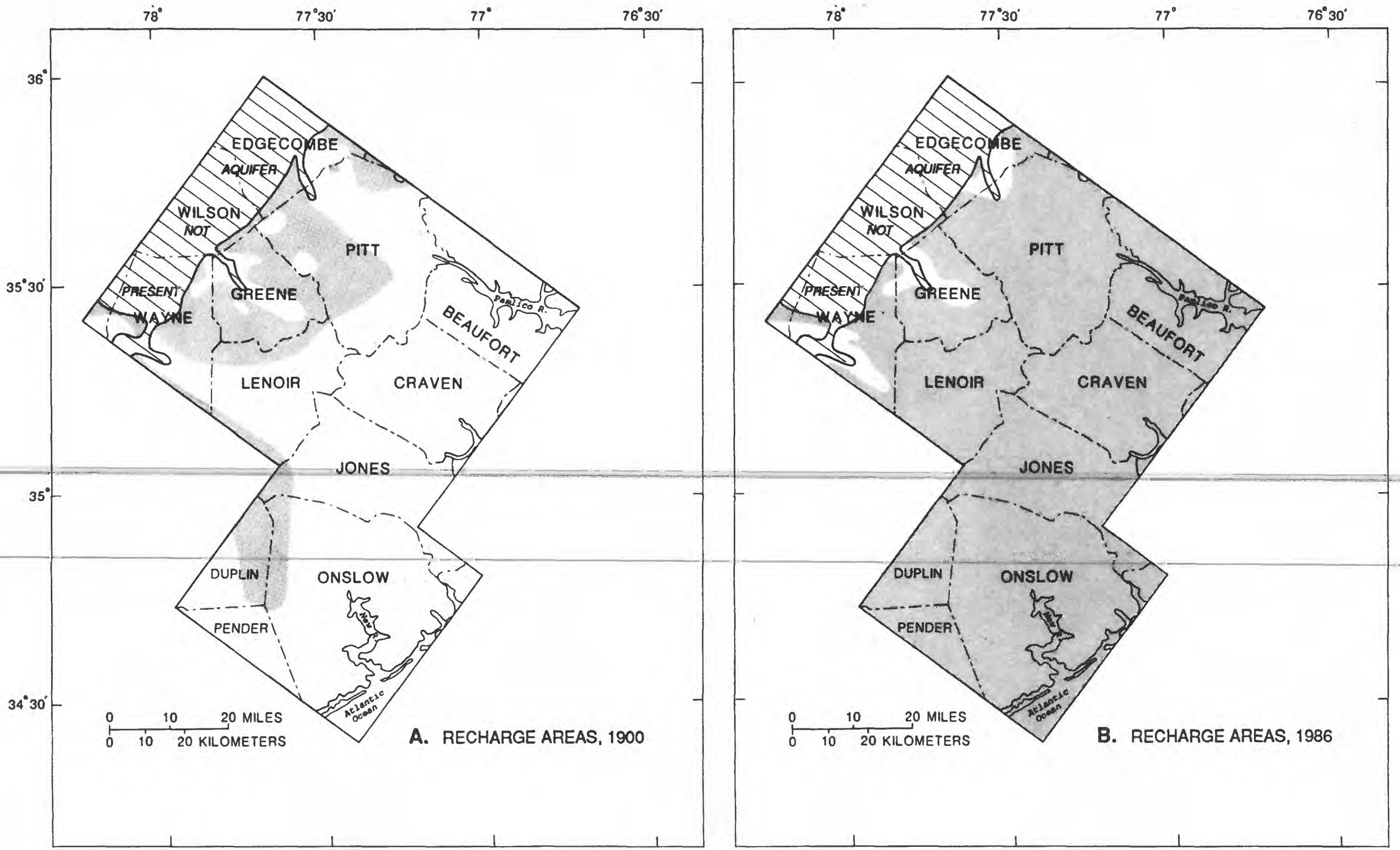

Figure 37.--Model-derived recharge areas for the Black Creek aquifer from overlying sediments in (a) 1900, prior to withdrawals, and (b) 1986, under stressed conditions. (Shaded area indicates recharge areas.)

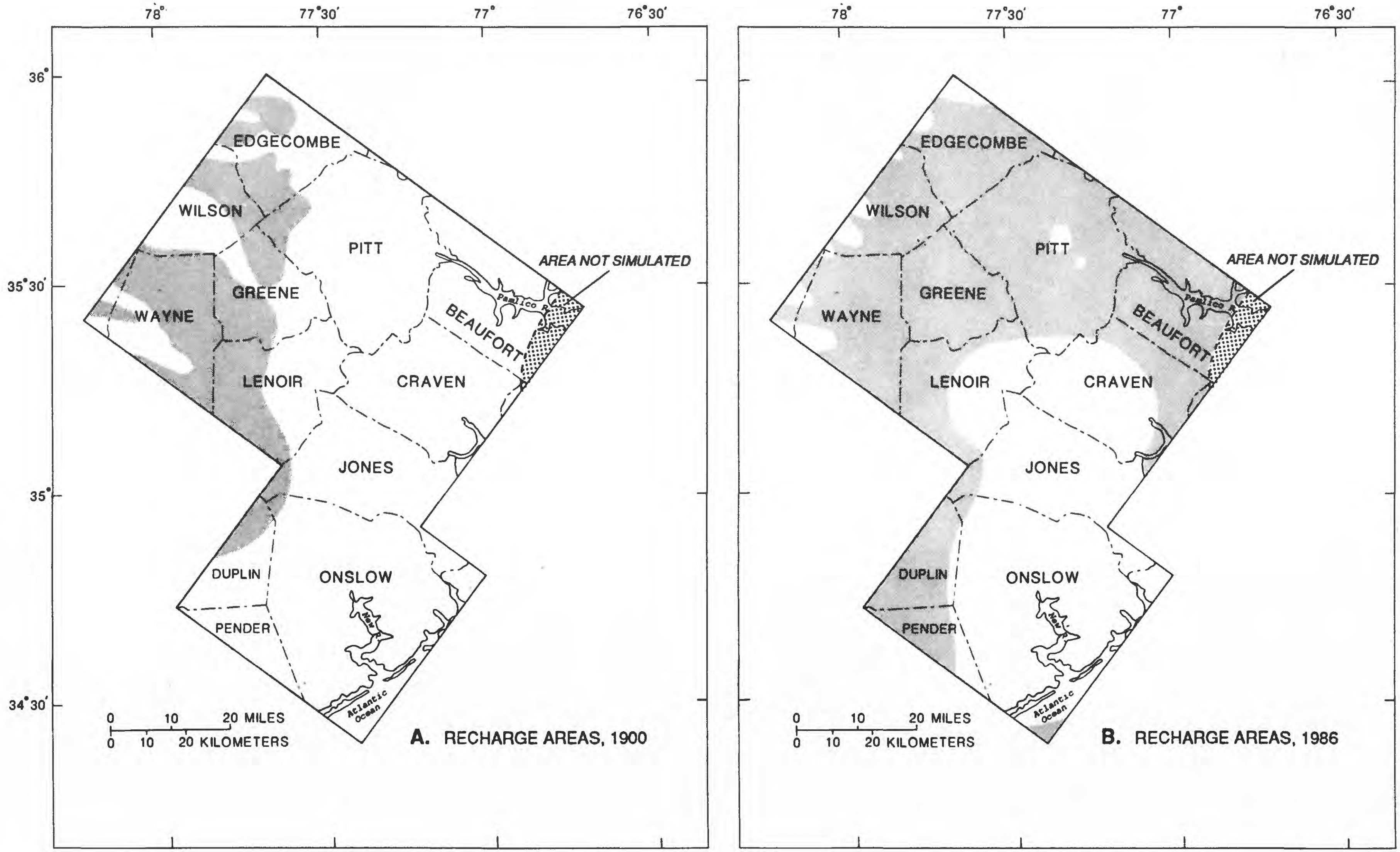

Figure 38.--Model-derived recharge areas for the upper Cape Fear aquifer from overlying sediments in (a) 1900, prior to withdrawals, and (b) 1986, under stressed conditions. (Shaded area indicates recharge areas.)

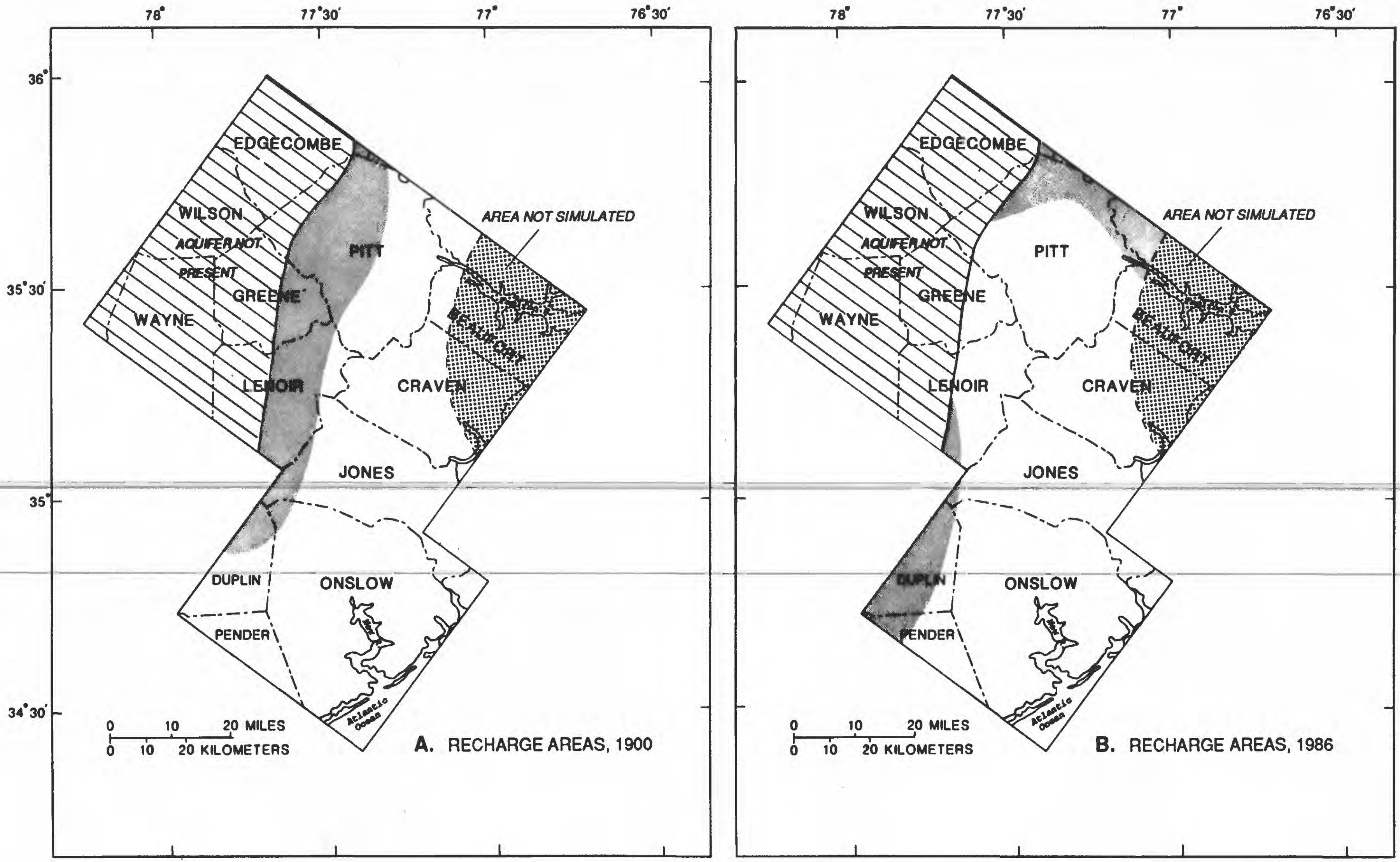

Figure 39.--Model-derived recharge areas for the lower Cape Fear aquifer from overlying sediments in (a) 1900, prior to withdrawals, and (b) 1986, under stressed conditions. (Shaded area indicates recharge areas.)

Total amounts of simulated recharge to and discharge from the Black Creek aquifer for the end of 1986 are 24 and 8 Mgal/d, respectively. Both the maximum recharge and the maximum discharge occur in Greene County (0.8 and 0.6 Mgal/d, respectively); both the minimum recharge and the minimum discharge occur in Edgecombe County, (3×10^{-6} and 2×10^{-5} Mgal/d, respectively).

The 1986 recharge area in the upper Cape Fear aquifer also increased (fig. 38b). However, the central part of the study area, parts of Craven, Jones, Lenoir, and Pitt Counties, remained a discharge area because of withdrawals from the overlying Black Creek aquifer. In Onslow County, the area of discharge from the upper Cape Fear aquifer was reduced. Nevertheless, because of significant pumpage from the overlying Black Creek aquifer in the area, water continued to flow upward throughout most of the county. Total amounts of recharge and discharge across the top of the upper Cape Fear aquifer for the end of 1986 are 6 and 1 Mgal/d, respectively. A maximum recharge of 4×10^{-2} Mgal/d occurs in Greene County; a maximum discharge of 4×10^{-2} Mgal/d occurs in Edgecombe County. Both minimum recharge and minimum discharge occur in Pitt County (1×10^{-7} and 1×10^{-8} Mgal/d, respectively).

The distribution of recharge areas in the lower Cape Fear aquifer changed from 1900 to 1986 (fig. 39) in response to withdrawals from the overlying upper Cape Fear aquifer. In 1986, the central part of the study area and along the western limit were discharge areas, as water flows upward into the upper Cape Fear where water-supply wells withdraw water from that aquifer in Lenoir and Craven Counties. Along the western limit of the lower Cape Fear aquifer, recharge occurs in parts of Duplin and Lenoir Counties. The remaining recharge area has shifted eastward, occurring in parts of Pitt and Beaufort Counties. Total amounts of recharge and discharge across the top of the lower Cape Fear aquifer for the end of 1986 are 0.01 and 1 Mgal/d, respectively. A maximum recharge of 9×10^{-4} Mgal/d occurs in Edgecombe County; a maximum discharge of 7×10^{-3} Mgal/d occurs in Lenoir County. A minimum recharge of 3×10^{-6} Mgal/d occurs in Pitt County; a minimum discharge of 1×10^{-6} Mgal/d occurs in Duplin County.

Analysis of the calibrated simulation supports the changes in the regional flow system from 1900 to 1986 described in the conceptual model (fig. 10). In particular, (1) pumping and natural discharge exceeded recharge in 1986, and a small amount of ground water was released from aquifer storage as water levels declined; (2) ground water flowed downward through confining units from aquifers overlying the aquifer system in Cretaceous rocks; and (3) little discharge occurred upward from the aquifer system in Cretaceous rocks to the overlying aquifer system in Quaternary and Tertiary rocks.

In 1900, there existed a net discharge from the aquifer system in Cretaceous rocks of about 2 Mgal/d (fig. 40). By 1986, the direction of net flow across the top of the system had reversed; a net recharge of about 18 Mgal/d entered through the top of the aquifer system at the end of 1986. The area of ground-water recharge through the top of the aquifer system (top of Peedee aquifer, fig. 36) increased from about one-third of the total area to over four-fifths of the total area. The 1-million-gallon-per-day loss in ground-water storage at the end of 1986 was less than 4 percent of the total amount of ground water pumped. At the end of 1986, the net flow through the top of the aquifer system, 18 Mgal/d, represented more than 67 percent of the total amount of ground water pumped. About 8 Mgal/d (30 percent) is supplied by increased lateral flux into the aquifer system and (or) decreased lateral natural discharge. Only about 1 Mgal/d (3 percent) is derived from ground-water storage in response to increased pumpage.

PREDICTIVE SIMULATIONS

The model presented in this report is a tool that can assist in the management of ground-water resources in the aquifer system in Cretaceous rocks in the central Coastal Plain of North Carolina. The model can be used to evaluate local or system-wide changes in ground-water flow in response to different withdrawal scenarios. Examples are presented here to demonstrate the capabilities of the model and how these capabilities could be useful to water managers in the study area. Results from these simulations are limited to the central Coastal Plain study area. Because of continually changing patterns of water use and development, data updates and periodic calibration of the model are necessary for its continued use for ground-water resource management.

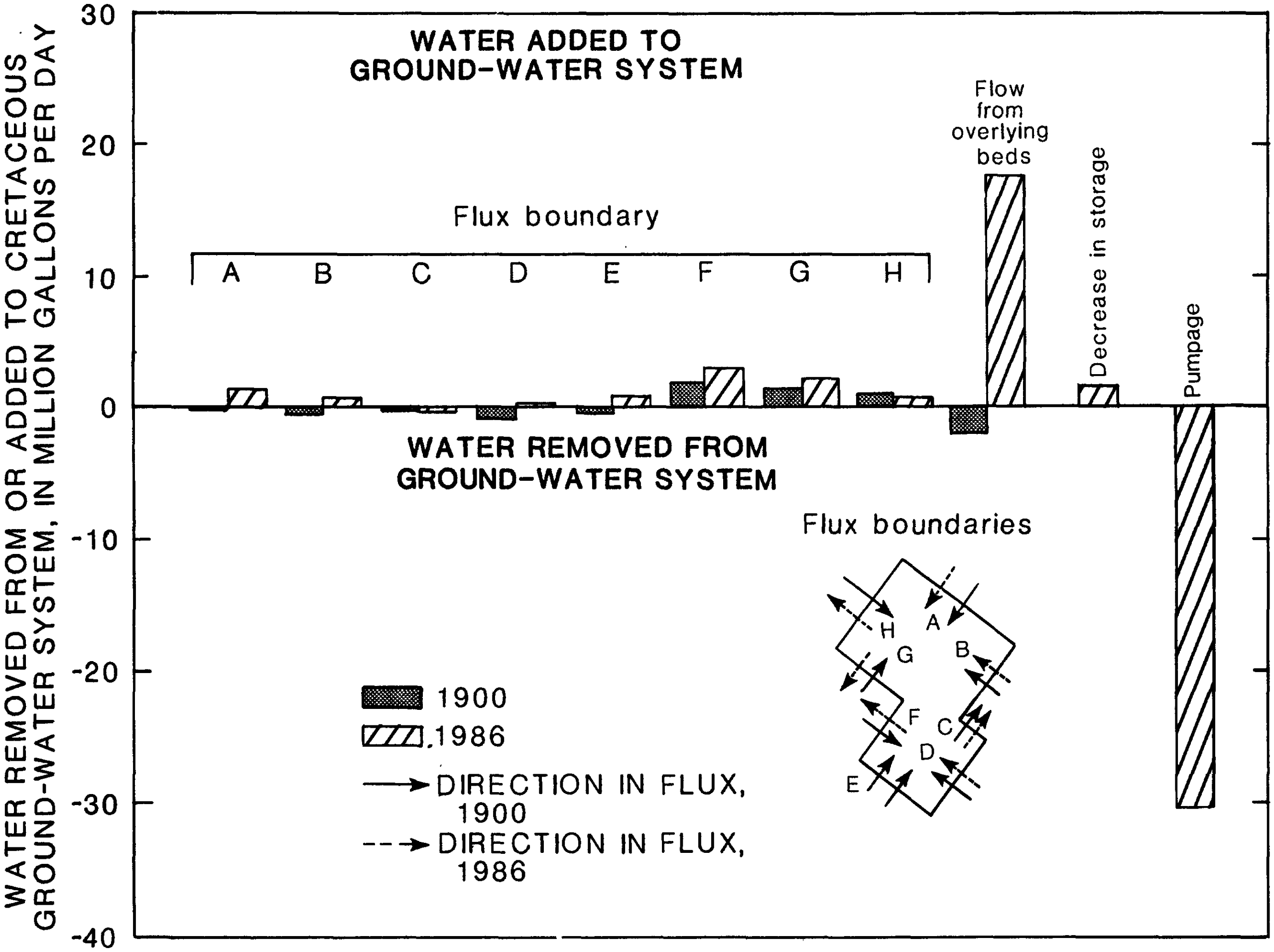

Figure 40.--Comparison of 1900 and 1986 ground-water budgets for aquifers in Cretaceous rocks in the central Coastal Plain.

Simulation Examples

The predictive capability of the model is demonstrated by simulating ground-water levels in 1991 resulting from two pumping scenarios. These scenarios do not reflect historical or future patterns of water use by individual users, nor do they reflect official estimates of future use. The sole purpose of analyzing the results of these simulations is to demonstrate how the model may be used.

The 1986 hydraulic heads, the initial conditions for these predictive simulations, were provided by the calibrated model. The final time period in the calibration simulation represented average pumping conditions over the years 1984-86. To produce predictive simulations, pumpage estimates for 1987 to 1991 were included in the model simulation. Estimates of total pumpage from the aquifer system in Cretaceous rocks in the study area and those for each of the water-supply aquifers for each of the scenarios are shown graphically in figure 41.

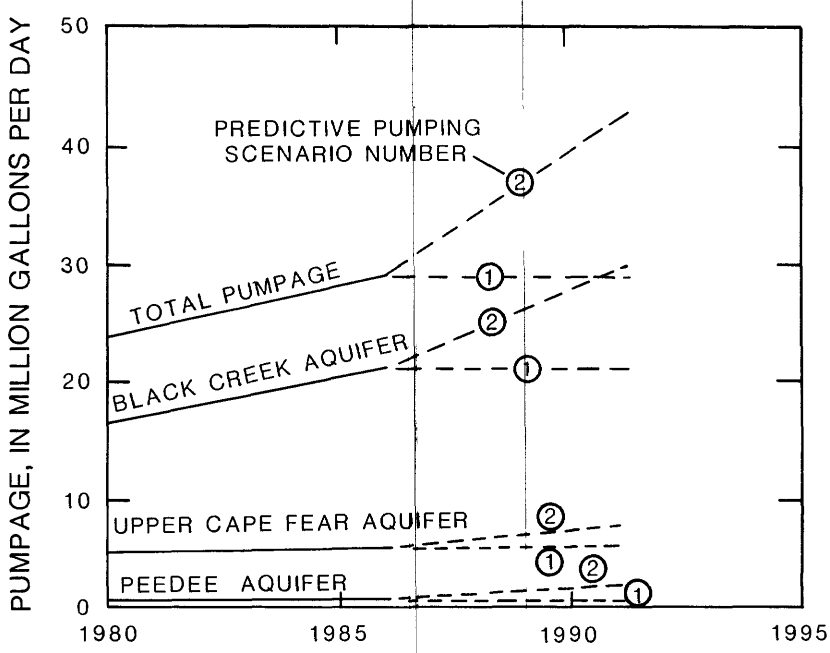

Figure 41.--Projected ground-water pumpage for two predictive scenarios.

In the first scenario, pumpage remained constant through 1991 at the 1986 rate for each water user in the entire North Carolina Coastal Plain. This scenario was chosen because it is a rough estimate of minimum pumpage in the future. However, this scenario may underestimate future pumpage, because only 12 of 49 water systems in the study area experienced no change in their rate of pumping from 1980 to 1986 (table 2).

Figure 42 depicts the change in water levels in each aquifer from 1986 through 1991, resulting from the simulated conditions of scenario 1. As might be expected, the largest changes in water levels occurred at pumpage centers and in areas farthest from recharge areas. However, water levels generally declined throughout the study area in each of the aquifers. In the Peedee aquifer, water levels generally fell less than 1 ft throughout the study area. Declines in water levels exceeded 5 ft locally in the Black Creek, upper Cape Fear, and lower Cape Fear aquifers in southern Craven County, Jones County, and Onslow County. These water-level declines occurred in both the upper and lower Cape Fear aquifers even though they are not pumped in this area. Water from these aquifers moved upward in response to upward head gradients induced by withdrawals from the overlying Black Creek aquifer. The maximum water-level decline experienced in any aquifer was 10 ft in the Black Creek aquifer in northern Onslow County; the Black Creek is the major source of water in the area.

As a result of scenario 1, water levels rose about 1 ft over 1986 water levels in only two areas (fig. 42): in Onslow and Duplin Counties in the Peedee aquifer and in Pitt County in the Peedee, Black Creek, and upper Cape Fear aquifers. Rises in water levels are generally small and are a function of the assumptions made concerning future pumping rates. In these areas mentioned above, the amount of pumping in 1986 was lower than the average pumping rates from 1984 to 1986 used in the final time period in the calibrated model. This decrease in pumping from 1987 to 1991 would result in higher estimated water levels in 1991.

When pumpage is held constant in any area, water levels generally would still be expected to decline. However, the rate of decline would decrease until the amount of water supplied by the aquifer equals the amount of water pumped. Water levels would not change after this equalibrium in the ground-water flow system is reached. In scenario 1, the amount of time required for water levels to stabilize is about 5 years. Therefore, there is a lag time between stabilizing pumping rates and reaching stable water levels.

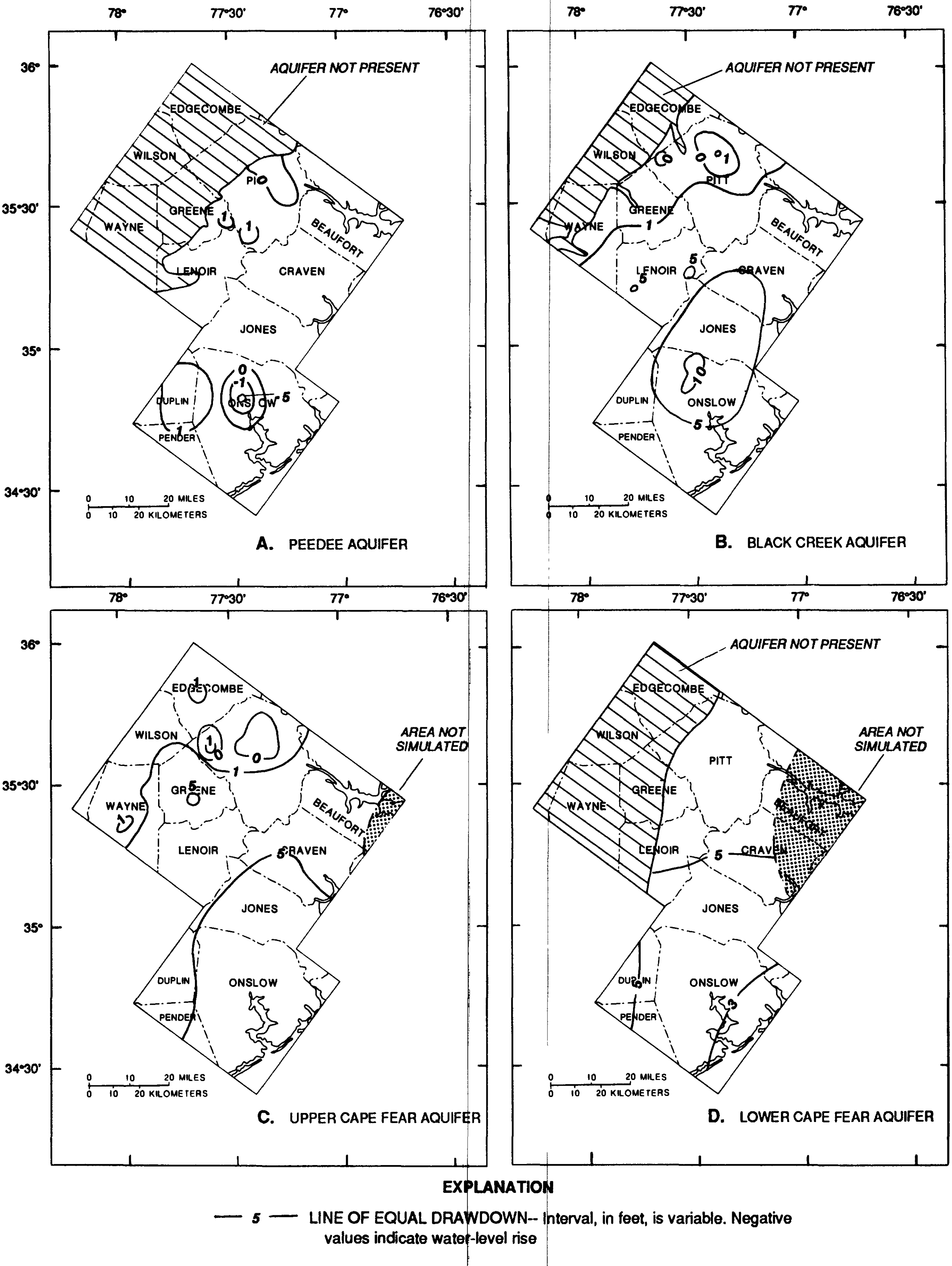

Figure 42.--Scenario 1, simulated additional drawdown from 1986 through 1991 in the aquifer system in Cretaceous rocks resulting from continued pumpage at the 1986 rate: (a) Peedee aquifer, (b) Black Creek aquifer, (c) upper Cape Fear aquifer, and (d) lower Cape Fear aquifer. (Contour interval variable, in feet)

Scenario 2 simulates continuing increases in pumping rates projected from 1986 through 1991 throughout the North Carolina Coastal Plain and was based on the 1980-86 rates from each of the aquifers in Cretaceous rocks in the study area. These increasing rates of pumpage were estimated to be about 10 percent per year for the Peedee aquifer, 19 percent per year for the Black Creek aquifer, and 14 percent per year for the upper Cape Fear aquifer. No pumpage was assumed for the lower Cape Fear aquifer in the study area. Although only 26 of the 48 water systems included in this study had actually experienced increases in pumpage from 1980 to 1986, simulated increases in pumpage were applied to each water system. In the five aquifers overlying the aquifer system in Cretaceous rocks and in all aquifers outside the study area, pumpage was estimated to increase at about 15 percent per year.

Water levels decreased throughout the study area in each of the aquifers in Cretaceous rocks in response to increased pumpage in scenario 2 (fig. 43). Water levels decreased less than 1 ft near the northwestern boundary of the Peedee, Black Creek, and upper Cape Fear aquifers where they thin to extinction but increased as much as 30 ft in some centers of pumping.

More than 5 ft of drawdown occurred in the Peedee aquifer around pumping centers in Greene, Pitt, and Onslow Counties. The Black Creek aquifer experienced 10 to 30 ft of drawdown over much of the study area, and about 30 ft in pumping centers in Lenoir, Craven, and Onslow Counties. Water levels in the upper Cape Fear aquifer declined about 20 ft near pumping centers in Craven and Lenoir Counties. Five to 10 ft of additional drawdown occurred throughout much of the lower Cape Fear aquifer, although there was no simulated pumping from this aquifer in the study area.

Uses of the Model

This model can be a tool for managing ground-water resources of the aquifer system in Cretaceous rocks in the central Coastal Plain of North Carolina. Results from the model, such as estimates of water levels, drawdown, and aquifer properties provide information needed for some types of water management decisions. This information could be used to evaluate alternative withdrawal scenarios, select sites for new well fields that

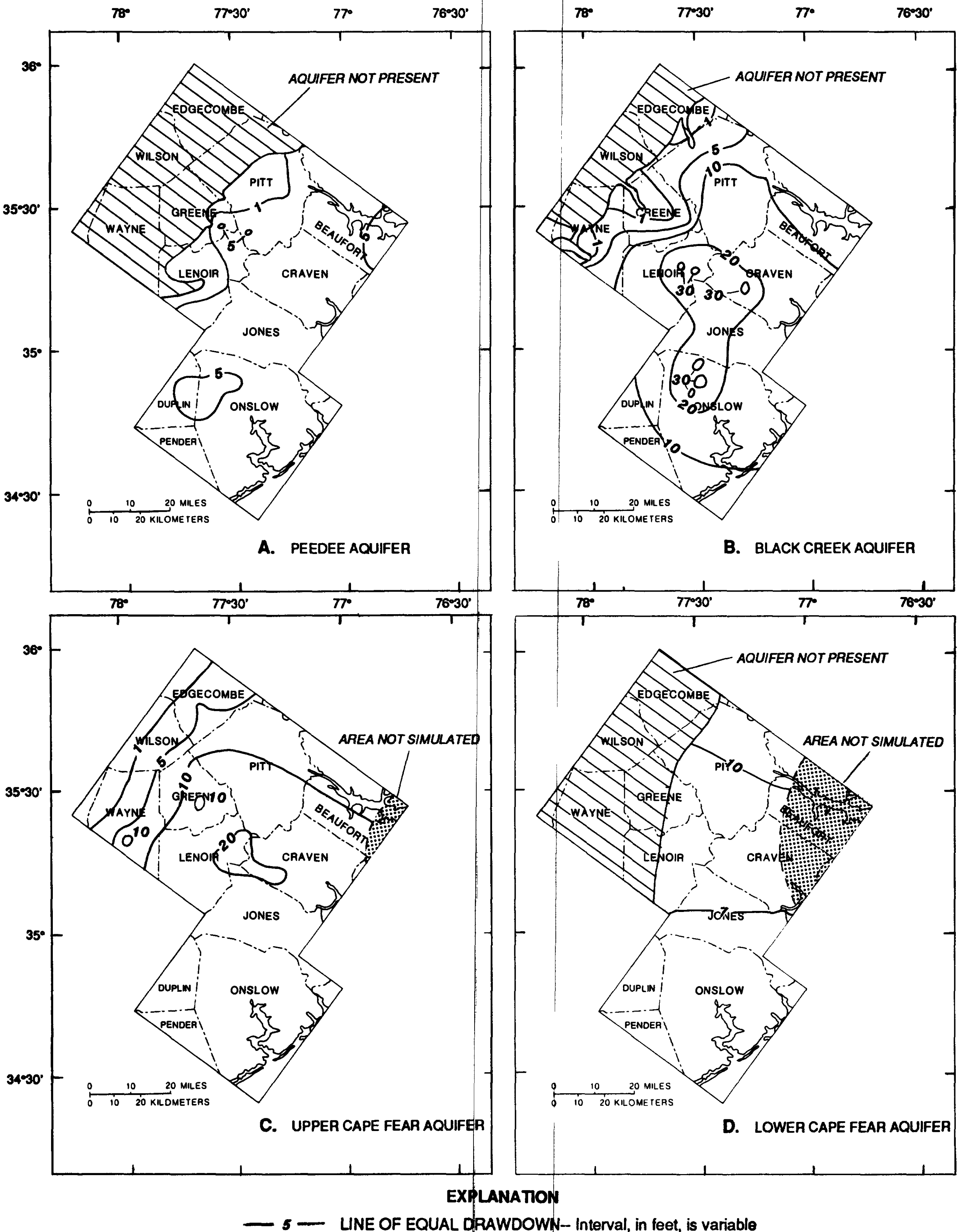

Figure 43.--Scenario 2, simulated additional drawdown from 1986 through 1991 in the aquifer system in Cretaceous rocks resulting from projected increased pumpage: (a) Peedee aquifer, (b) Black Creek aquifer, (c) upper Cape Fear aquifer, and (d) lower Cape Fear aquifer. (Contour interval variable, in feet)

minimize drawdown, appraise sources of recharge, and identify discharge areas.

As demonstrated in simulation examples 1 and 2, the amount of water-level decline resulting from different pumpage scenarios can be estimated. This model can be used to evaluate alternative pumpage scenarios for an area or individual water system. This information would help managers determine the effect of future withdrawals on ground-water flow and water levels locally and region-wide.

This model could also be used in selecting new well-field sites. Locating new wells in either an existing well field or a previously unpumped area would result in declines in water levels in the area as these wells are pumped. The effect of withdrawals from these wells on water-levels and the ground-water flow system can be estimated with this model. Given a choice in the location of wells, this model could help select the site that would cause the least amount of water-level decline at other water-supply wells. Estimates of hydrogeologic parameters produced by the model, such as transmissivity, could also aid in the design of wells and well fields.

Other model parameters, such as the vertical leakance of confining units, provide useful information for resource management. Values of vertical leakance and vertical head gradients can be used to indicate the rate of vertical flow into or out of each aquifer and identify recharge and discharge areas of these aquifers. Downward migration of pollutants in recharge areas is a potential source of contamination to water-supply aquifers. Information regarding recharge areas and rates of recharge to water-supply aquifers could help managers identify these environmentally sensitive areas.

Limitations of Predictions

Those using this model as a predictive tool should be aware of limitations and assumptions inherent in ground-water flow models that produce uncertainty in model results. Inaccurate model predictions could stem from several sources, including assumptions made in the conceptual model, spatial and temporal discretization required by the model, forecasts of future withdrawals, and uncertainty in estimates of hydrogeologic parameters.

Early in the calibration process, the period from 1980-86 was treated as a prediction (Eimers, 1988a) as the RASA model had been calibrated through 1980. RASA data were used to run the model in early calibration simulations. Predicted 1986 water levels were most reliable in areas where pumping wells did not exist. Differences between 1986 computed and observed heads in these areas were less than a few feet.

Predictions were less reliable at pumping centers before and after 1980. The model had been calibrated through 1980. Differences between 1986 computed and observed heads in areas pumped before and after 1980 were less than 60 ft.

Predictions are least reliable in areas where pumping began after the calibration time period. Differences between 1986 computed and observed heads in early calibration simulations reached 90 ft in areas where pumping began after 1980. A sensitivity analysis of the RASA ground-water flow model (Eimers, 1986) concluded that the model is most sensitive to estimates of transmissivity and vertical leakance in these areas.

The primary limitation in the use of this model to evaluate various scenarios is that results apply only to the aquifers in Cretaceous rocks in the central Coastal Plain, even though the entire North Carolina Coastal Plain was modeled. The other aquifers inside and outside the study area were included in the model only to provide adequate model boundaries for the study area. No measured hydraulic heads outside the central Coastal Plain study area since 1980 were used to calibrate the model. No additional data about flow parameters collected for areas outside the study area were used; therefore, this model does not provide a more accurate analysis of ground-water flow in these other aquifers than that provided by the RASA model.

Another limitation in the use of this model to evaluate predicted pumping scenerios is that the model does not simulate the movement of saltwater. The flow of all ground water in the study area with a chloride content of less than 10,000 mg/L is simulated. The model outputs hydraulic head but not the chloride content of this water. It is left to the model user to base predictions of chloride content of withdrawals on the lateral or vertical proximity of pumping wells to the freshwater-saltwater transition zone.

The conceptual model of ground-water flow, by definition, is a simplification of the complex ground-water flow system and will not represent the actual flow of water under all conditions. In the model, the specified head boundary assigned to the surficial aquifer would supply an unlimited amount of ground water to underlying aquifers in response to extremely large pumping from the underlying aquifers. Therefore, the specified head boundary condition does not represent actual ground-water conditions in all situations. Calculating the amount of ground-water flux going from the unconfined aquifer to the upper most confined aquifer and verifying that this amount of flux is reasonable would improve the accuracy of model predictions.

Model parameters are estimated for each cell and represent average values for the area of the cell. Because of this, care should be used in interpreting the results of model simulations. For example, due to the variability in well spacing and the large number of wells, observation wells are usually not located at nodes (the geographic center of cells). The estimated water level at a node represents the average water level for the cell and does not represent the water level in a pumping well. Similarly, all data that change with time, including pumpage and computed and observed water levels, are averages for each pumping period and do not represent seasonal changes in pumpage or in water levels.

Errors in estimates in historical and future ground-water withdrawals can also affect predicted values of water levels. Although recorded pumpages were used where available, estimates of withdrawals were made where data were unavailable and where wells were open to more than one aquifer.

Hydrogeologic parameters are subject to natural variability and, therefore, estimates of these parameters are subject to error, particularly in areas not stressed by pumping. Model-derived parameter estimates are most accurate in stressed areas. However, computed water levels best matched measured water levels in areas not being pumped.

Model Updating

The ground-water flow model described in this report is capable of estimating the effect of future ground-water pumpage from the aquifer system in Cretaceous rocks in the central Coastal Plain. However, periodic updates to the model data base and model calibration are needed to refine estimates of hydraulic parameters and improve the accuracy of the model.

Information needed to extend and refine the data base includes ground-water pumpage (amounts and locations), ground-water level measurements, and additional estimates of transmissivity based on aquifer tests. Some of this information is currently collected through existing Federal-State cooperative programs. Annual values of ground-water pumpage after 1986 are needed for each well pumping more than 10,000 gal/d from aquifers in Cretaceous rocks in the study area and from wells pumping more than 100,000 gal/d from all aquifers in the entire North Carolina Coastal Plain. Predictive simulations will be most accurate if they are based on the most accurate and recent pumpage data.

Water-level measurements from aquifers in Cretaceous rocks are needed in the study area on a periodic basis. These data provide a measure of the effect of pumpage on the ground-water flow system and can be used to recalibrate the model to obtain a better match between computed and observed water levels. Also, transmissivity estimates from additional aquifer tests are needed to refine the hydraulic parameters in the model. Areas where data are needed could be prioritized for data-collection activities. Data needs are most critical in areas that are identified as potential well sites.

Periodic calibration of the model would be needed to maintain the integrity of the model. An efficient time period for data collection and recalibration might be about every 5 years. Data collected as described above could be utilized, and new estimates of ground-water flux across the Virginia and South Carolina State borders with North Carolina could be incorporated into the model. These flux estimates could be derived from the northern Atlantic Coastal Plain RASA ground-water flow model.

SUMMARY

The sedimentary aquifers in the central Coastal Plain of North Carolina are composed primarily of sand and limestone and confining units composed primarily of silt and clay. These aquifers generally thicken and dip toward the coast. The Coastal Plain sediments contain two aquifer systems--those aquifers and confining units in sediments of Quaternary and Tertiary age and those in Cretaceous rocks. Aquifers and associated confining units in the aquifer system in Cretaceous rocks, the focus of this study, include the Peedee aquifer and confining unit, the Black Creek aquifer and confining unit, the upper Cape Fear aquifer and confining unit, and the lower Cape Fear aquifer and confining unit.

Saltwater is present in the eastern part of each of these aquifers. The saltwater transition zone, where water contains more than 250 mg/L chloride, is farthest west in the lower Cape Fear aquifer, the deepest aquifer, and farthest east in the Peedee aquifer, the shallowest aquifer.

Total ground-water pumpage from the aquifers in Cretaceous rocks have increased from about 0.25 Mgal/d in 1910 to about 29.35 Mgal/d in 1986. The Black Creek aquifer has historically been the primary source of ground water in the study area, producing about 20.5 Mgal/d (68 percent of the total water withdrawn from the aquifers in Cretaceous rocks) in 1986. In 1986, the upper Cape Fear aquifer produced 8.3 Mgal/d (27 percent of the total) and the Peedee aquifer about 1.5 Mgal/d (5 percent of the total). No water is withdrawn from the lower Cape Fear aquifer, because the water has a chloride concentration higher than that recommended by the drinking-water standards.

Ground-water flow through the central Coastal Plain aquifers is simulated in a quasi-three dimensional finite-difference model. The period since predevelopment (1900) is discretized into 12 periods ranging in length from 3 to 21 years. In the area of interest, the grid spacing is 0.875 mi by 0.875 mi. Hydraulic parameters used in the model simulation included aquifer transmissivity, vertical leakance of confining units, and aquifer storage coefficient.

The entire North Carolina Coastal Plain is simulated in order to provide accurate boundaries for the central Coastal Plain study area. The Virginia and South Carolina stateline boundaries are specified flux boundaries. The northwestern pinchout of the Coastal Plain sediments, the southeastern extent of water with less than 10,000 mg/L dissolved solids, and the contact with basement rocks are treated as no-flow boundaries. The upper boundary is a specified head assigned to the water table.

The model is calibrated from 1,867 comparisons of observed and computed heads at 323 well sites. Large differences between computed and observed heads resulted in some wells because (1) flow during the period before 1940 and in aquifers outside the central Coastal Plain is not modeled accurately, and (2) the coarse mesh of the finite-difference model and the simulated timesteps do not define all of the variations of hydraulic properties and observed heads.

The objective function is a quantitative measure of how well calculated water levels match observed water levels; it measures the model's overall goodness-of-fit. This function is a simple formula that provides a single value summarizing the absolute value of the average weighted differences between computed and observed hydraulic head. The objective function for all 1,867 observations of hydraulic head is 10.9 ft; differences between computed and observed heads are assumed normally distributed with mean zero. Among non-pumped wells, the objective function is 10.4 ft. For pumped wells only, the objective function is 22.4 ft.

Median model-derived transmissivity estimates for the aquifers in Cretaceous rocks range from 1,200 to 3,400 ft^2/d, and tend to increase toward the coast. These are within about 100 percent of measured values from aquifer tests. Vertical leakance estimates range from 2.00×10^{-7} to 1.70×10^{-6} 1/d, tending to decrease toward the coast. Also, vertical leakance estimates decrease with depth, except for the lower Cape Fear confining unit.

The calibrated model confirms the basic functioning of the ground-water flow system described by the conceptual flow model. In response to increased pumpage from predevelopment (1900) to 1986 conditions, water flowed toward pumping centers rather than toward the coast or natural discharge areas. Net recharge across the top of the aquifer system in Cretaceous rocks increased to 18 Mgal/d in 1986; a reversal in the direction of net flow since the simulated flow across that boundary was about 2 Mgal/d of discharge in 1900. Net depletion of ground water in storage during 1980-86 was only about 1 Mgal/d. Increased lateral flux from outside the central Coastal Plain and decreased lateral discharge accounted for the remaining 8 Mgal/d of pumpage from wells.

To demonstrate the use of the model as a tool for managing the central Coastal Plain ground-water resources in the aquifers in Cretaceous rocks, two pumpage scenarios were simulated through 1991. In the first scenario, 1986 pumping rates were held constant through 1991. This is intended as a rough estimate of minimum future pumpage. The maximum drawdown occurring from 1986 through 1991 was a 10-foot decline in the Black Creek aquifer in northern Onslow County. The second scenario simulates continuing increases in rates of withdrawal from 1986 through 1991--about 10 percent per year increase in the Peedee aquifer, 19 percent per year increase in the Black Creek aquifer, and 14 percent per year increase in the upper Cape Fear aquifer. Pumpage from the lower Cape Fear aquifer was assumed to remain zero. Under this scenario, water levels decreased throughout the study area in each of the aquifers in the Cretaceous rocks. The maximum drawdown from 1986 through 1991, about 30 feet, occurred in pumping centers in Lenoir, Craven, and Onslow Counties in the Black Creek aquifer.

The model can also be used to evaluate alternative withdrawal scenarios, select sites for new well fields that minimize drawdown, and identify changes in recharge and discharge areas for the aquifer system in Cretaceous rocks.

The model has limitations which lead to uncertainty about model results. This uncertainty should be considered in management decisions about the ground-water resources. Predictive model results for parts of the study area, which are stressed by pumping, may be less accurate than results in other parts of the study area. If a predictive simulation includes significant pumpage in an area that has not been calibrated under pumping conditions, predicted heads may differ from measured heads by as much as 90 ft.

Periodic updates to the model data base and model calibration are required for the continued use of the model for management purposes, as well as to protect the integrity of the model's predictive capabilities. Recalibration is done by refining estimates of hydraulic properties and testing them with newly acquired head and pumpage data.

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GLOSSARY

Aquifer: A water-bearing layer of rock that will yield water in a usable quantity to a well or spring.

Conceptual model: A conceptual model of ground-water flow illustrates how the ground-water system functions, how water flows through the system, how the system responds to changes, such as withdrawals of water from wells, and the nature of system boundaries.

Confined aquifer: An aquifer bounded above and below by confining units.

Confining unit: A layer of rock having very low hydraulic conductivity that hampers the movement of water into and out of an aquifer. In this report, a confining unit is associated by name with the underlying aquifer.

Discharge: In general, discharge refers to the removal of water from an aquifer by any means, such as discharge to wells or to springs. In this report, discharge refers to the removal of water from an aquifer to the overlying aquifer.

Hydraulic conductivity: Hydraulic conductivity of the porous medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient: Change in hydraulic head along a unit distance.

Ground water: The water that occurs beneath the land surface in the zone where all interconnected openings are full of water.

Model code: A numerical procedure that solves the ground-water flow equations.

Objective function: An objective measure of the model's overall goodness of fit. The purpose of model calibration is to minimize this function, subject to some constraints, such as the difference between h_c and h_o in a cell that is pumped.

$$\sum_{1900}^{1986} \sum_{\text{all locations}} \left[\frac{w_s\, w_t \,|h_c - h_o|}{N} \right]$$

where:

w_s = spatial weighting factor (0.85 for wells outside the study area, or 1.00 for wells within the study area [dimensionless]);

w_t = temporal weighting factor (0.70 for measurements taken on or before 1940, or 1.00 for measurements taken after 1940 [dimensionless]);

h_c = computed hydraulic head (L);

h_o = observed hydraulic head (L); and

N = total number of years of record, summed over all observation wells.

Recharge: In general, recharge refers to the entry of water into an aquifer by any means, such as by injection, artificial recharge, or by precipitation infiltrating through the unsaturated zone to reach the water table. In this report, recharge refers to the entry of water into an aquifer from the overlying aquifer.

Saltwater: In this report, saltwater is water with a chloride concentration of ≥ 250 mg/L.

Saltwater-freshwater transition zone: The boundary between freshwater and saltwater approaching seawater in composition is called the transition zone in this report. The zone, containing a gradational mix of freshwater and saltwater, extends both laterally and vertically within an aquifer. The contact between freshwater and water of the transition zone is an imaginary plane defined by 250 milligrams per liter chloride ion concentration in water; in cross section, the plane is depicted as an upward concave line. On maps, the plane is shown as two lines, one where it intersects the bottom of the aquifer and one where it intersects the top of the aquifer.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head, expressed as a decimal fraction.

Transmissivity: The rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient, expressed in ft^2/d.

Unconfined aquifer: An aquifer in which the water table forms the upper boundary.

Vertical conductance: Vertical conductance of a confining unit is the ratio of vertical hydraulic conductivity times the area perpendicular to flow divided by effective thickness of the confining unit.

Vertical leakance: Vertical conductance of a confining unit divided by cell area, expressed in 1/day.

Water table: The top of the uppermost zone containing ground water.

Well objective function: An objective measure of the model's goodness of fit at one observation well.

$$w_s \left(\sum_{\substack{\text{All years 1900 to 1986} \\ \text{for which there is observed} \\ \text{data.}}} \left[\frac{w_t \left| h_c - h_o \right|}{N_w} \right] \right)$$

where:

- w_s = spatial weighting factor (0.85 for wells outside the study area, or 1.00 for wells within the study area [dimensionless]);
- w_t = temporal weighting factor (0.70 for measurements taken on or before 1940, or 1.00 for measurements taken after 1940 [dimensionless]);
- h_c = computed hydraulic head (L);
- h_o = observed hydraulic head (L); and
- N_w = total number of years of record for this well.

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