

ABSTRACT

Jeffrey W. Reynolds. **AQUIFER DEPRESSURIZATION FOR MINING AT TEXASGULF, INC.: EVALUATION AND MODELING OF HYDROGEOLOGIC IMPACTS AND POTENTIAL MITIGATIVE STRATEGIES.** (Under the direction of Richard K. Spruill, Department of Geology, October, 1992)

Texasgulf, Inc. has been open-pit mining phosphate ore at the Lee Creek Mine since 1965. The phosphate ore is in the Pungo River Formation, which along with the Yorktown Formation serves as an upper confining layer for the prolific Castle Hayne aquifer system. The potentiometric surface of the Castle Hayne aquifer was slightly above the land surface prior to mining. Aquifer pressures had to be locally lowered for mining to proceed. Approximately 50 million gallons per day (MGD) of water is now pumped from the aquifer. This pumping results in changed flow directions in the Castle Hayne system and increased chloride concentrations in the upper unit of the Castle Hayne at the pumping center due to upconing from underlying aquifers that contain saline waters. A slight potential for land subsidence due to groundwater extraction exists, but precise leveling surveys in the area are inconclusive.

Due to the eastward-thickening, wedge shape of the coastal plain sedimentary units, increased pumping rates are anticipated as the mining advances to the northeast. The U.S. Geological Survey modular, finite-difference flow model (MODFLOW) was used to 1) evaluate the effects of increased pumpage from the aquifer, and 2) estimate pumping rates required to dewater the ore bed when the deeper ore bed to the

northeast is mined. Simulations indicate that withdrawal rates from 50 to 65 MGD will be required. Higher pumping rates (53 to 69 MGD) will be necessary if a low-permeability zone of the Pungo River Formation (referred to as the "lean ore") is missing from the stratigraphic section.

Withdrawals from a wellfield near Washington, NC and declining potentiometric levels in the Cretaceous aquifer beneath the Castle Hayne would reduce the required pumping rates only slightly (± 1 percent) at the mine.

Simulations indicate that a series of injection wells at various distances from the pumping center would reduce the widespread impacts on the potentiometric surface of the upper Castle Hayne unit, but would require significant additional pumping at the mine center.

**AQUIFER DEPRESSURIZATION FOR MINING AT
TEXASGULF, INC.: EVALUATION AND MODELING OF
HYDROGEOLOGIC IMPACTS AND POTENTIAL MITIGATIVE STRATEGIES**

A Thesis
Presented to
the Faculty of the Department of Geology
East Carolina University

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of the Requirements for the Degree
Master of Science in Geology

by
Jeffrey W. Reynolds

October, 1992

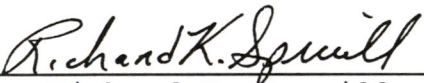
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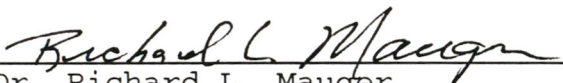
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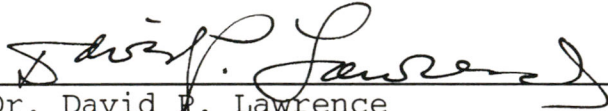
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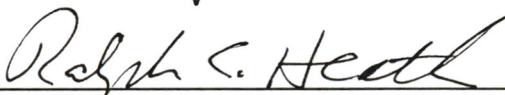
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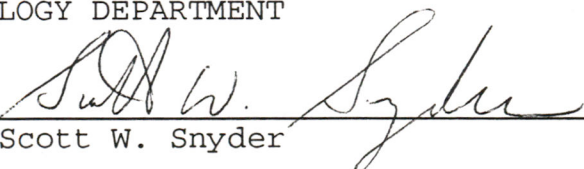

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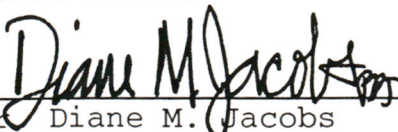

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INTRODUCTION

Location

The Lee Creek Mine is located in the Coastal Plain Province of North Carolina along the south bank of the Pamlico River between South and Durham Creeks (Figure 1). It is located in Beaufort County approximately 5 miles north of the Town of Aurora.

Purpose and Scope

Texasgulf, Inc. began mining phosphate at the Lee Creek Mine in 1965. The company investigated the feasibility of slurry mining, but decided that dry-pit mining was most efficient (DeWiest, et al., 1967). The dry-pit method requires that the potentiometric surface of the Castle Hayne aquifer be lowered below the elevation of the ore bed. Pumping has averaged approximately 57 million gallons per day (MGD) since mining commenced (Leggette, Brashears and Graham (LBG), Inc., 1991). Groundwater levels in an extensive area surrounding the mine are being impacted as a result. The elliptically-shaped area of influence extends 30-40 miles from the pumping center.

Concern over the hydrogeologic impacts resulting from the mining operation led to State designation of a Capacity Use Area which includes Beaufort, Pamlico and Washington counties, and parts of Carteret, Craven, Hyde, Martin and Tyrrell counties (NCDNER, 1974). In a Capacity Use Area, a permit is required for withdrawal of over 100,000 gallons per day of

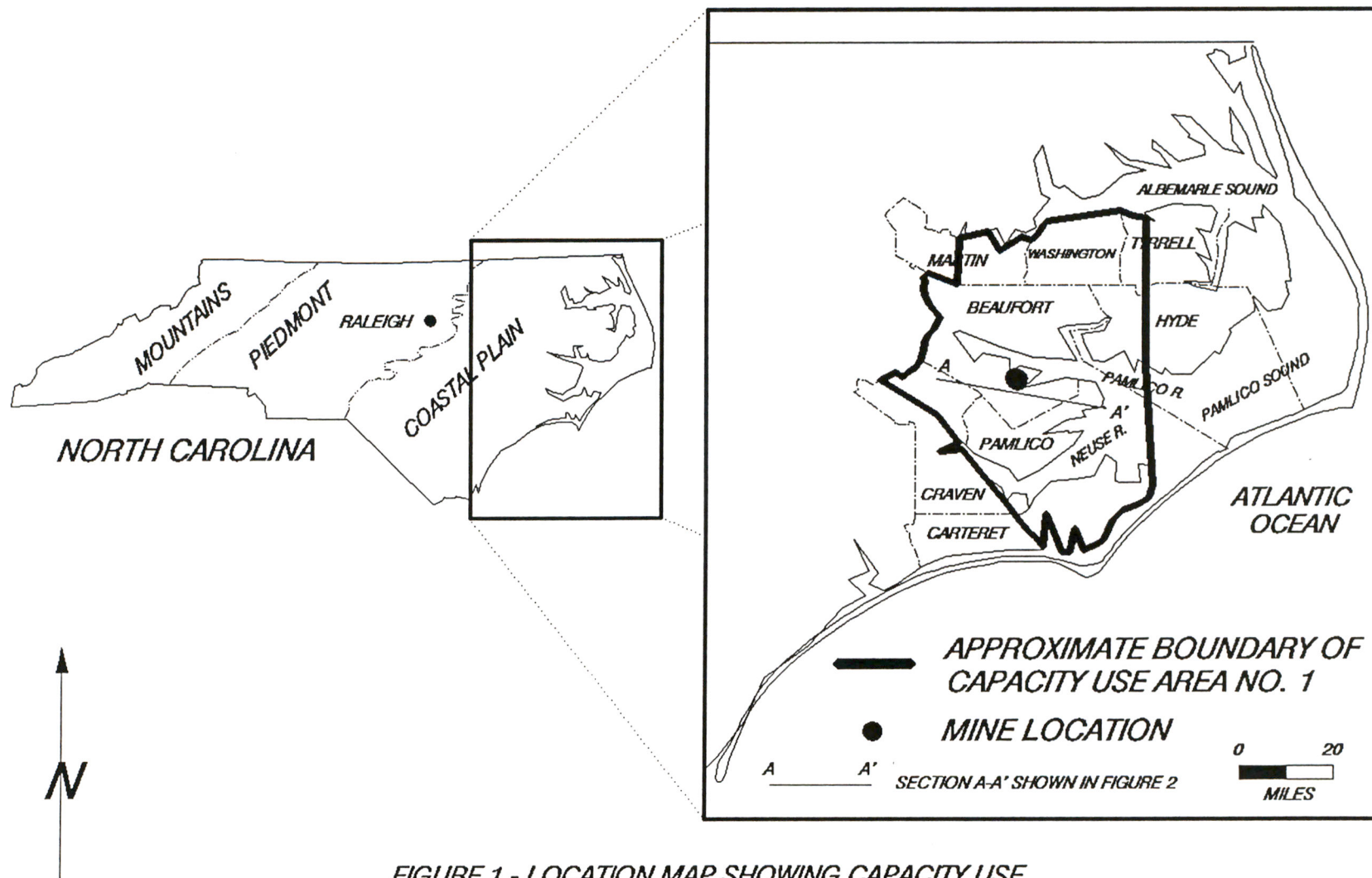


FIGURE 1 - LOCATION MAP SHOWING CAPACITY USE AREA AND MINE LOCATION

groundwater and/or surface water (NCDNER, 1974).

Texasgulf's future mining endeavors depend on renewal of Water Use Permits. Therefore, the company has a great interest in studies that might reduce the hydrogeologic impacts due to its mining operations.

The objective of this study was to evaluate the effects of aquifer depressurization on the groundwater system and to propose/evaluate potential strategies for minimizing those impacts. The following specific items and methodologies were addressed:

- After correlation of the geologic and hydrogeologic units in the study area, information on the pre-pumping hydrogeologic conditions in the mine area was evaluated. Changes in the hydrogeologic conditions due to depressurization pumping were then evaluated.
- Potential hydrogeologic effects due to pumping such as saltwater encroachment and land subsidence were also evaluated.
- A three-dimensional, finite-difference flow model (U.S.G.S. MODFLOW, McDonald and Harbaugh, 1988) was used to simulate the hydrogeologic conditions of the aquifer system in the vicinity of the mine. The model was then used to evaluate the effects of increased pumpage from the Castle Hayne aquifer system.
- Three possible methods for reducing hydrogeologic impacts were investigated. Where appropriate, the computer model was used to investigate the possibility of reducing pumping rates in response to: 1) regional head declines in underlying aquifers, 2) effects of other permitted withdrawals in the vicinity of the mine, and 3) the effects of artificial recharge on the aquifer system.

GEOLOGY AND HYDROGEOLOGY

Geologic Framework

The Coastal Plain Province comprises approximately 45 percent of North Carolina (DeWiest, et al., 1967), and extends eastward from a western boundary with the Piedmont Physiographic Province (often referred to as the fall line, (Figure 1). Elevations range from 100 feet above sea level at the western boundary to mean sea level. Most of the eastern coastal plain consists of swampy areas, pocosins, and wide, shallow estuaries.

Strata beneath the coastal plain comprise a wedge of marine and transitional sedimentary deposits of Cretaceous through Cenozoic ages. Thickness ranges from zero at the fall line to nearly 10,000 feet at Cape Hatteras (Richards, 1950). A cross-section of the coastal plain sediments in the vicinity of the mine is presented in Figure 2. At depth, these sedimentary deposits rest on a crystalline "basement" of pre-Mesozoic igneous and metamorphic rocks.

Stratigraphic units are subdivided on the basis of geologic age and lithology; hydrogeologic units are based on the water-bearing properties of the stratigraphic units (Table 1).

Hydrogeologic Units

The U.S. Geological Survey developed a system for characterizing hydrogeologic units in the Regional Aquifer

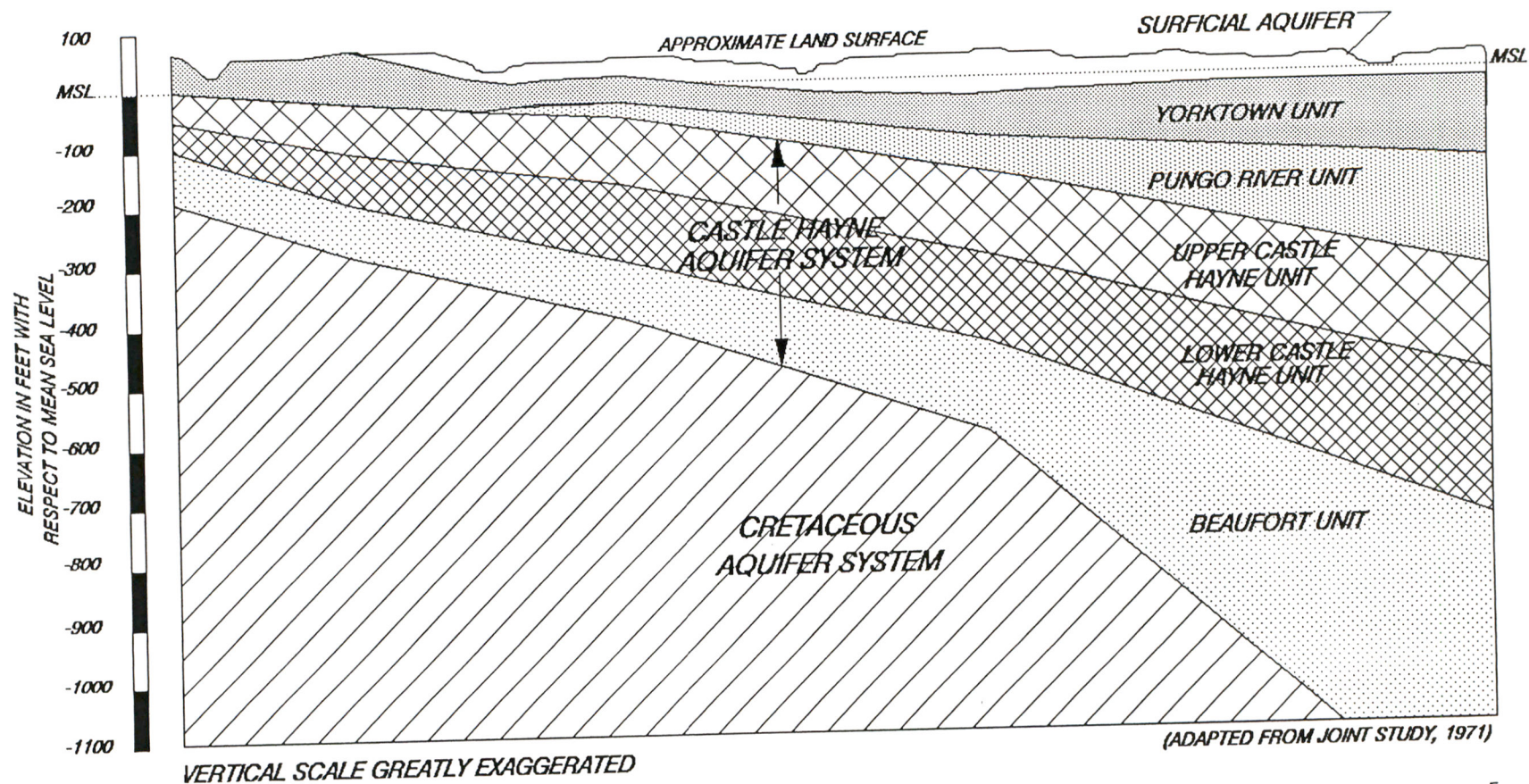


FIGURE 2 - STRATIGRAPHIC CROSS-SECTION A-A'

SYSTEM	SERIES	STRATIGRAPHIC UNITS	HYDROGEOLOGIC UNITS		DESCRIPTION
QUATERNARY	RECENT	TERRACE DEPOSITS	SURFICIAL AQUIFER		SHALLOW AQUIFER AND CHANNEL SAND UNIT SAND, SILT, SHELLS, AND SOME CLAY. THIS UNIT COMPRISES THE UNCONFINED (WATER TABLE) AQUIFER INCLUDING BEDS OF CROATAN FORMATION.
	PLEISTOCENE	CROATAN FORMATION			
TERTIARY	PLIOCENE	YORKTOWN FORMATION	YORKTOWN UNIT		INTERBEDDED SAND AND CLAY WITH SOME SHELL LENSES. CLAYS ARE GENERALLY SANDY AND COMPRISE CONFINING BEDS OVER MUCH OF AREA.
	MIOCENE	PUNGO RIVER FORMATION	PUNGO RIVER UNIT		PHOSPHATIC QUARTZ SAND, SILT, CLAY, LIMESTONE. UNIT SERVES AS CONFINING BED IN AREA OF THE MINE.
	EOCENE	CASTLE HAYNE FORMATION	CASTLE HAYNE AQUIFER SYSTEM	UPPER CASTLE HAYNE UNIT	PERMEABLE AND POROUS SHELL LIMESTONE. AN EXCELLENT AQUIFER AND MOST PRODUCTIVE OF THE REGIONAL SYSTEM.
				LOWER CASTLE HAYNE UNIT	SHELL LIMESTONE INTERBEDDED WITH CALCAREOUS SANDS MODERATELY PRODUCTIVE AQUIFER, LESS PERMEABLE THAN UPPER CASTLE HAYNE UNIT.
	PALEOCENE	BEAUFORT FORMATION		BEAUFORT UNIT	FINE GLAUCONITIC SAND, PARTIALLY SILTY AND CLAYEY. INCLUDES UPPER PORTION OF PEEDEE UNIT IN SOME AREAS LOW PERMEABILITY AQUIFER AND NOT HIGHLY PRODUCTIVE.
	CRETACEOUS	UPPER CRETACEOUS		CRETACEOUS AQUIFER SYSTEM	PEEDEE FORMATION
BLACK CREEK FORMATION			BLACK CREEK UNIT		
CAPE FEAR FORMATION			CAPE FEAR UNITS		
LOWER CRETACEOUS		UNNAMED DEPOSITS	—		
MESOZOIC - pC	BASEMENT COMPLEX				

(modified from Leggette, Brashears and Graham, Inc., 1991a)

TABLE 1 - STRATIGRAPHIC AND HYDROGEOLOGIC CORRELATIONS

System Analysis (RASA) study (Winner and Coble, 1989). Nineteen aquifers and confining units were identified in the North Carolina Coastal Plain. For this study, the hydrogeologic units were combined into three main aquifers (surficial, Castle Hayne, and Cretaceous), and two confining units (Yorktown-Pungo River, and Peedee).

Surficial Aquifer

Post-Pliocene units include two unconsolidated aquifers separated by leaky confining units. The Croatan and post-Croatan units are the aquifers, and are collectively referred to as the surficial aquifer. Near Texasgulf, the surficial aquifer system (water-table aquifer) extends from the surface to the top of the Yorktown unit. In the western areas of the coastal plain (west of Greenville), it directly overlies the Castle Hayne aquifer. Thicknesses are highly variable (one foot to approximately 200 feet at the Outer Banks (Heath, 1975)). Average thickness is approximately 20 feet (Sherwani, 1973). The surficial aquifer is thickest in interstream areas and decreases to a thin veneer near streams.

A permeable subunit of the surficial aquifer near the mine is called the "channel sand unit" by mine personnel (LBG, Inc., 1991). It is a sand bed incised into the underlying Yorktown unit in some areas, but is included in the surficial aquifer system.

Permeability values of up to 62 feet per day (ft/d) were

reported for the surficial aquifer by Leggette, Brashears and Graham, Inc. (1991). Winner and Coble (1989) estimated it to average about 29 ft/d. The permeability of the channel sand unit is reported to be on the order of 88.5 ft/d (LBG, Inc., 1991). For parts of the surficial aquifer composed of peats, the hydraulic conductivity may be as high as 120 ft/d, depending upon the extent of decomposition/compaction of the peat material (Daniel, 1980).

Yorktown and Pungo River Units

The Yorktown unit is the basal confining unit for the surficial aquifer (Figure 2). This unit is not continuous in the coastal plain and crops out in stream valleys. In some areas, highly permeable lenticular sand or shell beds are present. The thickness of the Yorktown unit ranges from 20 to 150 feet (Joint Study, 1971).

The Pungo River unit contains the phosphate ore. It occurs only in the subsurface and, as in the Yorktown unit, local sands may be highly permeable. The unit ranges in thickness from 0 to 180 feet (Joint Study, 1971).

The Yorktown and Pungo River units together serve as an aquitard between the surficial aquifer and the Castle Hayne aquifer system. Thickness of this aquitard ranges from about 20 to 220 feet (Joint Study, 1971). The vertical permeability of these units decreases from west to east due to higher clay contents and increased compaction of the sediments. Vertical

permeability values range from about 0.018 ft/d in the western coastal plain to about 5.0E-04 ft/d at the Pamlico River-Pamlico Sound junction were reported in the Joint Study (1971).

Castle Hayne Aquifer System

The Castle Hayne aquifer system is the most productive in the State. It varies in thickness from zero in western Beaufort County to over 640 feet in east Beaufort County (Joint Study, 1971). It is approximately 370 feet thick in the mine area (LBG, Inc., 1991).

The Castle Hayne aquifer system includes three hydrogeologic units: a) the upper Castle Hayne unit (Eocene), b) the lower Castle Hayne unit (Eocene), and c) the Beaufort unit (Paleocene). Hydraulic conductivities range from 15 ft/d, where the system is predominately sand (lower Castle Hayne), to 200 ft/d for the porous limestone of the upper Castle Hayne unit (Giese, et al., 1991). Transmissivity values for each unit increase from west to east due to increasing thickness and/or increasing hydraulic conductivity.

The upper Castle Hayne unit consists of a very porous and permeable limestone. Transmissivity values range from 10,000 to 70,000 ft²/d in Beaufort County. In the vicinity of the mine, the upper Castle Hayne unit is approximately 130 feet thick and has a reported transmissivity of 33,400 ft²/d. (LBG, Inc., 1991).

The lower Castle Hayne unit includes sands and limestones that are less permeable than the overlying upper Castle Hayne unit. Transmissivities range from 1,340 to 4,680 ft²/d in Beaufort County, and the unit is approximately 190 feet thick in the vicinity of the mine (LBG, Inc., 1991).

The Beaufort unit constitutes the basal portion of the Castle Hayne system. The unit is approximately 80 feet thick in the vicinity of the mine; estimated transmissivity values range from 270 to 940 ft²/d (LBG, Inc., 1991).

The Joint Study Report (1971) estimated that 89 percent of the water pumped from the Castle Hayne aquifer system is derived from the upper Castle Hayne unit. Horizontal permeability ratios for the three units (upper Castle Hayne: lower Castle Hayne:Beaufort) are on the order of 50:5:1.

Cretaceous Aquifer System

The Cretaceous Aquifer System is the deepest hydrogeologic unit in the study area. It extends from the base of the Beaufort unit to the top of the basement-rock unconformity beneath the coastal plain (LBG, Inc., 1991). It consists of three hydrogeologic units (from top to bottom): the 1) Peedee unit, 2) Black Creek unit, and 3) Cape Fear unit. The Cape Fear unit is subdivided into an upper and lower unit. The Cretaceous aquifer system is the major source of groundwater in the central coastal plain.

The Peedee unit serves as a lower confining layer for the

Castle Hayne aquifer system and as an upper confining layer for permeable units below (Hargis, 1982); its thickness ranges from 0 to 200 feet (Giese, et al., 1991) and averages approximately 50 to 100 feet at the mine.

The top of the Black Creek unit ranges in elevation from over 50 feet above sea level at its western extent to over 1000 feet below sea level. The Black Creek unit ranges in thickness from 10 to 500 feet and averages 230 feet (Eimers, et al., 1990). The minimum and maximum reported transmissivity values for the Black Creek unit in Beaufort county are 2300 and 4300 ft²/day, respectively, and averages 3200 ft²/day (Eimers, et al., 1990). Information on the transmissivity of the Black Creek unit east of Beaufort County is not available.

The top of the upper Cape Fear unit ranges in elevation from around 70 feet above sea level at the western edge of the coastal plain to over 1400 feet below sea level. The thickness of the upper Cape Fear unit ranges from less than 10 feet to the west, to over 400 feet in Beaufort County (Winner and Lyke, 1989). The transmissivity value for the upper Cape Fear unit in Beaufort County averages 3050 ft²/day (Eimers, et al., 1990). Little information exists on the transmissivity of the upper Cape Fear unit east of Beaufort County.

The top of the lower Cape Fear unit is present at elevations of 400 to 1800 feet below sea level. Thicknesses range from a few feet at the western boundary of the coastal plain to an estimated 600 feet in Beaufort County (Winner and

Lyke, 1989). Transmissivity of the lower Cape Fear unit is unknown.

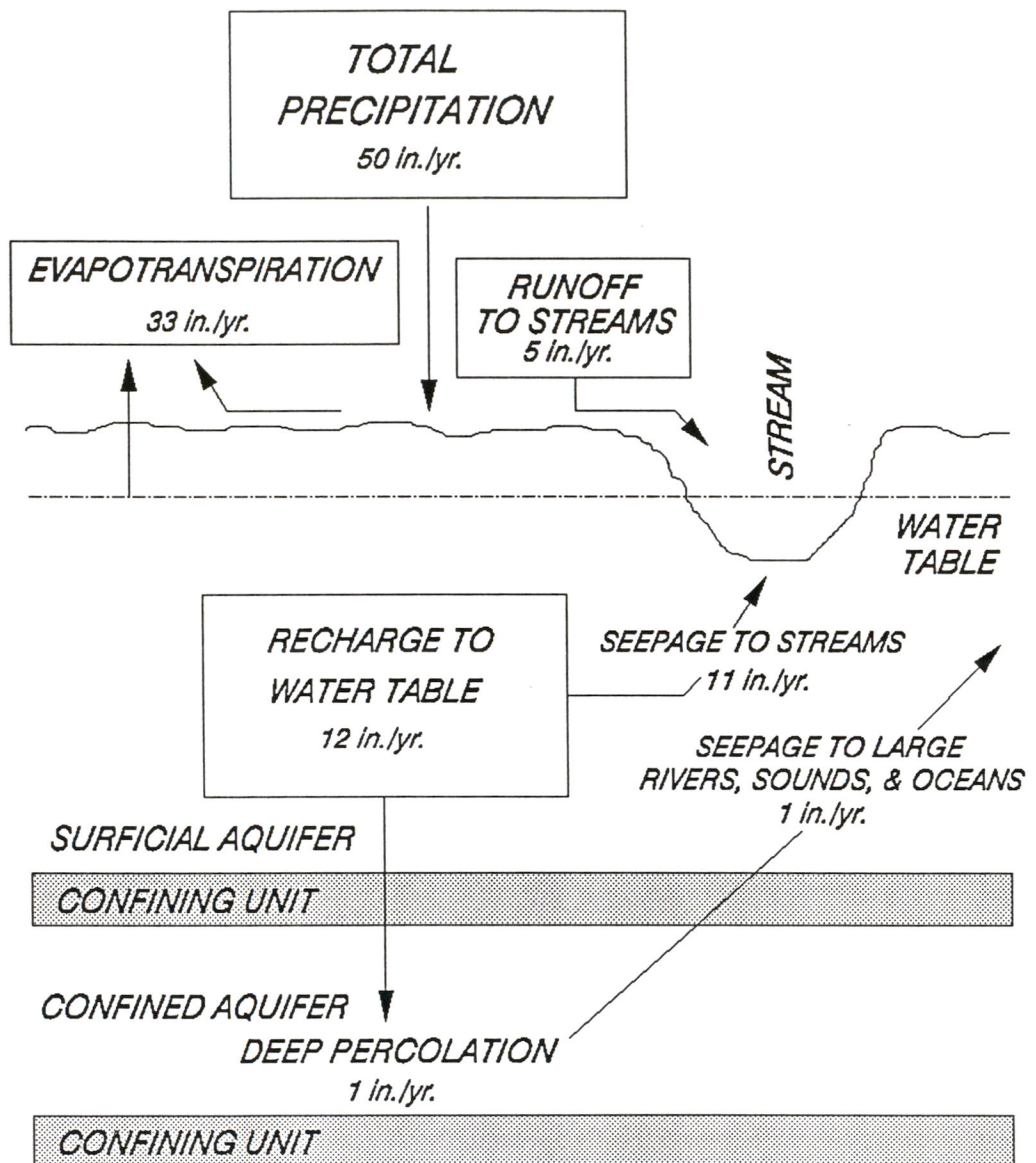
Natural Hydrogeologic Conditions

In general, water enters aquifers in recharge areas, and moves through aquifers to discharge areas. Water may also move into or out of the aquifers by leakage, depending upon the aquifer heads and vertical permeabilities of the confining units. The following sections describe the hydrogeologic conditions in the primary aquifer units and their effects on recharge, water movement, and discharge prior to depressurization pumping at Texasgulf (i.e. before 1965).

Recharge to Aquifers

Figure 3 provides a graphical representation of the water budget for the North Carolina Coastal Plain. The budget indicates that of the average precipitation of ± 50 inches per year (in/yr), the majority (33 in) is reintroduced to the atmosphere by evapotranspiration. Of the remaining 17 inches of potential recharge to the surficial aquifer, 5 inches is diverted to streams and rivers by overland flow and about 11 inches flows through the surficial aquifer to be discharged to streams. Therefore, only about 1 inch of the 50 inches of precipitation percolates downward to the deeper aquifers (Giese, et al., 1991).

The surficial aquifer functions as a reservoir from which



(modified from Gleason, et al., 1991)

FIGURE 3 - N.C. COASTAL PLAIN WATER BUDGET

water moves to deeper aquifers and to streams, lakes, and springs. Recharge to the surficial aquifer averages approximately 14 in/yr and ranges from 12 to 20 in/yr, depending on the local permeability of the aquifer (Giese, et al., 1991). The shape and position of the water table is variable and dependent upon climatic conditions. Where undisturbed by artificial drainage, the water table is typically a few feet below the land surface and generally follows topography (Figure 4). This morphology was disturbed before the start of mining at Texasgulf, beginning with the drainage of swamps and lowlands for agriculture in the late 18th century (Heath, 1975). Construction of drainage canals result in lowering of the water table; and reduced downward recharge to lower aquifers due to the lowered water table (Heath, 1975).

Prior to large-volume, sustained pumping at Texasgulf, the potentiometric surface of the Castle Hayne aquifer was above sea level (Figure 5). Direct recharge of the Castle Hayne aquifer (i.e. water that does not move through confining units) occurs only in areas where the Castle Hayne crops out, or is overlain only by permeable sandy materials. Direct recharge occurs predominantly in areas west of the pinchout of the Pungo River unit, including areas north and south of the upper reaches of the Pamlico River. Estimates of the magnitude of direct recharge vary widely. An initial estimate, (DeWiest, et al., 1967), based on an estimated outcrop area of

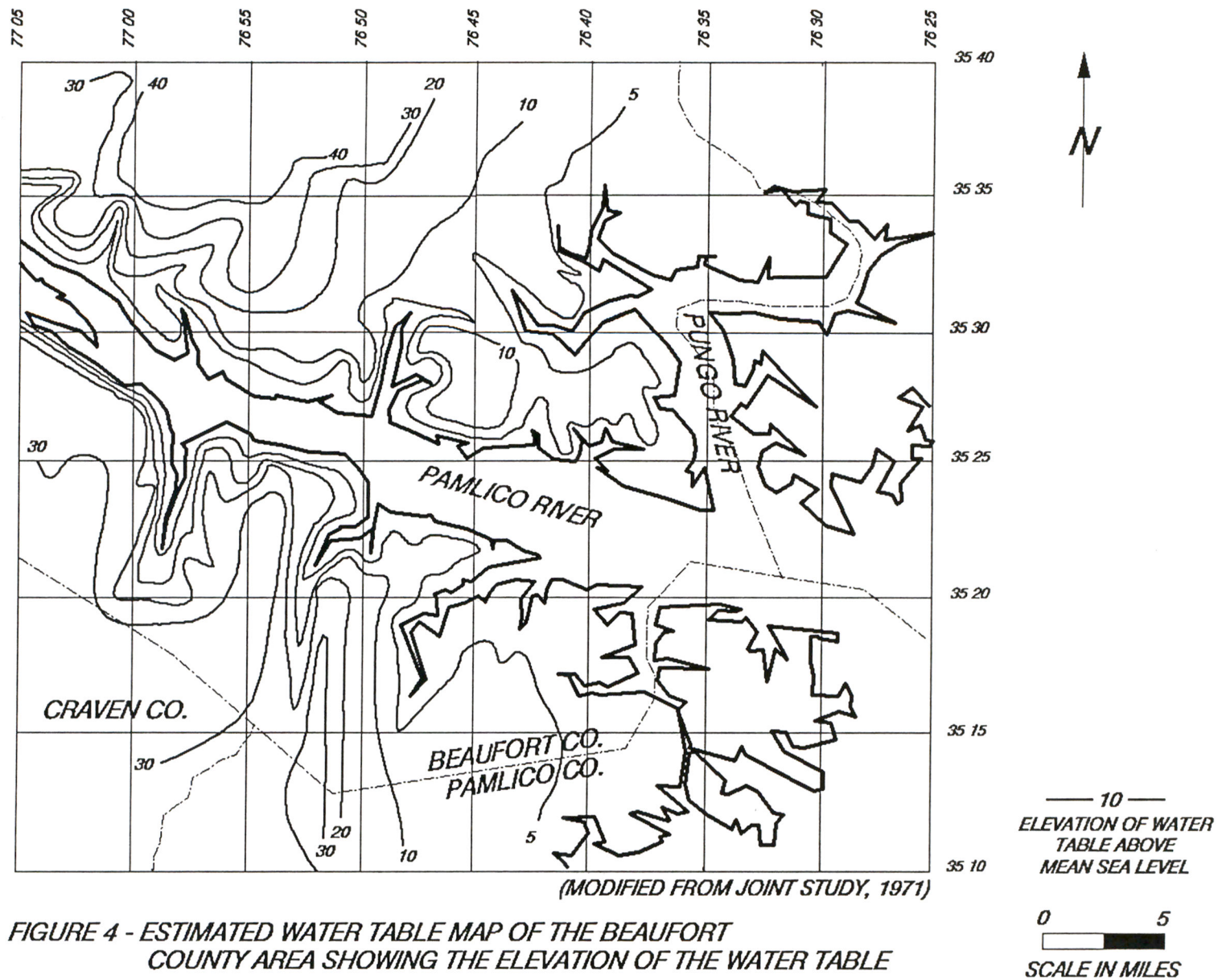


FIGURE 4 - ESTIMATED WATER TABLE MAP OF THE BEAUFORT COUNTY AREA SHOWING THE ELEVATION OF THE WATER TABLE

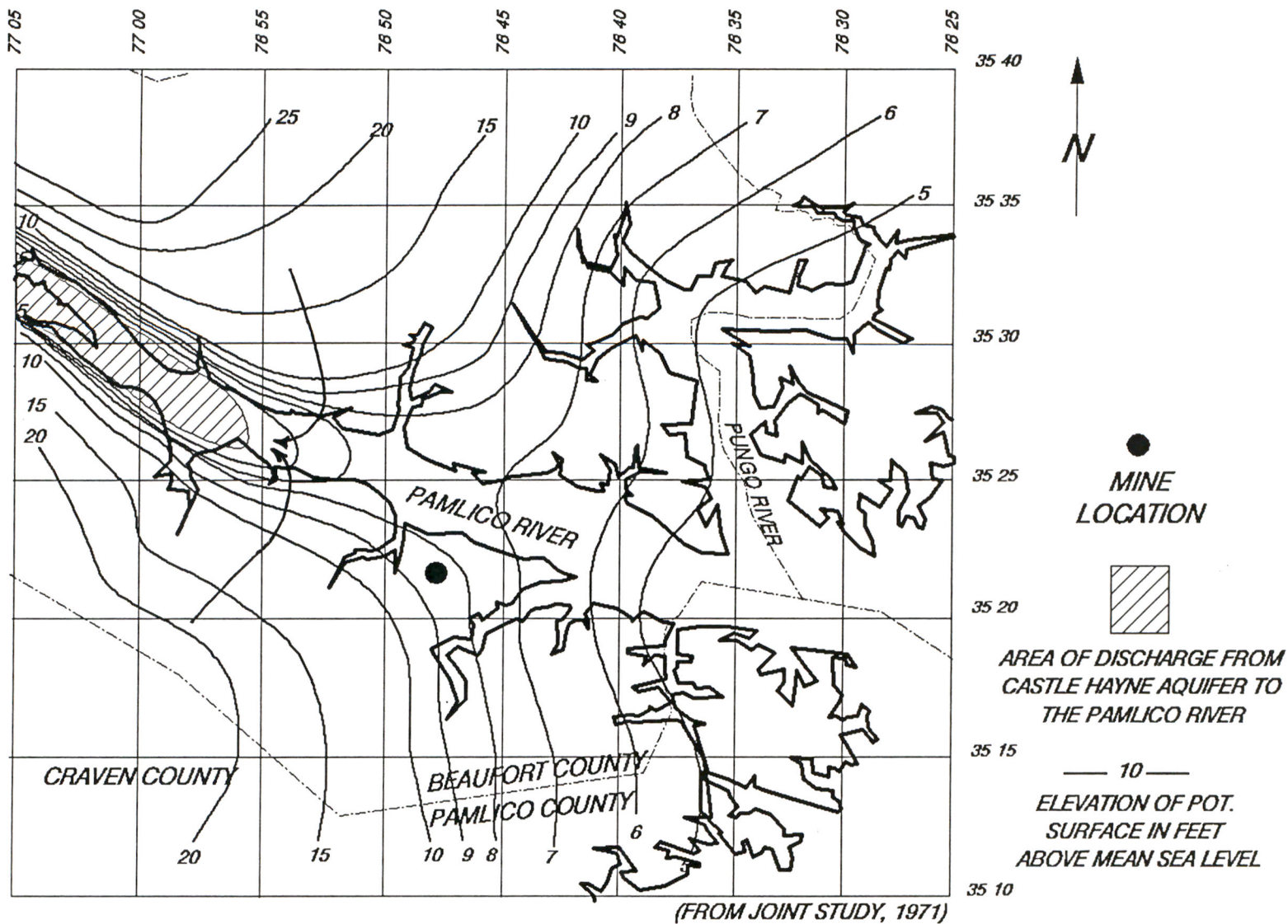


FIGURE 5 - PREDEVELOPMENT POTENTIOMETRIC SURFACE MAP
OF THE CASTLE HAYNE AQUIFER

the Castle Hayne Formation northeast of the Neuse River of approximately 170 mi², was 65 million gallons per day (MGD). Floyd (1969) estimated that the area of direct recharge was about 380 sq. mi. and average recharge was approximately 100 MGD. DeWiest later estimated that recharge available for development was from 74 to 139 MGD, depending upon baseflow of the major rivers in the area (Sherwani, 1973).

Recharge to units of the Cretaceous aquifer system occurs in interstream areas where the heads in Castle Hayne units are higher than those of the Cretaceous system (Winner and Lyke, 1989). Due to the overlying, prolific Castle Hayne aquifer system, very little is known about the Cretaceous aquifer system in the eastern coastal plain. The Cretaceous system provides water supplies to a number of municipalities west of the study area. Therefore, most of the hydraulic parameters and heads for the Cretaceous system are estimated from reports on the hydrogeology of Cretaceous aquifers west of the study area. An estimation of the predevelopment potentiometric surface of the Cretaceous aquifer system is presented on Figure 6.

Discharge from Aquifers

Water in the surficial aquifer eventually discharges into streams, rivers, or drainage canals.

Prior to pumping at Texasgulf, water in the Castle Hayne aquifer moved, from recharge areas in the west, towards the

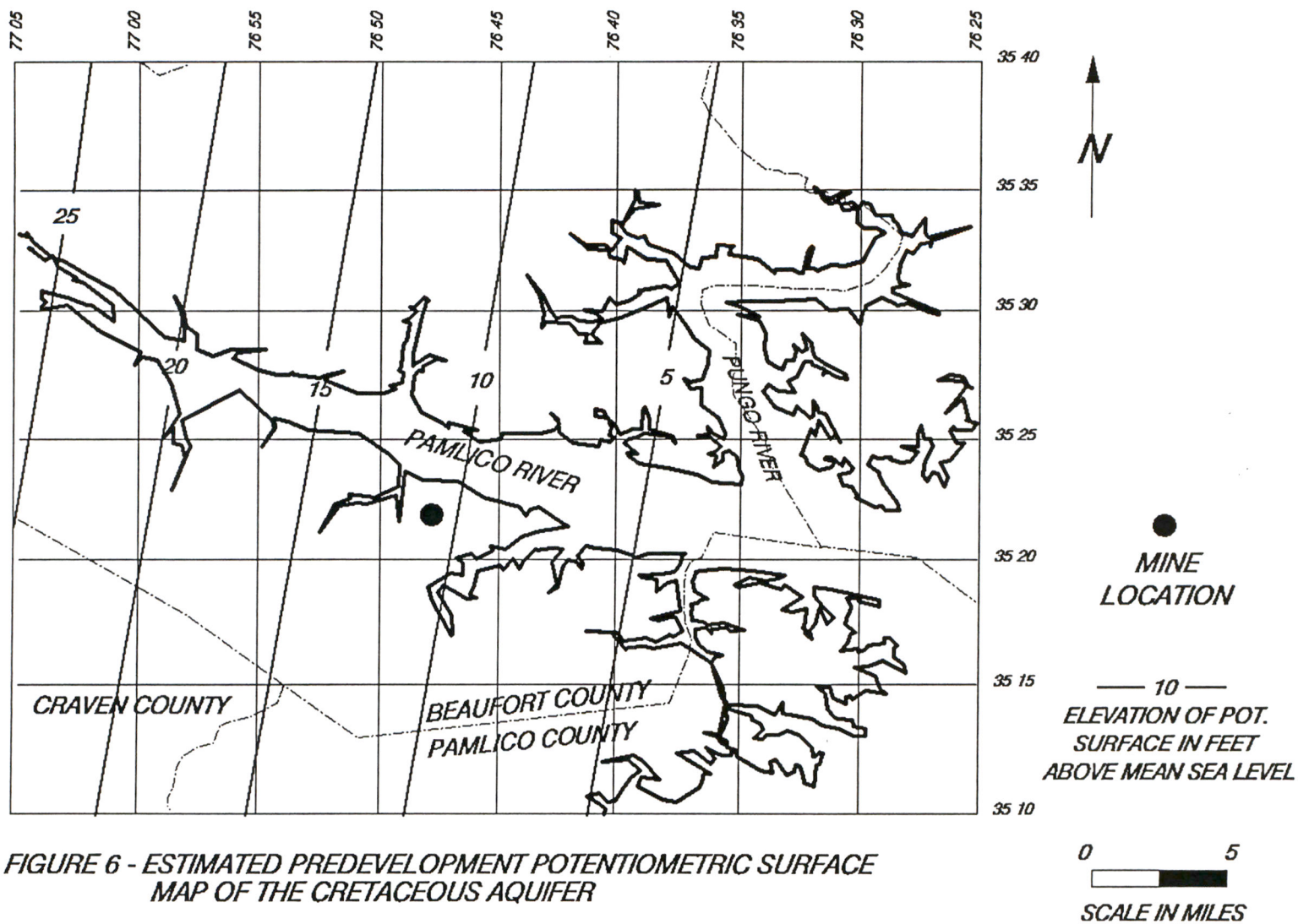


FIGURE 6 - ESTIMATED PREDEVELOPMENT POTENTIOMETRIC SURFACE
MAP OF THE CRETACEOUS AQUIFER

southeast under an average hydraulic gradient of approximately 0.3 ft/mi. Since the potentiometric surface of the Castle Hayne aquifer was significantly above the land surface, water from the Castle Hayne aquifer discharged naturally into the Pamlico River through overlying sediments/aquifers. Water not discharged into the Pamlico continued eastward until it encountered saltwater. Due to density contrasts, freshwater in the Castle Hayne then moved eastward and upward parallel to the freshwater-saltwater interface and discharged through overlying aquifers into the Pamlico Sound or offshore.

The Cretaceous aquifer system discharges into overlying aquifer units in areas where the head of the Cretaceous aquifer exceeds that of the overlying aquifer. In the extreme western coastal plain, streams or rivers incise into the Cretaceous units and water discharges directly into the streams (Winner and Lyke, 1989).

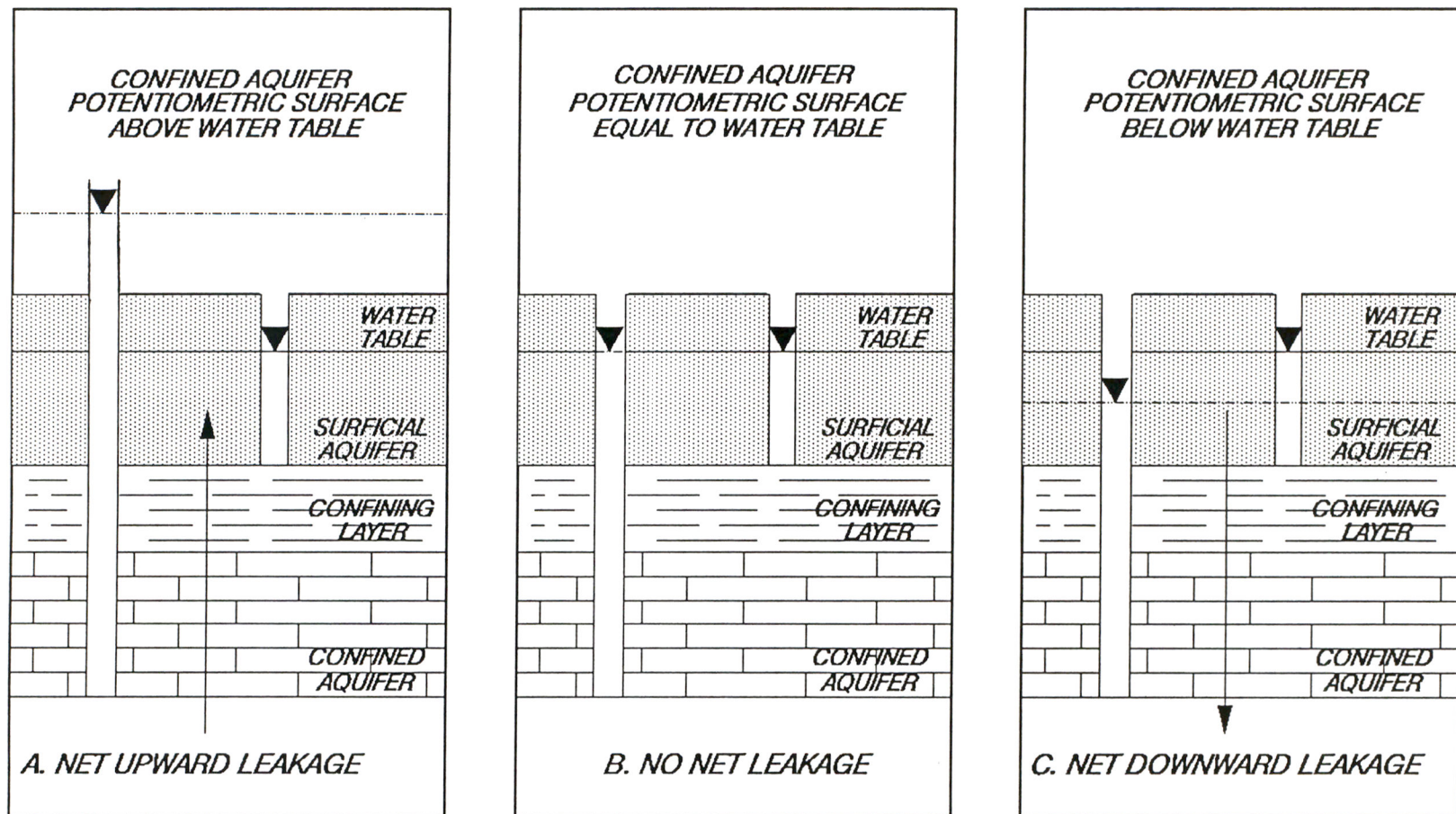
Leakage

Aquifer recharge and discharge occurs not only by direct sources, but also by leakage from overlying and/or underlying units where significant vertical hydraulic gradients exist (Hargis, 1982). Specifically, water can be transmitted through confining units at rates and volumes dependent upon the vertical hydraulic conductivity of the aquitard material, and the difference in heads of the aquifers separated by the confining layer. For example, the surficial aquifer may be

recharged from underlying aquifers, or water may be discharged downward into underlying aquifers, depending upon the direction of the head difference between the adjacent aquifers (Figure 7).

Figure 8 is a map of prepumping head differences between the surficial and Castle Hayne aquifers. It is evident that in much of the area, the potentiometric surface of the Castle Hayne aquifer is significantly higher than the potentiometric head (water table) of the surficial aquifer. Therefore, much of the region was an area of upward leakage from the Castle Hayne aquifer system to the surficial aquifer/Pamlico River prior to depressurization pumping.

The rate and amount of water discharged into the upper aquifer and the river is dependent upon the head difference between the aquifers and the vertical hydraulic conductivity of the confining layer between the aquifers. The prepumping potentiometric surface map of the Castle Hayne aquifer (Figure 5) also illustrates the movement of Castle Hayne water into the Pamlico River. Flowlines indicate a hydraulic connection between the aquifer and the river. Estimates of the amount of water naturally discharged into the upper 16 miles of the Pamlico River range from 21 MGD (Sherwani, 1973) to 30 MGD (DeWiest, et al., 1967). It was estimated for this study that approximately 24 MGD of water naturally discharged into the Pamlico River prior to depressurization pumping.



(ADAPTED FROM HARGIS, 1982)

FIGURE 7 - DIAGRAM OF HEAD-DEPENDENT VERTICAL
LEAKAGE BETWEEN AQUIFER UNITS

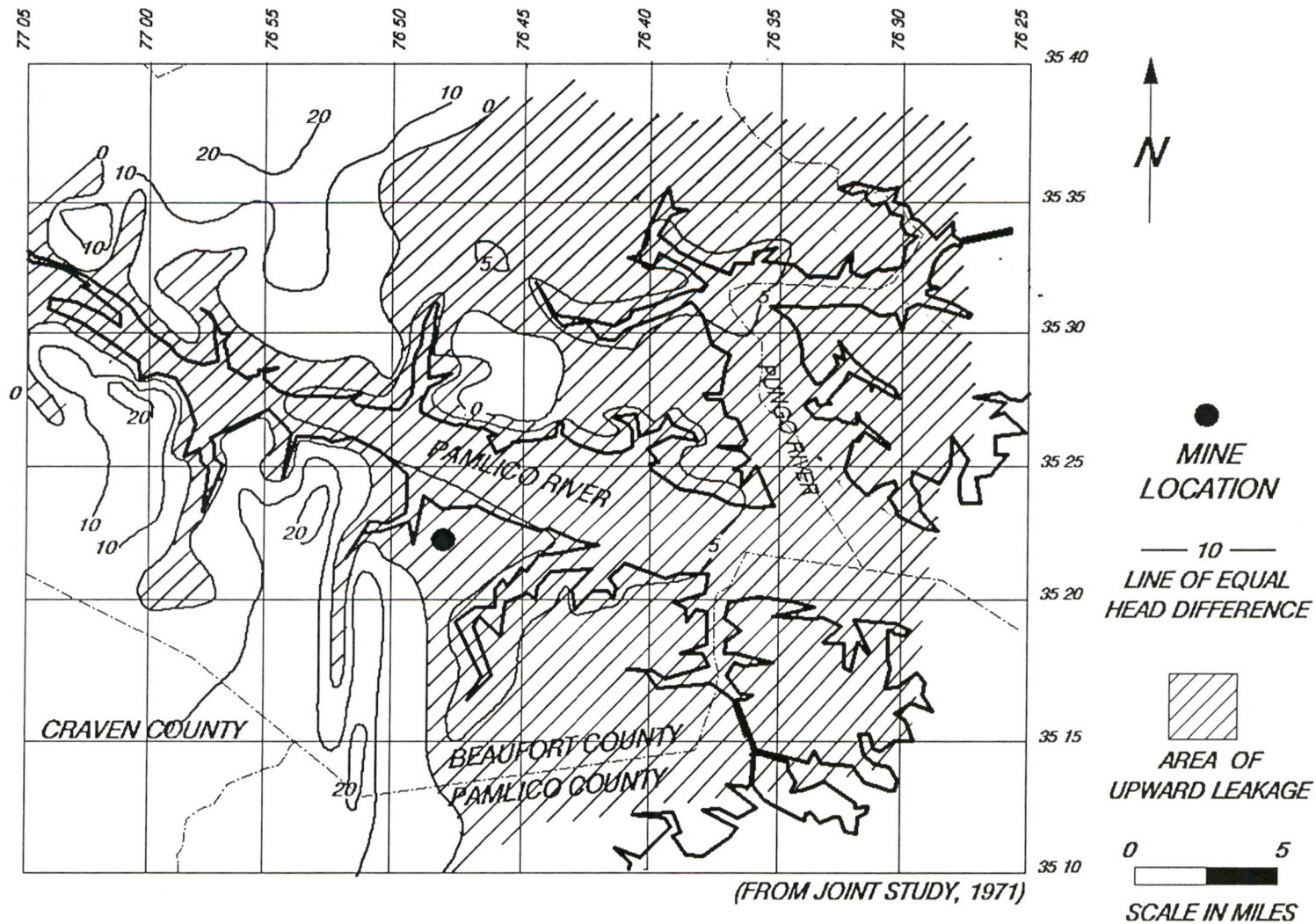


FIGURE 8 - PREDEVELOPMENT HEAD-DIFFERENCE BETWEEN THE SURFICIAL AQUIFER AND CASTLE HAYNE AQUIFER

OBSERVED EFFECTS OF MINE DEWATERING

Texasgulf constructed and has maintained an extensive groundwater monitoring system. The U.S. Geological Survey and the N.C. Department of Environment, Health, and Natural Resources (NCDEHNR) have also constructed wells and monitor them. The monitoring wells have been constructed in the surficial aquifer system and Castle Hayne aquifer system. The majority of the wells are open only to the upper Castle Hayne unit, but a few are open to the lower Castle Hayne and Beaufort units. Water levels and water quality in the upper Castle Hayne unit have been monitored on a continuous basis since 1965, prior to mining.

The most significant effect on the hydrogeologic environment is the extensive cone-of-depression formed on the potentiometric surface of the Castle Hayne aquifer. This changes the overall flow pattern of groundwater in the aquifer system.

An additional effect is a change in water quality at the mine site. Variations in chloride concentrations have been detected at and near the active mine areas. The following sections are intended to provide an overview of these effects.

Water-Level Changes

Significant changes in regional flow patterns of the Castle Hayne aquifer system are directly attributable to mining operations at Texasgulf. Prior to depressurization

pumping, groundwater flow in the upper Castle Hayne unit was from major areas of recharge in western Beaufort County to discharge areas along the Pamlico River and eastern Beaufort County (Figure 5).

Pumping at a uniform rate produces a rapidly stabilizing cone-of-depression centered at the active mine block, indicating steady-state conditions. The cone-of-depression is elliptical due to the wedge-shape of the Castle Hayne aquifer system, the pre-pumping hydraulic gradient and flow directions, the thickening of the Yorktown-Pungo River confining unit, and the balance of recharge and discharge. The center of the cone migrates with the active mine block, and its area depends upon the pumping rate. Although the location of the pumping center has changed, the configuration of the potentiometric surface has remained relatively stable.

Figure 9 presents the potentiometric surface of the upper Castle Hayne unit in late 1991 - early 1992 (Table 2) when the average annual pumping rate was approximately 48.3 MGD. Water levels are approximately 150-160 feet below mean sea level near the active mine block. Observation wells indicate a drawdown of approximately 10 feet at a location 20 miles east of the mine. The configuration of the equipotential surface indicates that groundwater flow is towards the pumping center within the cone, an area of over 1500 square miles.

There are a limited number of wells in the lower Castle Hayne and Beaufort units. The limited data from these wells

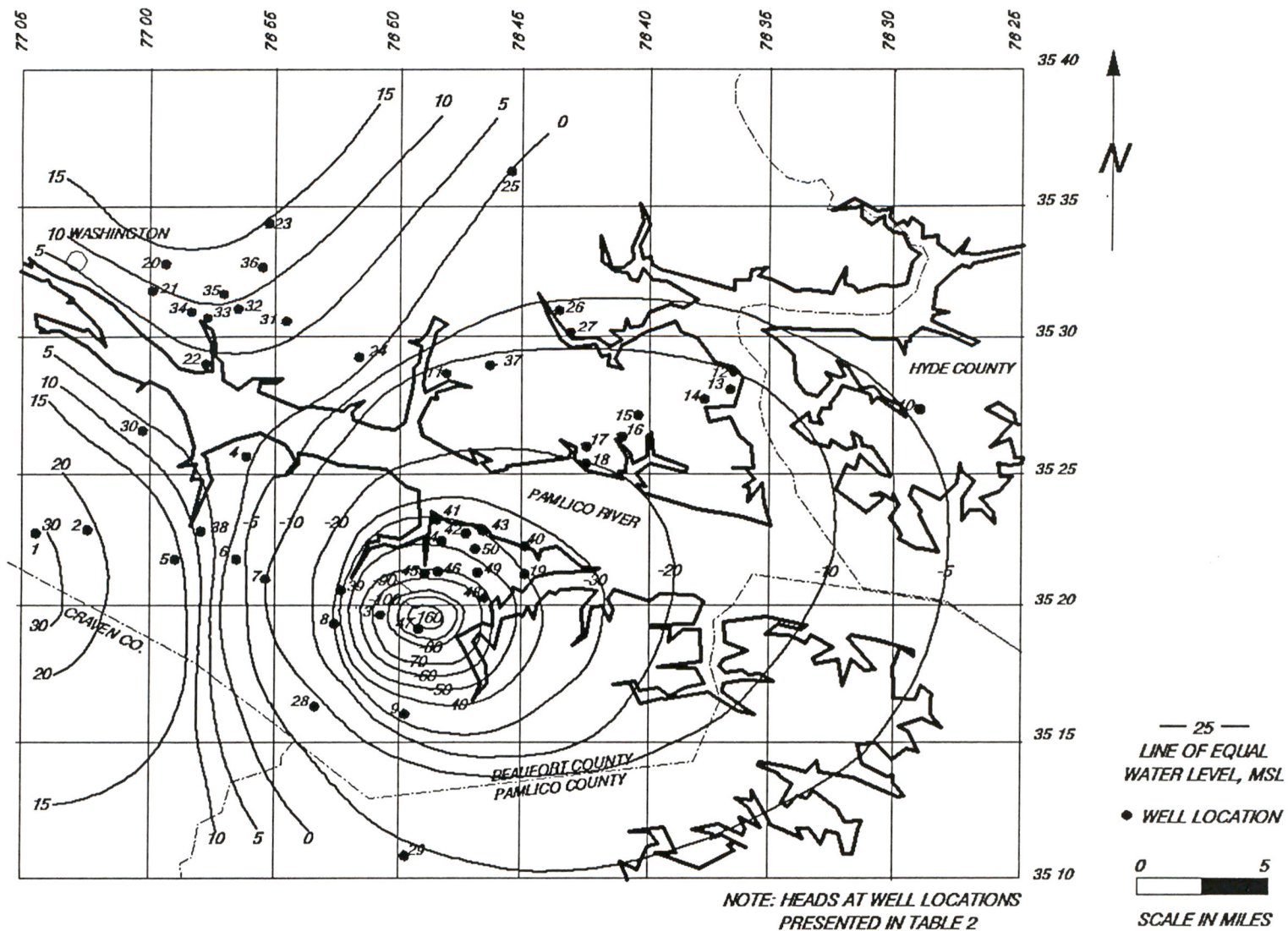


FIGURE 9 - OBSERVED POTENTIOMETRIC SURFACE OF
CASTLE HAYNE AQUIFER, 1991-1992

Table 2 - Head Measurements for Wells Presented in Figure 9

WELL NO.	HEAD (MSL)	DATE	WELL NO.	HEAD (MSL)	DATE
1	30.22	1/11/92	26	-8.10	1/13/92
2	20.87	1/11/92	27	-7.00	1/13/92
3	-75.79	1/11/92	28	-8.90	1/03/92
4	1.60	1/11/92	29	-3.95	1/03/92
5	15.74	1/11/92	30	7.00	1/03/92
6	-2.94	1/11/92	31	6.25	1/05/92
7	-11.15	1/11/92	32	8.90	1/05/92
8	-30.78	1/11/92	33	7.79	1/05/92
9	-33.26	1/11/92	34	9.75	1/05/92
10	-4.50	1/11/92	35	10.51	1/05/92
11	-19.36	1/11/92	36	12.03	1/05/92
12	-10.50	1/11/92	37	-12.58	11/4/92
13	-12.70	1/11/92	38	-1.05	11/4/92
14	-11.80	1/11/92	39	-43.59	11/4/92
15	-14.85	1/11/92	40	-38.22	11/4/92
16	-16.55	1/11/92	41	-45.58	12/25/91
17	-19.45	1/11/92	42	-41.45	12/25/91
18	-21.29	1/11/92	43	-38.10	12/25/91
19	-38.69	1/11/92	44	-47.39	12/25/91
20	14.30	1/13/92	45	-60.61	12/25/91
21	5.65	1/13/92	46	-39.75	12/25/91
22	4.30	1/13/92	47	-115.52	12/25/91
23	14.25	1/13/92	48	-65.25	12/25/91
24	0.30	1/13/92	49	-54.48	12/25/91
25	-0.30	1/13/92	50	-42.35	12/25/91

indicate that similar cones-of-depression exist in these units. The elevations of the potentiometric surfaces of these units are similar in the vicinity of the pumping center (LBG, Inc., 1991).

Water-level changes have been less dramatic in the other aquifer units. For instance, long-term water level data indicate that changes in patterns of the water table (surficial aquifer system) have been limited to the immediate vicinity of the Texasgulf mine (LBG, Inc., 1991).

Water Quality Changes

Since before mining began at Texasgulf, concerns were expressed that mining would adversely affect the quality of water in the aquifer units. Specifically, it was believed that heavy pumping at the mine would result in encroachment of salty water into the upper Castle Hayne unit by several processes. These include 1) lateral movement of saline water from the eastern reaches of the upper Castle Hayne unit, 2) vertical upward movement of saline water from underlying units, and 3) vertical downward movement of brackish water from the Pamlico River estuary.

Chloride concentrations are monitored in the surficial aquifer system (post-Croatan and Croatan units) and the upper Castle Hayne unit. In addition, chloride data is available for only a few wells in the lower Castle Hayne and Beaufort units of the Castle Hayne system and the Black Creek unit of the

Cretaceous system.

Prior to depressurization pumping, chloride levels ranged from about 30 parts per million (ppm) in the upper Castle Hayne unit, to about 200 ppm in the lower Castle Hayne unit. The estimated predevelopment distribution of chloride concentrations in the upper Castle Hayne unit is presented on Figure 10. Chloride levels were approximately 3000 ppm in the Beaufort unit of the Castle Hayne system (NCDNER, 1974). It is estimated that chloride levels in the Cretaceous units range from about 3000 ppm to over 10,000 ppm.

Locations of wells monitored for chloride concentrations in the upper Castle Hayne unit are shown in Figure 11. Historical chloride concentrations in the sentinel wells maintained by Texasgulf are presented on Figure 12. In addition, chloride concentrations are reported for county wells in Figures 13A and 13B. These plots indicate that chloride concentrations in several wells to the east of the mine location have slowly increased (S-1, S-2, S-3, S-7, S-12, and C-4). These plots indicate the possible onset of lateral encroachment of salty water. However, wells S-5 and S-4, located between S-7 and the mine site do not show an increase in chloride content.

Reports issued by the N.C. Dept. of Natural and Economic Resources (1974 and 1976) indicate that chloride concentrations increased at the active mine locations as a result of the pumping. In the early stages of mining, the

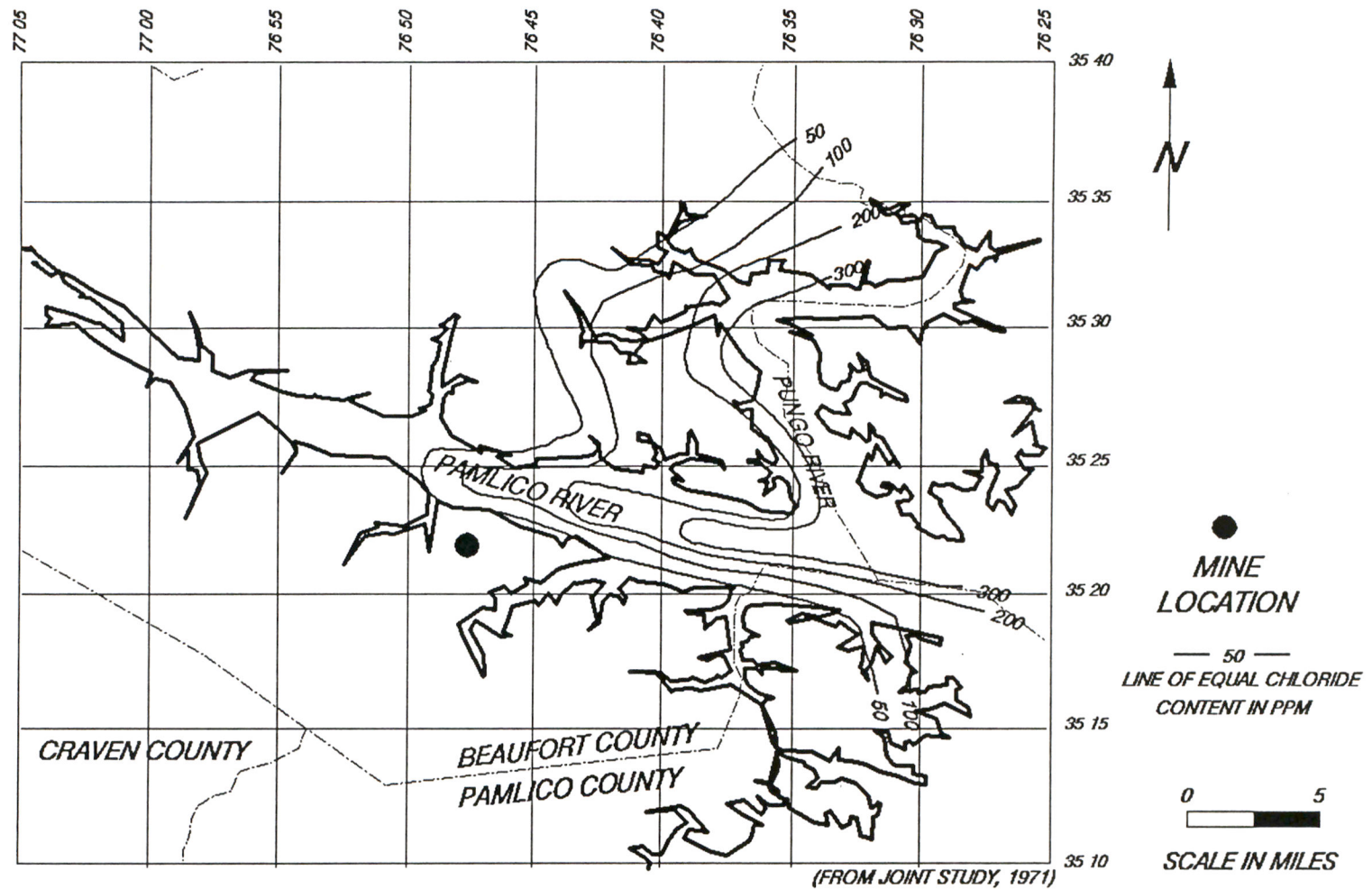


FIGURE 10 - ESTIMATED PREDEVELOPMENT CHLORIDE LEVELS IN UPPER CASTLE HAYNE UNIT

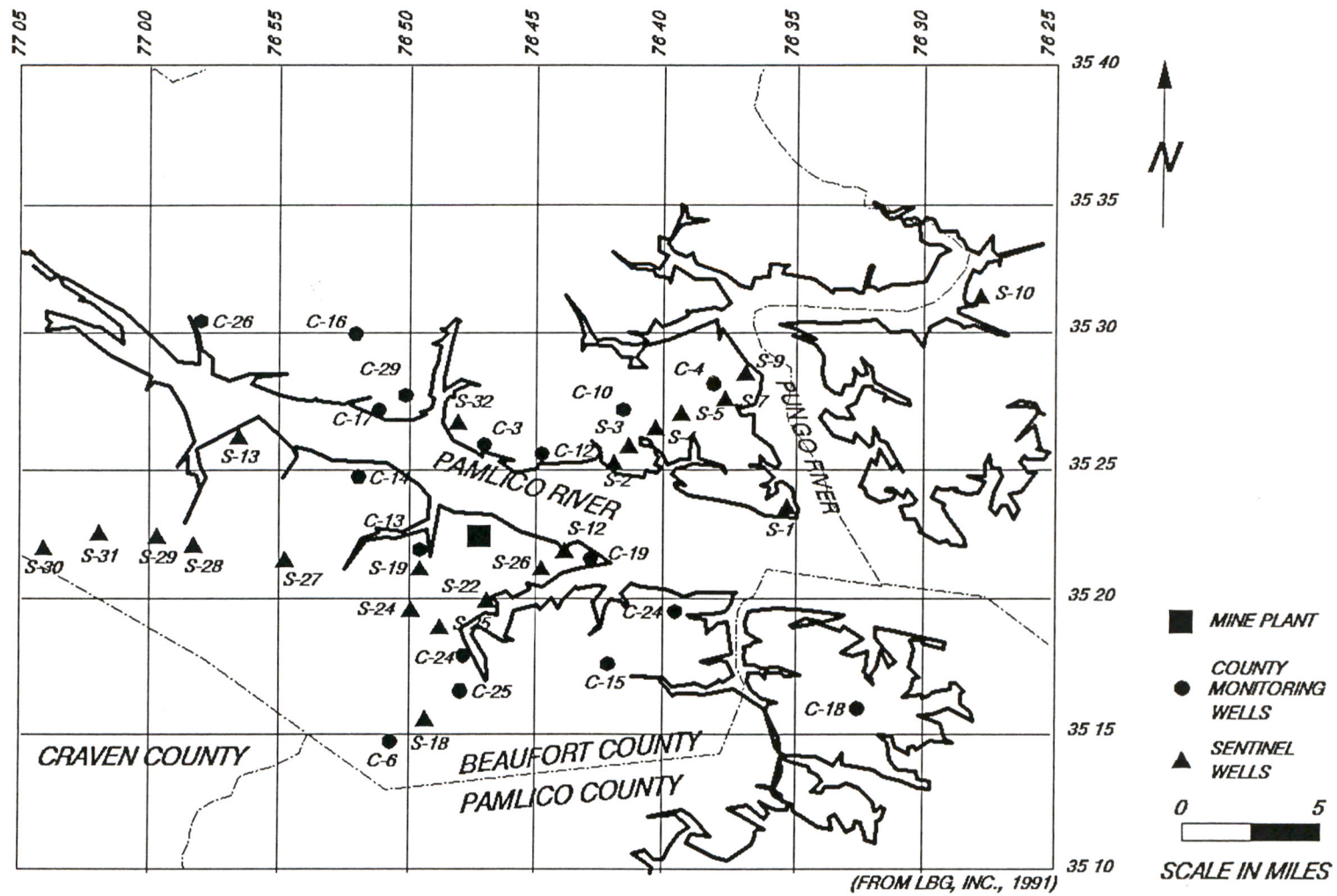


FIGURE 11 - LOCATIONS OF SENTINEL AND COUNTY MONITORING WELLS IN THE MINE VICINITY

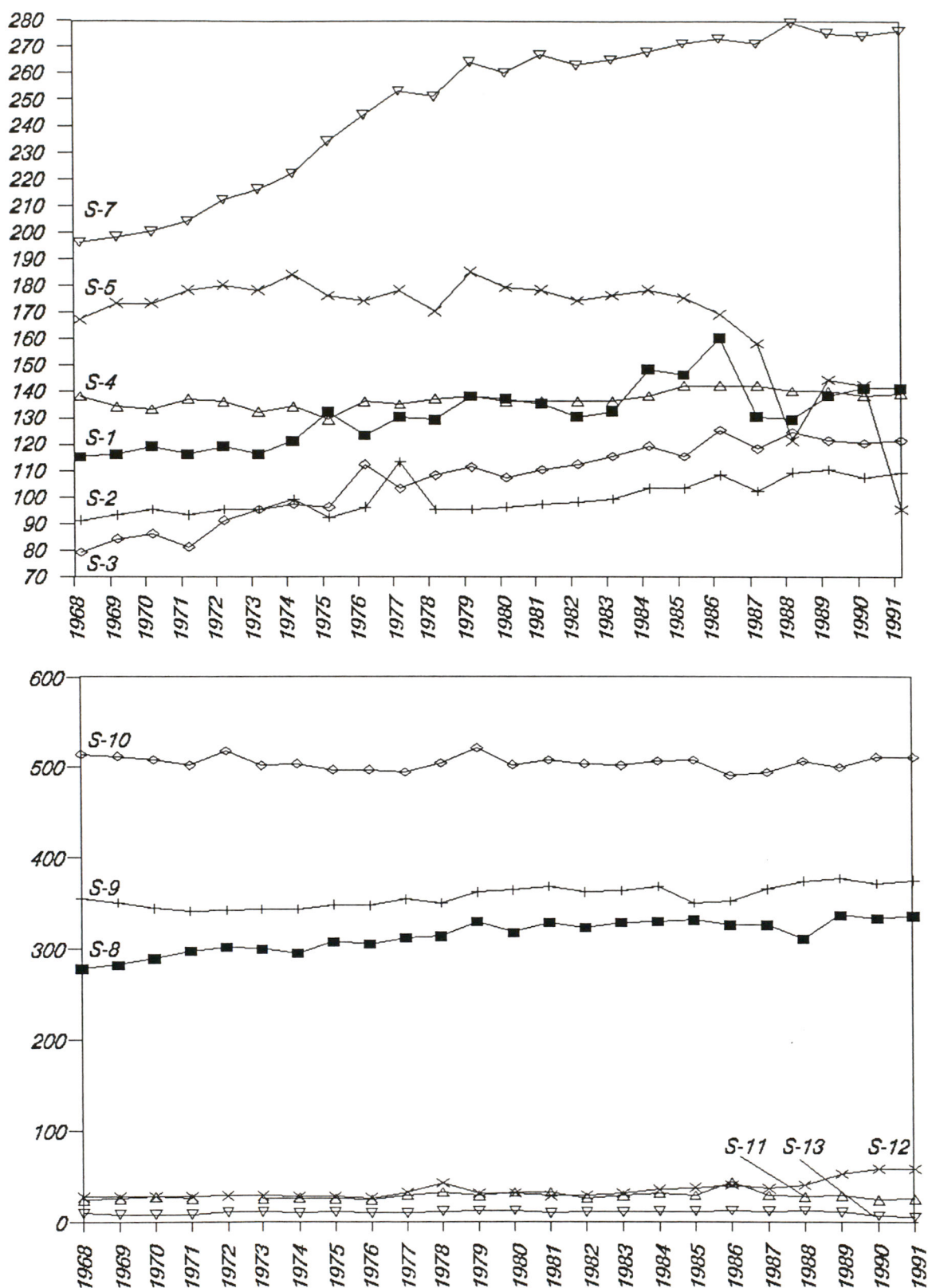


FIGURE 12 - CHLOROGRAPHS FOR SELECTED SENTINEL WELLS, 1968-1991
(SEE FIGURE 11 FOR WELL LOCATIONS)

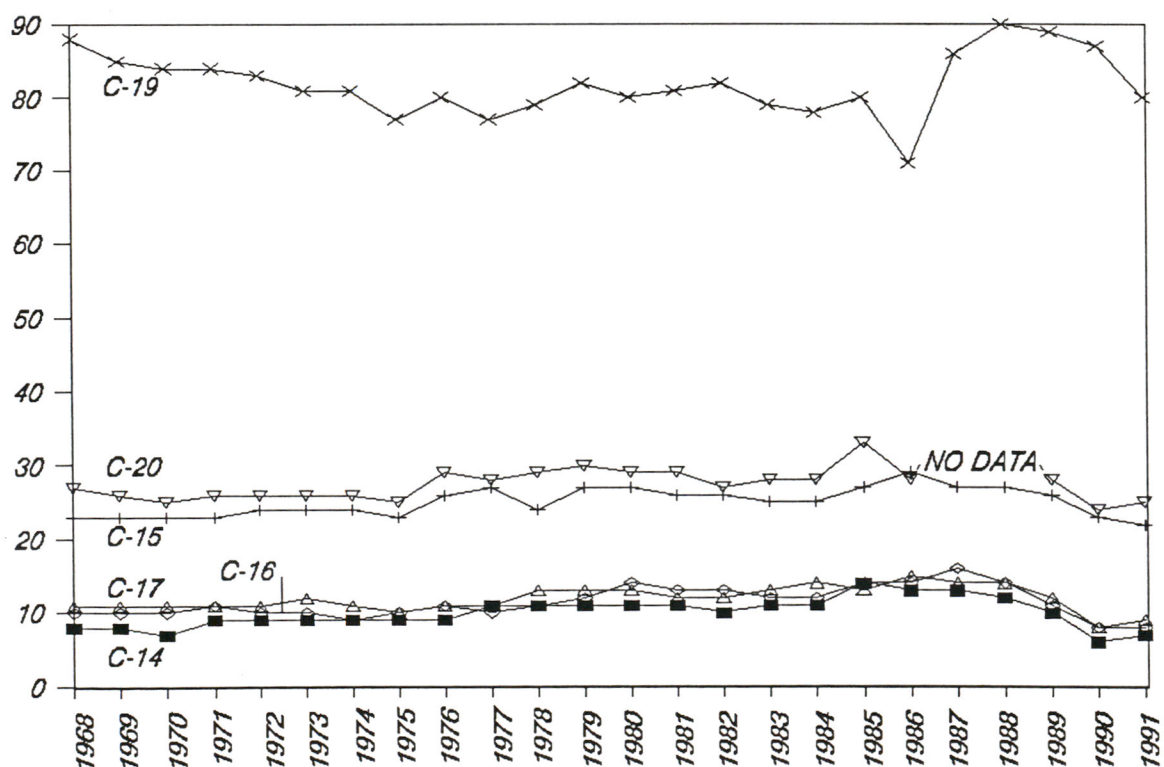
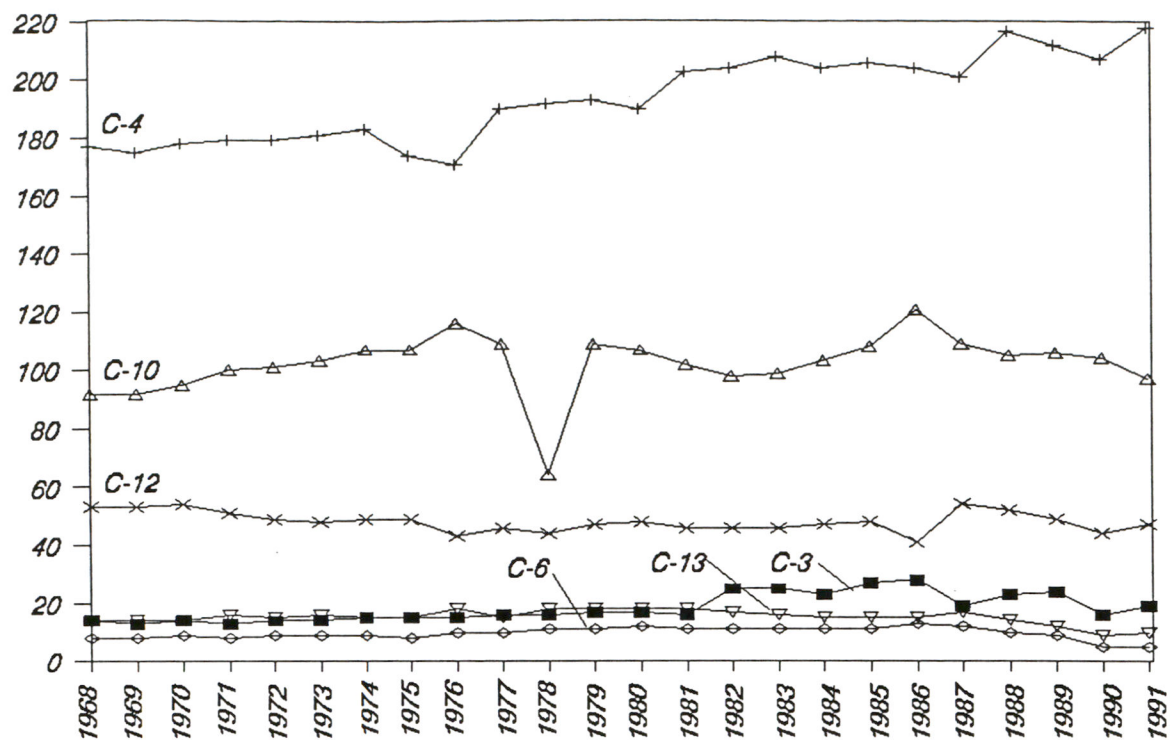


FIGURE 13A - CHLOROGRAPHS FOR SELECTED COUNTY WELLS, 1968-1991
(SEE FIGURE 11 FOR WELL LOCATIONS)

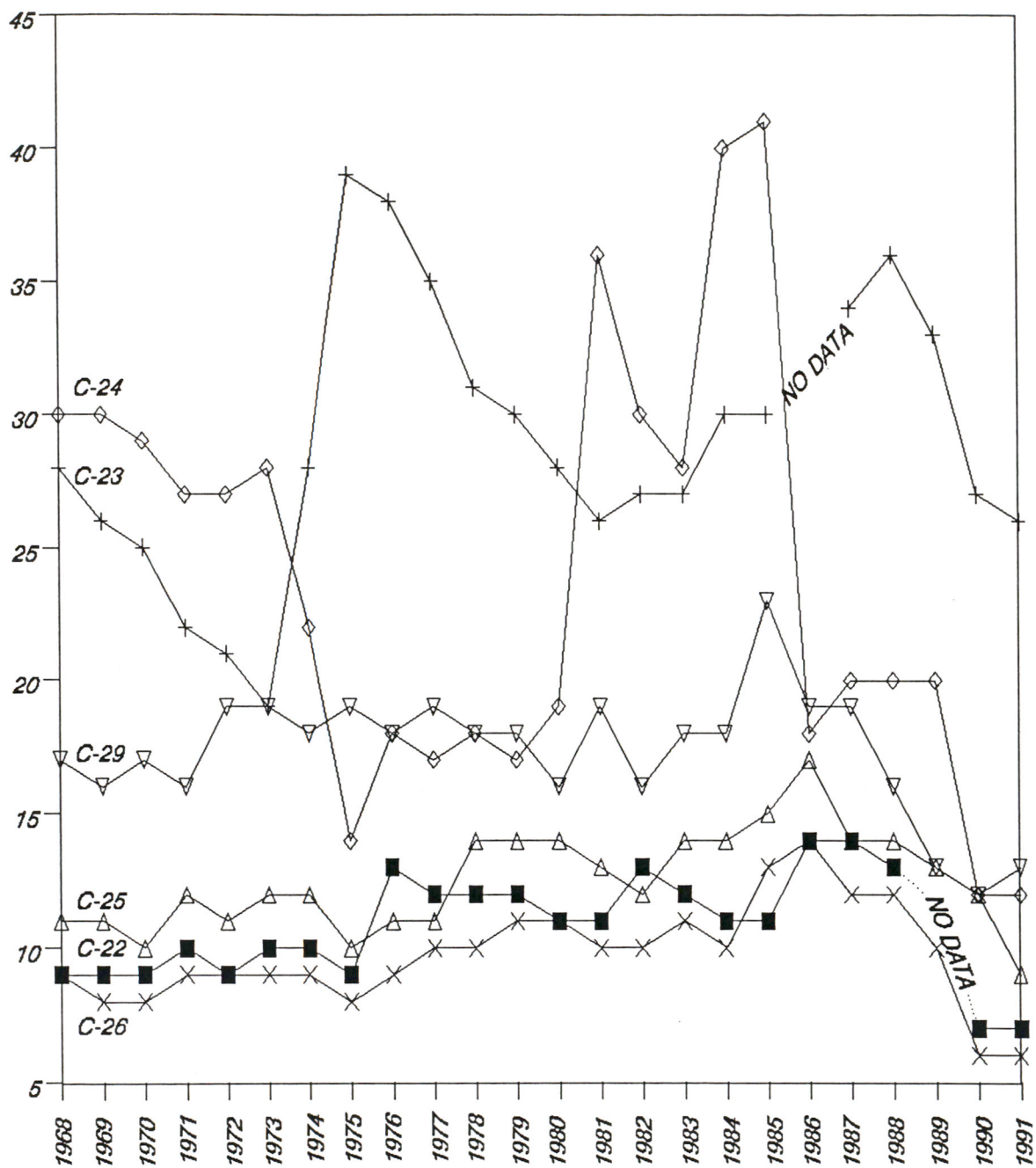


FIGURE 13B - CHLOROGRAPHS FOR SELECTED COUNTY WELLS, 1968-1991
(SEE FIGURE 11 FOR WELL LOCATIONS)

active mining locations were further north near the shore of the Pamlico River. Chloride levels of over 300 ppm were reported at the pumping centers of these northern mine locations. These elevated chloride levels were believed to result from upconing of saline water from lower units and lateral migration from a brackish zone beneath the Pamlico River (NCDNER, 1976). As the active mine center was moved to the south, the chloride concentrations at the mine center decreased. Presently, chloride concentrations at the pumping center average less than 55 ppm with the exception of one well with an average of 75 ppm (LBG, Inc., 1992). Higher chloride concentrations are reported in the wells located at the mine plant site near the Pamlico River. The current distribution of chlorides in the Castle Hayne aquifer is presented in Figure 14. This figure illustrates the higher chloride levels at the plant site.

The potential for vertical downward movement of brackish water from the Pamlico River into the Castle Hayne aquifer has been evaluated in several studies using the thickness and vertical hydraulic conductivity of the confining layer and the head difference between the river and the upper Castle Hayne aquifer. Sherwani (1973) estimated that the minimum time for brackish water from the Pamlico River to travel downward to the Castle Hayne aquifer would be 250 years at a pumping rate of 52 MGD. Peek and Nelson (1975) and the Joint Study (1971) estimated the minimum travel time would be 500 years at a

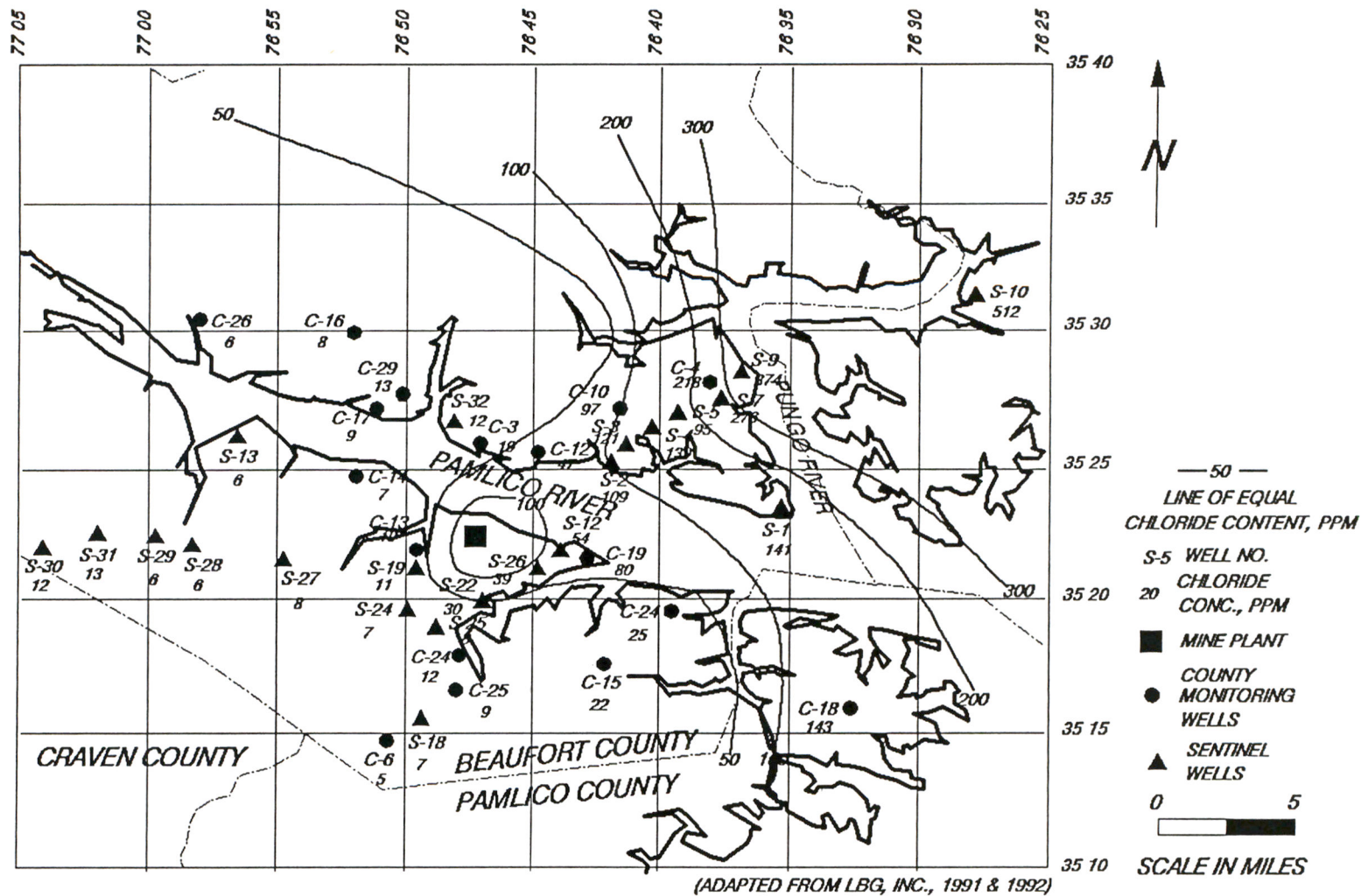


FIGURE 14 - OBSERVED CHLORIDE LEVELS IN CASTLE HAYNE UNIT, 1991-1992

(ADAPTED FROM LBG, INC., 1991 & 1992)

pumping rate of 78 MGD. Therefore, based on worst-case conditions, vertical movement of brackish water from the Pamlico River is not anticipated to be significant.

Increases in chloride concentrations in other aquifer units in the vicinity of the mine has not been significant. Chloride concentrations in the surficial aquifer (and channel sand unit) average 19 ppm and have remained relatively unchanged since dewatering of these units began in 1988 (LBG, Inc., 1992).

Summary

Based on previous investigations, the potential for vertical downward movement of saline water into the Castle Hayne aquifer is not considered to be significant. Chlorographs of wells to the east of the mine show increasing chloride levels, possibly indicating the onset of lateral encroachment. It does appear that the upconing of saline water from underlying units does occur at the active mine location. The area of upconing migrates with the pumping center location. Chloride levels are significantly higher at the plant site near the Pamlico River. It is believed that lateral encroachment of chloride-enriched water from beneath the Pamlico River is occurring at this location. As active mining locations migrate closer to the Pamlico River and its major tributaries, chloride levels at the mine centers are anticipated to increase.

POTENTIAL EFFECTS OF MINE DEWATERING

A potential hydrogeologic effect considered was the possibility of land subsidence resulting from pumping. Extensive land subsidence has occurred in several areas such as Houston-Galveston, Texas; the San Joaquin Valley in California; and Savannah, Georgia as a direct result of the extraction of groundwater. This section is intended to 1) provide an overview of the potential for compaction of units in the mine area as a result of groundwater withdrawals at the Texasgulf mine; and 2) determine if existing precise leveling data indicate subsidence is occurring in the mine area.

Potential for Compaction of Units

Land subsidence due to fluid withdrawals is a result of the increase in the effective (intergranular) stress in an aquifer as the porewater pressure decreases (Waltham, 1989). The rate and extent of land subsidence resulting from compaction of lithologic units is generally dependent upon the type (compressibility) and thickness of the lithologic units and the extent of groundwater extraction.

The stratigraphic framework of the coastal plain in the area of the mine is shown in Figure 2 and Table 1. The stratigraphic section is divided into four principal units: 1) the surficial aquifer system, 2) the Yorktown-Pungo River confining unit, 3) the Castle Hayne aquifer system, and 4) the Cretaceous aquifer system.

In the mine area, the surficial aquifer is composed predominantly of sands with thin clay subunits. Deposits of unconfined sediments are compressible and lowering of the water table causes compaction. The sands are relatively incompressible at shallow depths; only at substantial depths can grain fracturing occur resulting in significant compaction (Poland and Davis, 1969). Surficial sediments at the mine site are dewatered and then removed

as overburden by bucket-wheel excavators. Lowering of the water table in the area of the mine is limited to the immediate vicinity of the active mine block. Therefore, the potential is low for widespread subsidence due to dewatering of the surficial aquifer.

The Yorktown-Pungo River confining unit is composed primarily of clays interlayered with discontinuous sand units. The clayey nature of these units is favorable to compression as a result of the equalization of pore pressures induced by pumping from adjacent aquifers (Poland and Davis, 1969). Subsidence of these fine-grained units is typically slow and inelastic. There is expected to be a small potential for compaction in the more distant mine area due to lowered porewater pressures from depressurization pumping.

The Castle Hayne system includes porous, moldic limestone in the upper Castle Hayne unit, massive, sandy limestone and sands in the lower Castle Hayne unit, and sands in the Beaufort unit. Depressurization pumping is concentrated on the

upper Castle Hayne unit. This unit is very porous and contains sizable voids and solution cavities in some areas, but otherwise maintains a rigid skeleton. Sinkholes resulting from the dissolution and collapse of upper Castle Hayne limestone units are not evident in the Beaufort County area.

Depressurization of the upper Castle Hayne unit results in the reduction of pore pressures in the lower Castle Hayne and Beaufort units. Rearrangement of sand grains may result in slight compaction of the sand units, but the massive limestone subunits of the lower Castle Hayne unit would not be affected.

The Cretaceous units are composed primarily of clays and discontinuous, interlayered sand units. Heavy withdrawals of groundwater from the confined lower Cretaceous units in the Franklin-Suffolk, Virginia area has produced subsidence in that area. Maximum subsidence was observed to be 152 millimeters from 1953 to 1978 with a subsidence/head decline ratio of 0.0037 (Davis, 1987). The sands and sandy clays from which groundwater is withdrawn in this area are similar to the Cretaceous units in the vicinity of the mine. However, at the mine, water is not pumped from the Cretaceous units and the potentiometric surfaces of the Cretaceous aquifers have only slightly declined due to the depressurization pumping (Coble, et al., 1989). Potential for compaction of the Cretaceous units is small and extensive subsidence due to compaction of Cretaceous units is highly unlikely.

Results of Leveling Studies

Land subsidence is primarily evaluated by repeated, precise leveling surveys (Whalen, 1978). Benchmarks along roads and railways form a geodetic, vertical control net throughout the country. The accuracy of the leveling surveys are variable. Different levels of accuracy, referred to as "orders", are used to describe the locations of the control points (Bossler, 1984; Table 3). Control leveling has been performed in the vicinity of the mine. A third-order survey was performed in Beaufort County along N.C Hwy 33 in 1964 by the National Geodetic Survey. A second-order, class II survey was repeated along N.C. Hwy. 33 and N.C. Hwy. 306 in 1983. Only three control stations are common to both surveys (Figure 15). A comparison of these surveys is presented on Table 3. The later survey indicated significantly lower elevations for these points.

Table 3 - Elevation standards of accuracy

Classification	Maximum elevation difference accuracy (b)*
First-order, class I	0.5
First-order, class II	0.7
Second-order, class I	1.0
Second-order, class II	1.3
Third-order	2.0

* defined as the standard deviation of the vertical difference between points in millimeters (S) divided by the approximate horizontal distance between the points in kilometers (d) $b = S/\sqrt{d}$ (Bossler, 1984)

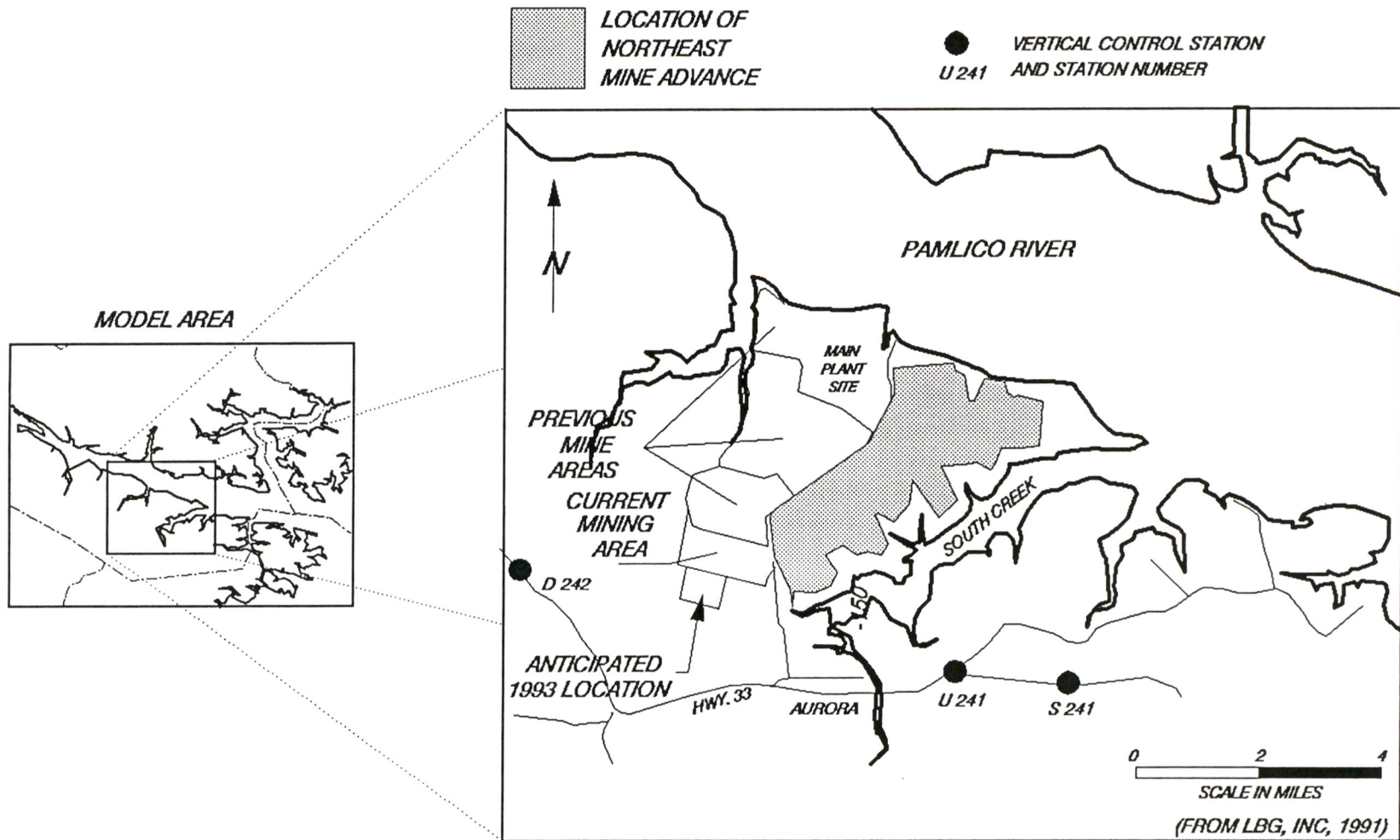


FIGURE 15 - LOCATIONS OF CONTROL POINTS COMMON TO THIRD- AND SECOND-ORDER LEVELING SURVEYS, BEAUFORT CO.

Summary

More than half of the water withdrawn from the groundwater system is from the upper Castle Hayne unit, which is composed of rigid, porous sandy limestone. The withdrawals have resulted in the less drastic reduction of water levels in other units as well. The decrease in pore pressures in these units may result in compaction of the clayey beds in the Yorktown-Pungo River confining unit and Cretaceous units. A comparison of third-order and second-order leveling surveys indicates that these control points have decreased in elevation. However, comparison of control points between two different orders of surveys may not be justified. In addition, only a few points in broad areas of the mine could be compared. Therefore, the potential for subsidence based on this limited information is inconclusive. A second-order, class II survey was performed in 1983 along N.C. Hwy 306 through the mine area. In order to accurately assess the potential for subsidence in the mine area, future second-order leveling should be compared to the 1983 second-order survey data present for the immediate mine area.

GROUNDWATER FLOW SIMULATION

A computer simulation of groundwater flow in the hydrogeologic system in the vicinity of the Texasgulf mine was performed in order to evaluate the response of the groundwater system to various pumping scenarios associated with mining at

Table 4 - Comparison of elevations at selected control points in Beaufort County

Station No.*	1964 Survey (Third-order)	1983 Survey (Second-order, II)	Difference (mm)
D 242	9.233m	9.1824m	51
S 241	2.371m	2.3467m	24
U 241	2.709m	2.6878m	21
*Note: Station locations (Thompson, personal comm. 1992) shown on Figure 15			

Texasgulf. The location of the area modeled is presented in Figure 16.

Previous Modeling Efforts

Sherwani (1973) prepared the first significant computer simulation of groundwater flow in the North Carolina Coastal Plain. His work describes the development and use of two-dimensional analog and digital, finite-difference models of the Castle Hayne aquifer system. Sherwani's model was primarily used to predict the effects of depressurization pumping of the aquifer for phosphate mining.

Hargis (1982) prepared a groundwater simulation for the area using a two-dimensional, finite-difference, regional flow model of the upper Castle Hayne unit as a consultant's report for the North Carolina Phosphate Company (NCPC). The simulation projected water levels based on anticipated pumping

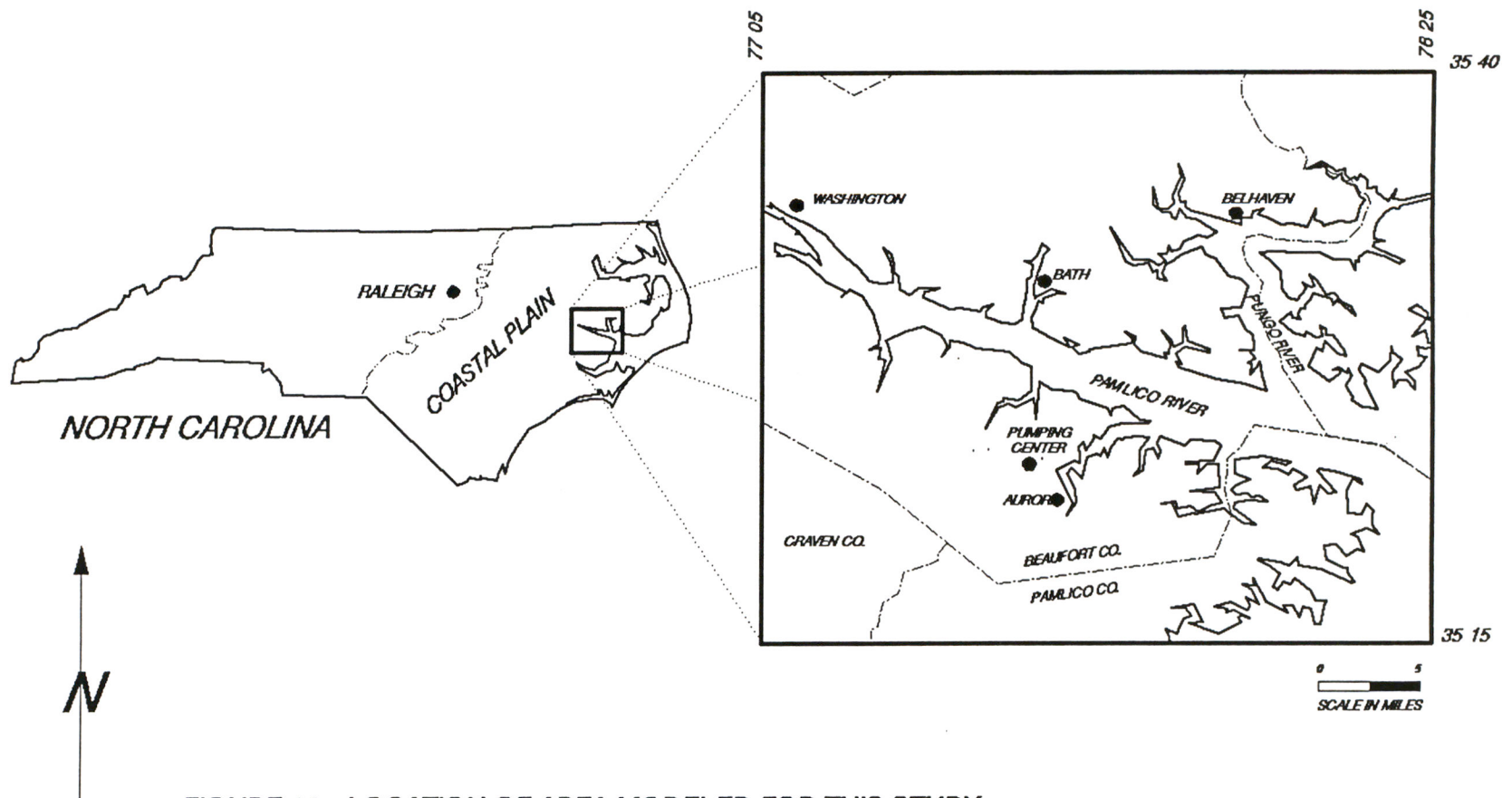


FIGURE 16 - LOCATION OF AREA MODELED FOR THIS STUDY

rates and locations for two pumping centers, the Texasgulf and NCPC mines.

Eimers, et al., (1990) prepared a simulation of groundwater flow in the Cretaceous hydrogeologic units using a three-dimensional, finite-difference flow model as part of a hydrogeologic study of the central coastal plain of North Carolina. The model was used to predict the effects of increased pumping from aquifers in that area.

The most recent computer simulation of North Carolina Coastal Plain aquifers was prepared by Giese, et al. (1991). This simulation used a three-dimensional, finite-difference model to "simulate ground-water flow in the 25,000 square mile aquifer system of the North Carolina Coastal Plain". The paper evaluated the effects of increases in groundwater withdrawal of 3 percent per year. Simulated conditions of the aquifer system from 1980 to 2000 were investigated in areas of the coastal plain where aquifers have shown significant effects due to pumping stresses.

Model Description

The model used for this thesis is the modular, three-dimensional, finite-difference model (MODFLOW) developed by McDonald and Harbaugh (1988) of the U.S. Geological Survey.

MODFLOW calculates the hydraulic head at a point (or node) for each subdivision of the area (cell). The differential equation used to describe the movement of

groundwater through a porous medium is presented below:

$$\frac{\partial}{\partial x} (K_{xx} \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (K_{yy} \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z} (K_{zz} \frac{\partial h}{\partial z}) - W = S_s \frac{\partial h}{\partial t}$$

where:

K_{xx} , K_{yy} , and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, assumed to be parallel to the major axes of hydraulic conductivity (feet/day);

h is the potentiometric head (feet);

W is a volumetric flux (per unit volume) and represents sources and/or sinks of water (feet³/day);

S_s is the specific storage of the porous material (dimensionless);

t is time (days)

(McDonald and Harbaugh, 1988)

This equation is typically approximated by a finite-difference method which solves a large number of simultaneous linear equations using the strongly implicit procedure (SIP). The steady-state iterations were performed using a one day time-step and the SIP convergence limits were set at 0.001 foot.

MODFLOW assumes the groundwater is constant in density, groundwater flow is horizontal in aquifers and vertical in confining units (McDonald and Harbaugh, 1988).

Finite-Difference Grid Selection

The finite-difference model requires that the model area be represented horizontally in a two-dimensional grid and vertically in layers. The grid is divided into 26 rows and 26 columns of variable dimensions which defines a total of 676 cells (per layer), encompassing a total area of approximately 1300 square miles (Figure 17). The grid is discretized into a relatively finer mesh size for increased accuracy at areas of particular interest (approximately 0.82 and 1.81 square miles at the Texasgulf mine area and Washington wellfield areas, respectively). The largest cells (6.76 square miles) are located in the north and southeast corners of the grid.

The model is divided vertically into three layers representing the surficial aquifer (layer 1), the Castle Hayne aquifer system (layer 2), and the Cretaceous aquifer system (layer 3). The vertical arrangement of layers in the system along section A-A' of Figure 17 is presented in Figure 18. The entire model therefore contains a total of 2028 variably-dimensioned blocks.

Model Parameters

Appropriate hydrologic and stratigraphic parameters are assigned to each cell. Those parameters include bottom elevations and hydraulic conductivity for the unconfined layer; and top and bottom elevations, transmissivities, and storage coefficients for the confined layers. The recharge to

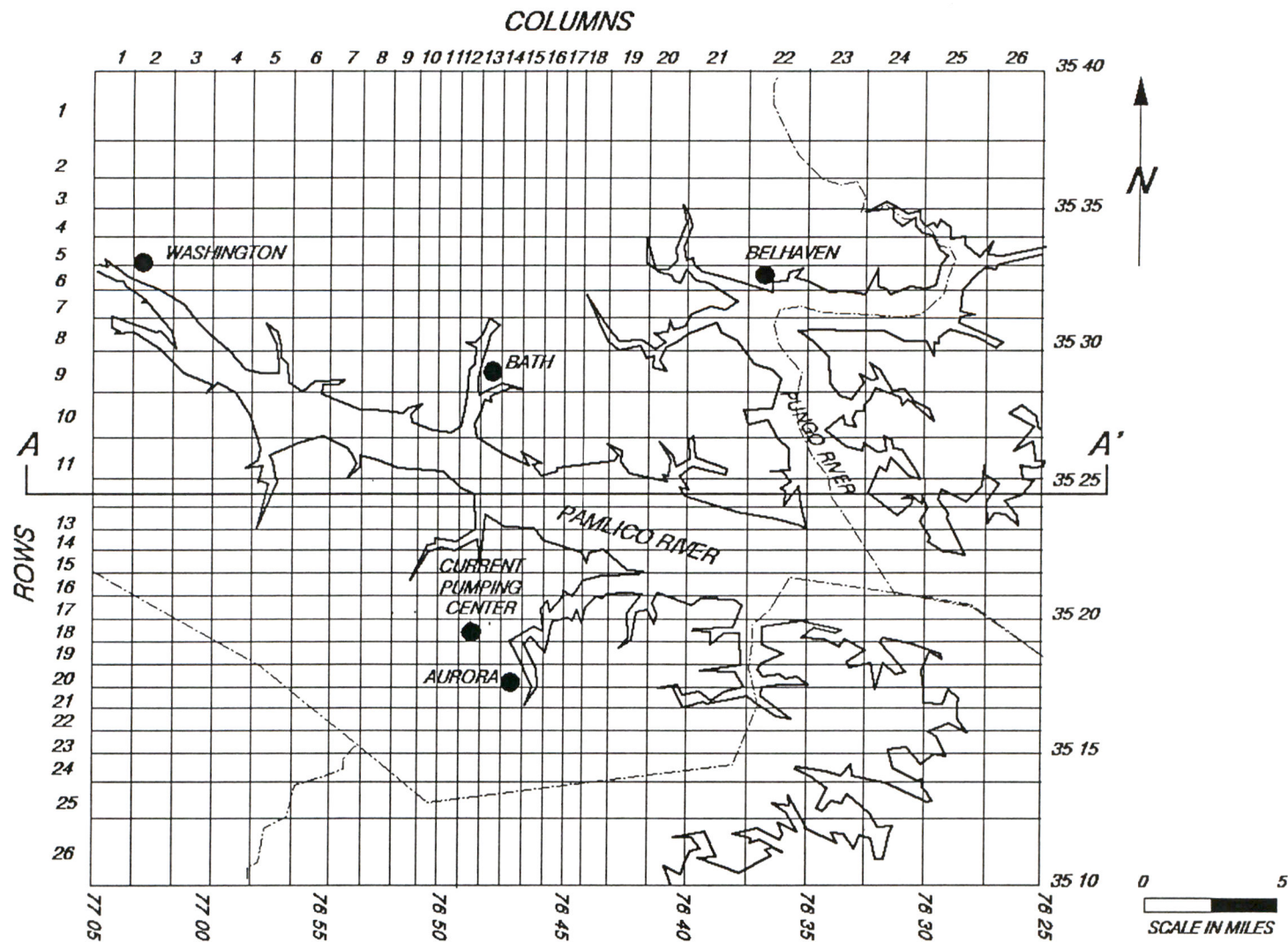


FIGURE 17 - FINITE-DIFFERENCE GRID USED
IN SIMULATIONS

NOTE: REFERENCE CROSS-SECTION
A-A' IN FIGURE 18

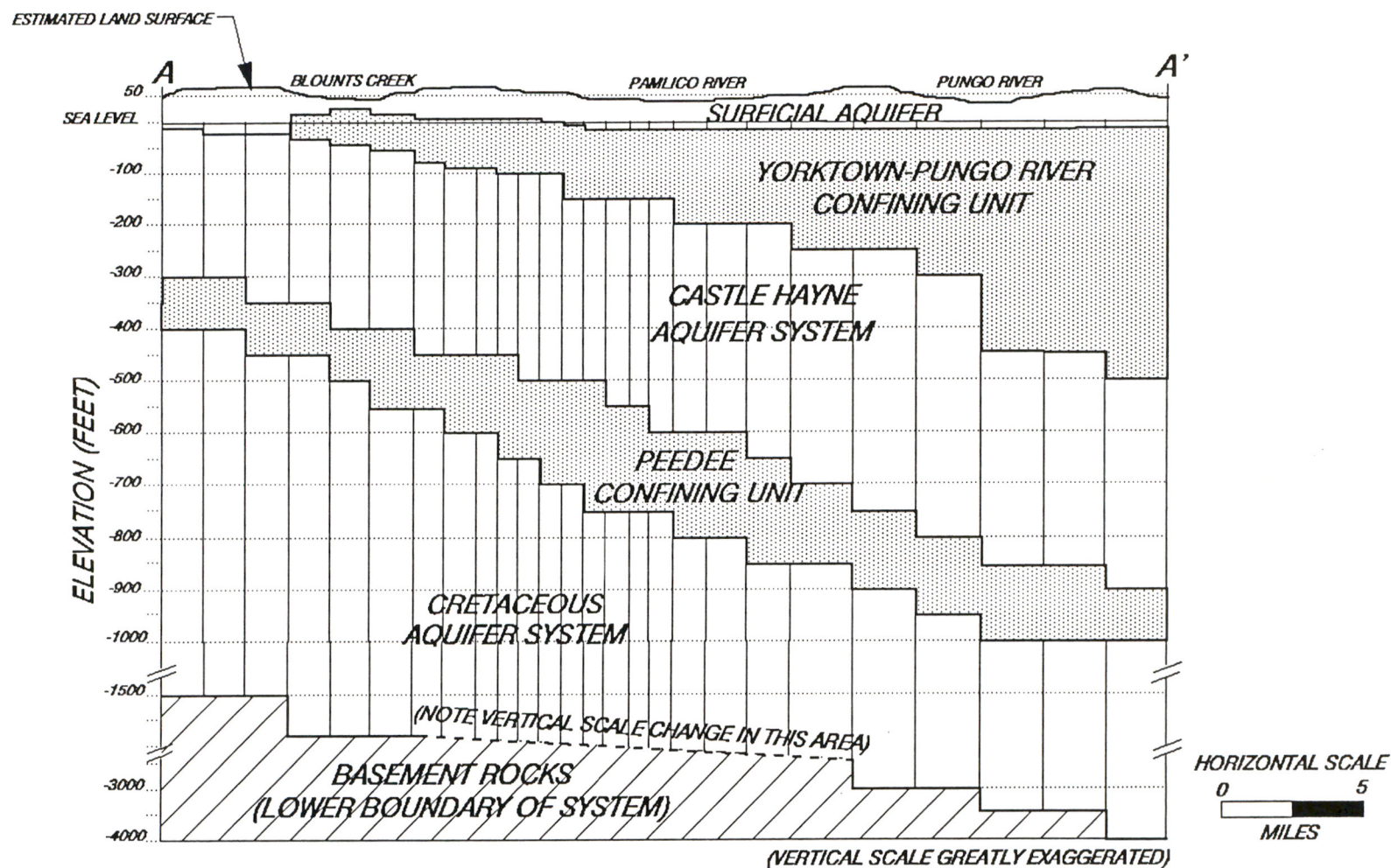


FIGURE 18 - CROSS-SECTION A-A' OF MODEL GRID (FIGURE 17)

the surficial aquifer and vertical leakance of confining layers are also entered into the model. The parameters used in the simulations are described in the following sections.

Top and Bottom Elevations

Only the bottom elevation for layer 1 (surficial aquifer) was entered into the model. The elevation is based on a map of the top of the Yorktown Formation (Joint Study, 1971). The elevation of the bottom of the surficial aquifer ranges from +30 to -10 feet (Figure 19).

The top elevation for layer 2 (Castle Hayne aquifer system) is taken from a map of the top of the upper Castle Hayne unit as reported by the NCDNER (1974). The elevation ranges from 20 to 400 feet below MSL and is presented in Figure 20. The bottom elevation for layer 2 corresponds to a map of the top of the Peedee unit (Joint Study, 1971). The elevation ranges from 200 to 950 feet below MSL (Figure 21).

The top elevation of layer 3 was approximated in much of the area based on a partial map of the elevation of the top of the Black Creek unit (Winner and Lyke, 1981). The elevation ranges from 300 to 1100 feet below MSL (Figure 22). The bottom elevation of layer 3 corresponds to the base of the hydrogeologic system. In this simulation, the top of the Precambrian basement rocks as mapped by Brown, et al. (1972) is considered to be the bottom of the system. The elevation ranges from 1400 to 4500 feet below MSL in the simulation area.

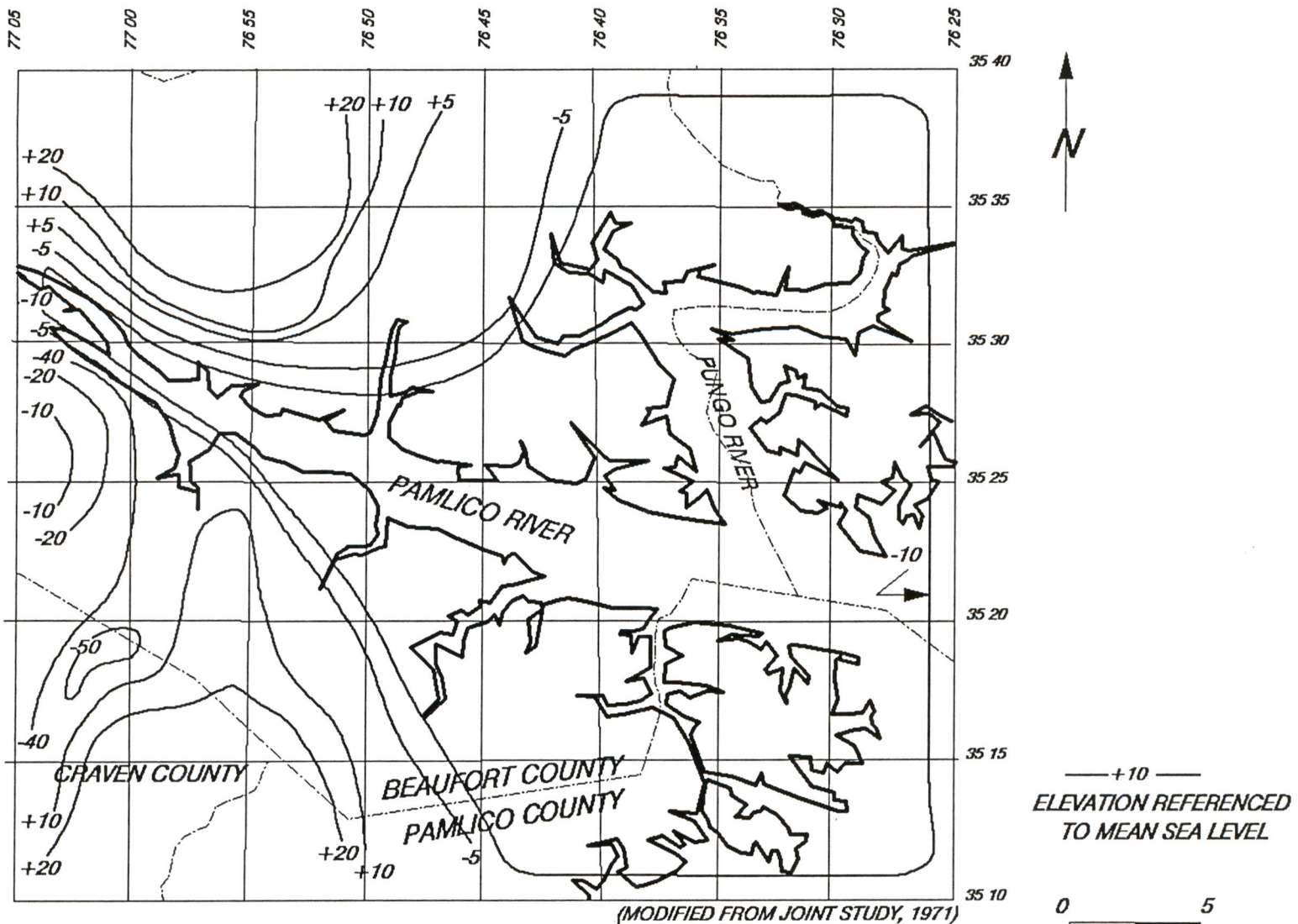
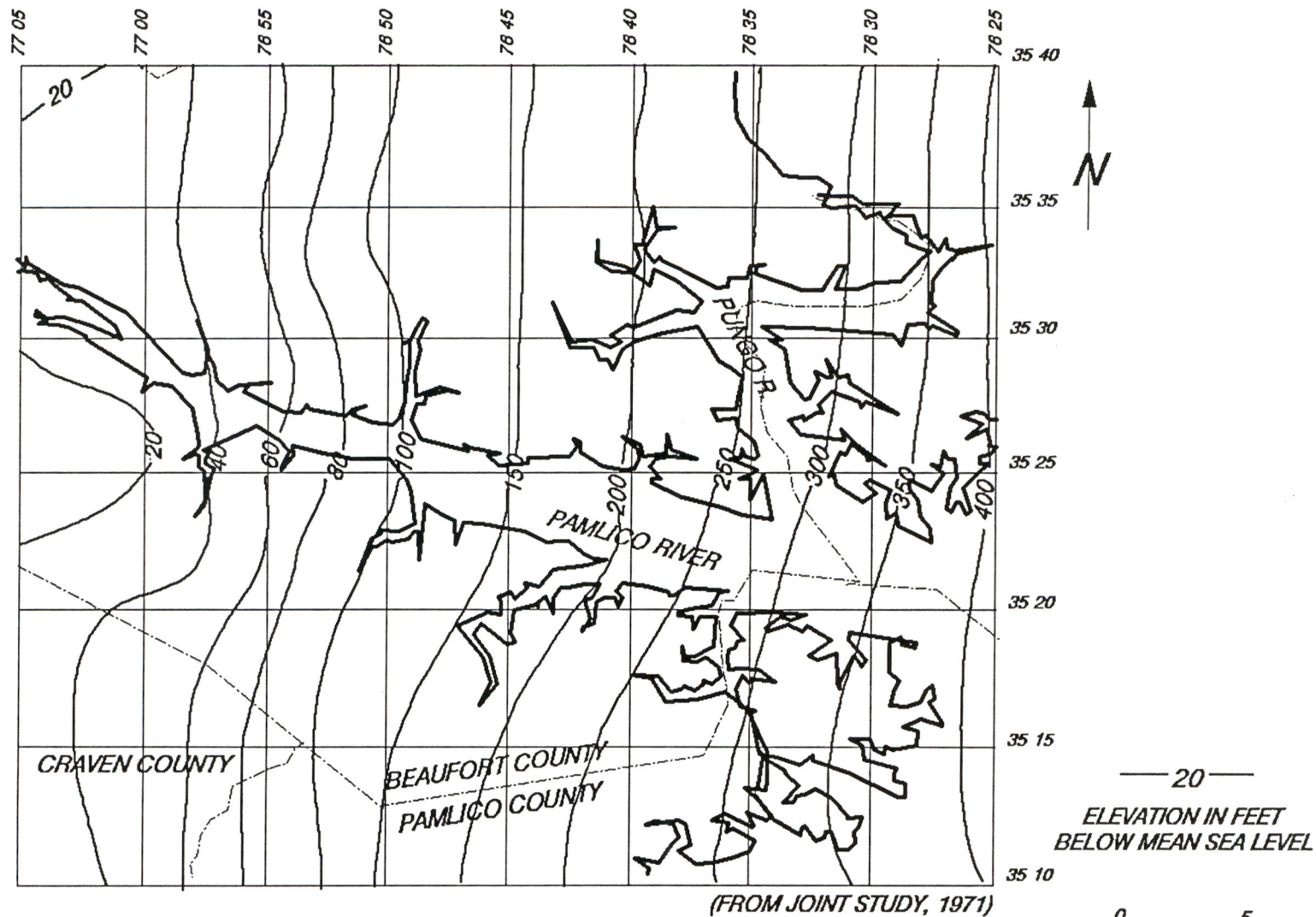
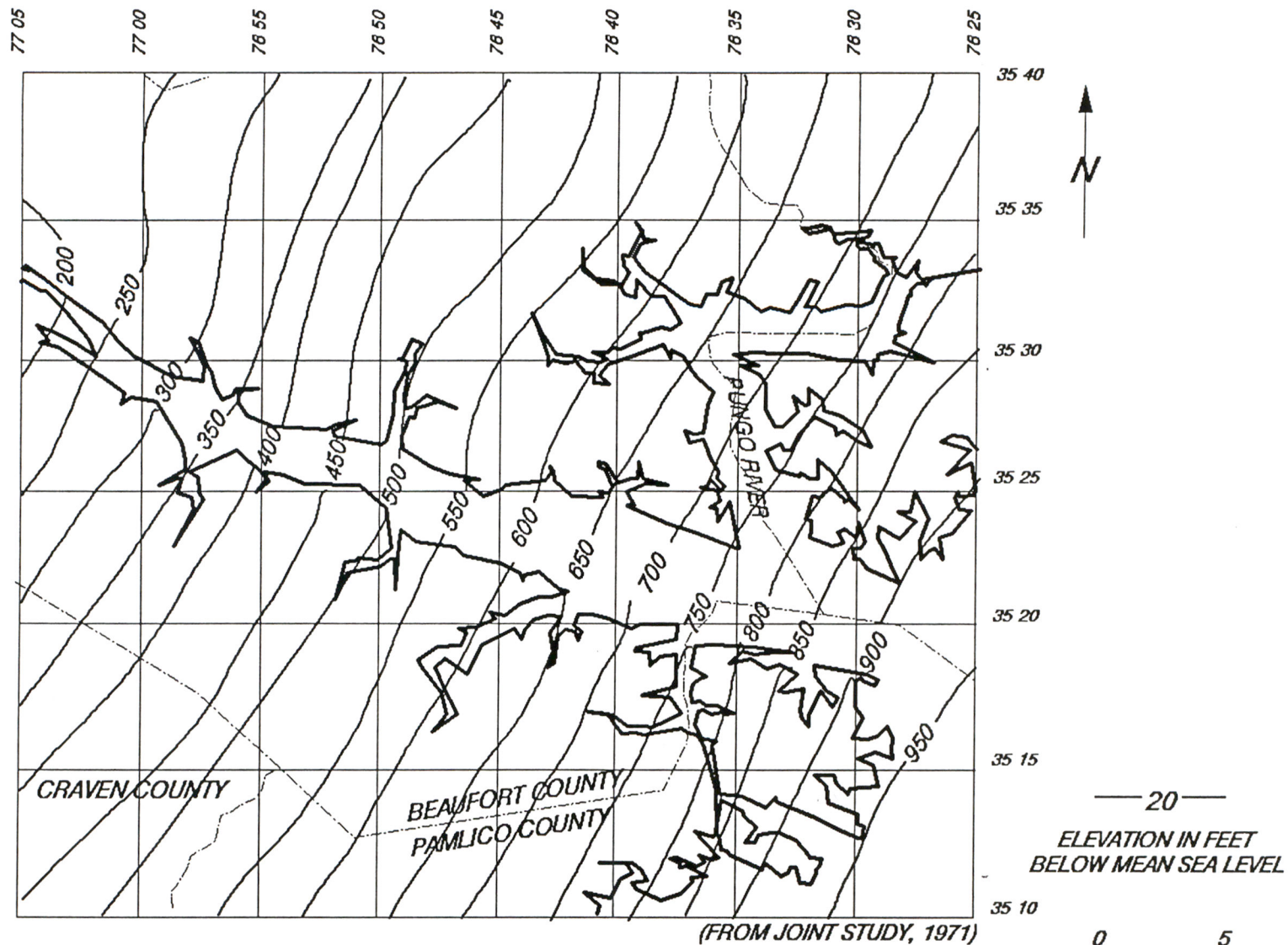


FIGURE 19 - BOTTOM ELEVATION OF SURFICIAL AQUIFER(LAYER 1) USED IN SIMULATIONS. ELEVATION IN EASTERN AREA SET TO -10FEET MSL TO SIMPLIFY MODEL CONFIGURATION IN THIS AREA.



**FIGURE 20 - TOP OF CASTLE HAYNE AQUIFER (LAYER 2)
USED IN SIMULATIONS**



**FIGURE 21 - BOTTOM OF CASTLE HAYNE AQUIFER (LAYER 2)
USED IN SIMULATIONS**

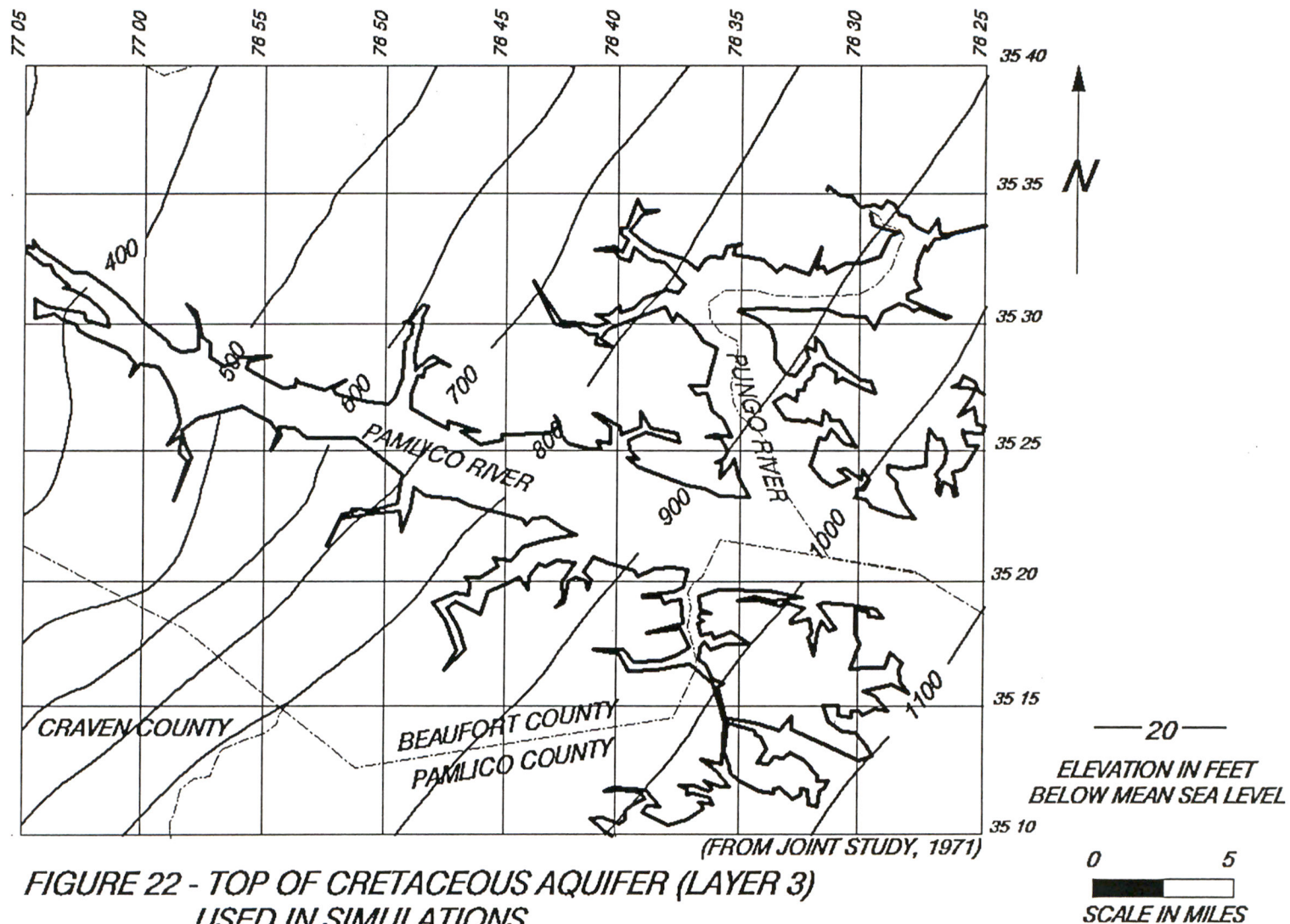


FIGURE 22 - TOP OF CRETACEOUS AQUIFER (LAYER 3)
USED IN SIMULATIONS

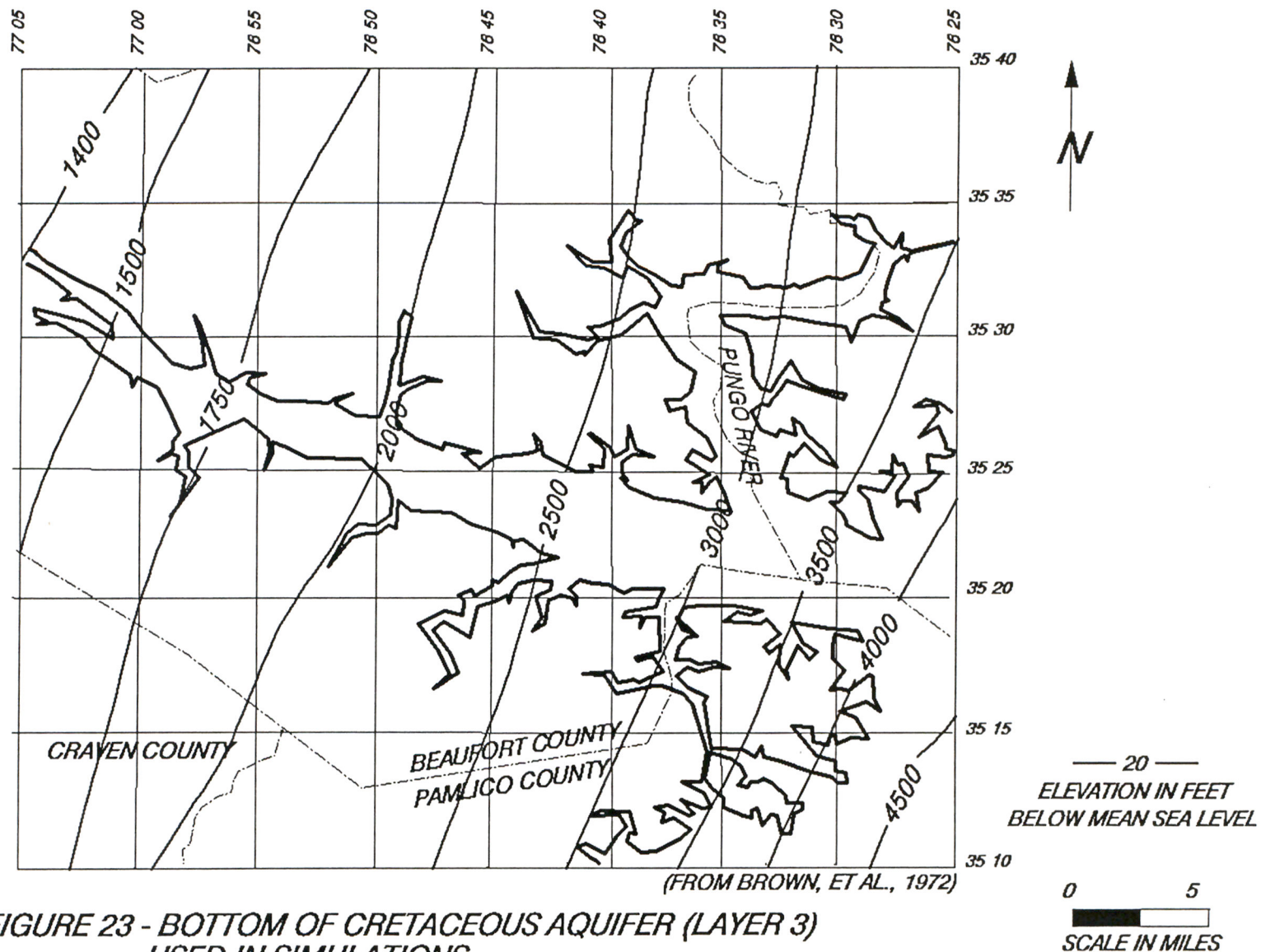


FIGURE 23 - BOTTOM OF CRETACEOUS AQUIFER (LAYER 3)
USED IN SIMULATIONS

(Figure 23).

Typically, the bottom of a layer corresponds to the top of the underlying layer. For the layer elevations previously described, there is a discrepancy between the elevations of the tops and bottoms of adjacent layers. This "gap" is considered to be a confining layer with a thickness (b') corresponding to the value of the discrepancy. These "confining layers" are assigned vertical leakance values as described later in this section.

Recharge

Recharge to the groundwater system occurs in the form of precipitation intercepted by the surficial aquifer. As shown in Figure 3, the recharge reaching the surficial aquifer (after evapotranspiration and runoff) averages 12 inches annually, depending upon the soil characteristics and stream baseflow estimates (Giese, et al., 1991). In MODFLOW, recharge values are expressed in units of feet per day (ft/d).

Much of the model area consists of swamps or pocosins which remain saturated through the majority of the year. This results in most of the precipitation being diverted to the numerous shallow streams in the area as rejected recharge. Since the surficial aquifer is not the principal aquifer of interest for this study, small streams were not included in the flow model. As a result, 12 inches per year is an extremely excessive estimate of recharge for the system. A

recharge value closer to an estimation of deep percolation to the lower aquifers was used. This value was determined during the calibration process for the surficial aquifer. In the absence of discharge areas for the surficial aquifer, recharge values greater than $3/8$ in/yr result in unrealistic potentiometric surface elevations. Therefore, the effective recharge to the surficial aquifer used in this simulation was $8.56\text{E-}05$ ft/d ($3/8$ inches per year).

Hydraulic Conductivity/Transmissivity

Values for hydraulic conductivity (K) were entered on a nodal basis for the unconfined layer (layer 1) in units of ft/d. Hydraulic conductivity is widely variable depending upon the type and degree of consolidation of the sediments in a layer. Much of the eastern and lowland regions in the model area consist of permeable sands and peats. The range of hydraulic conductivity values for layer 1 used in the simulations range from 50 to 80 ft/d (Figure 24).

The transmissivities of the confined layers (layers 2 and 3) are entered on a nodal basis in units of square feet per day (ft^2/d). The transmissivity values for layer 2 used in the simulations range from 10,800 to 55,000 ft^2/d (Figure 25). Values for layer 3 range from 3,000 to 10,000 ft^2/d (Figure 26).

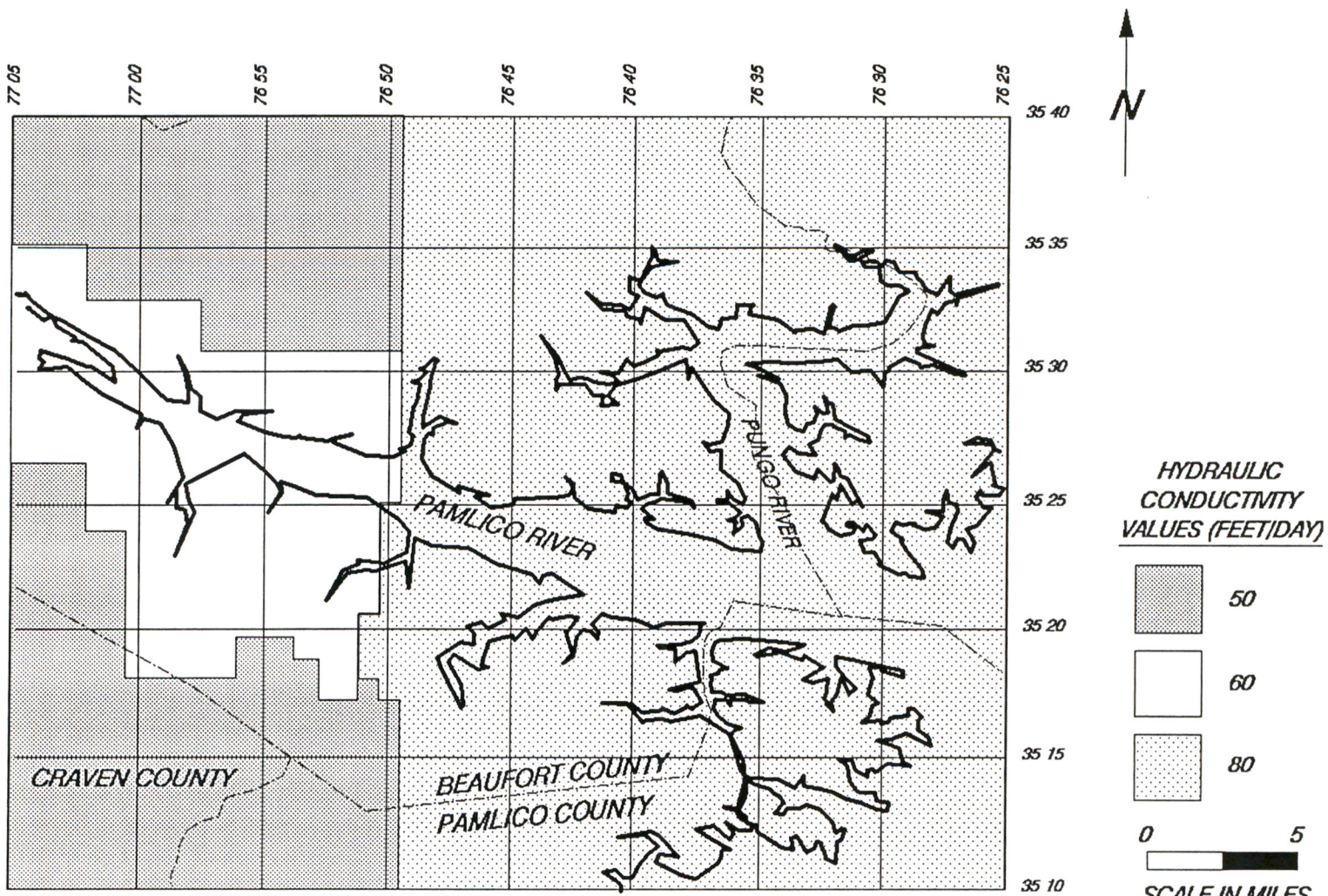
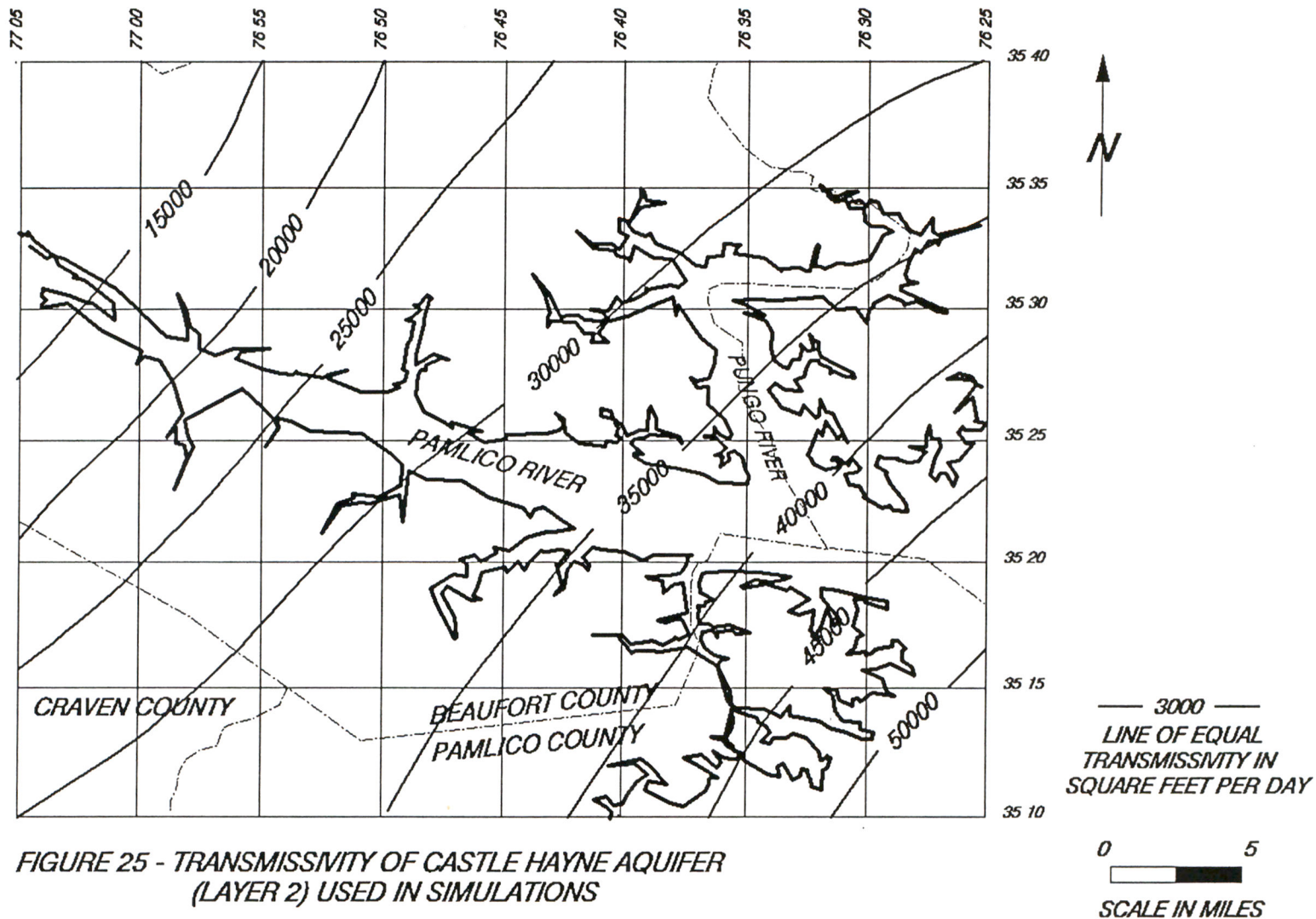


FIGURE 24 - HYDRAULIC CONDUCTIVITY OF THE SURFICIAL AQUIFER (LAYER 1) USED IN SIMULATIONS



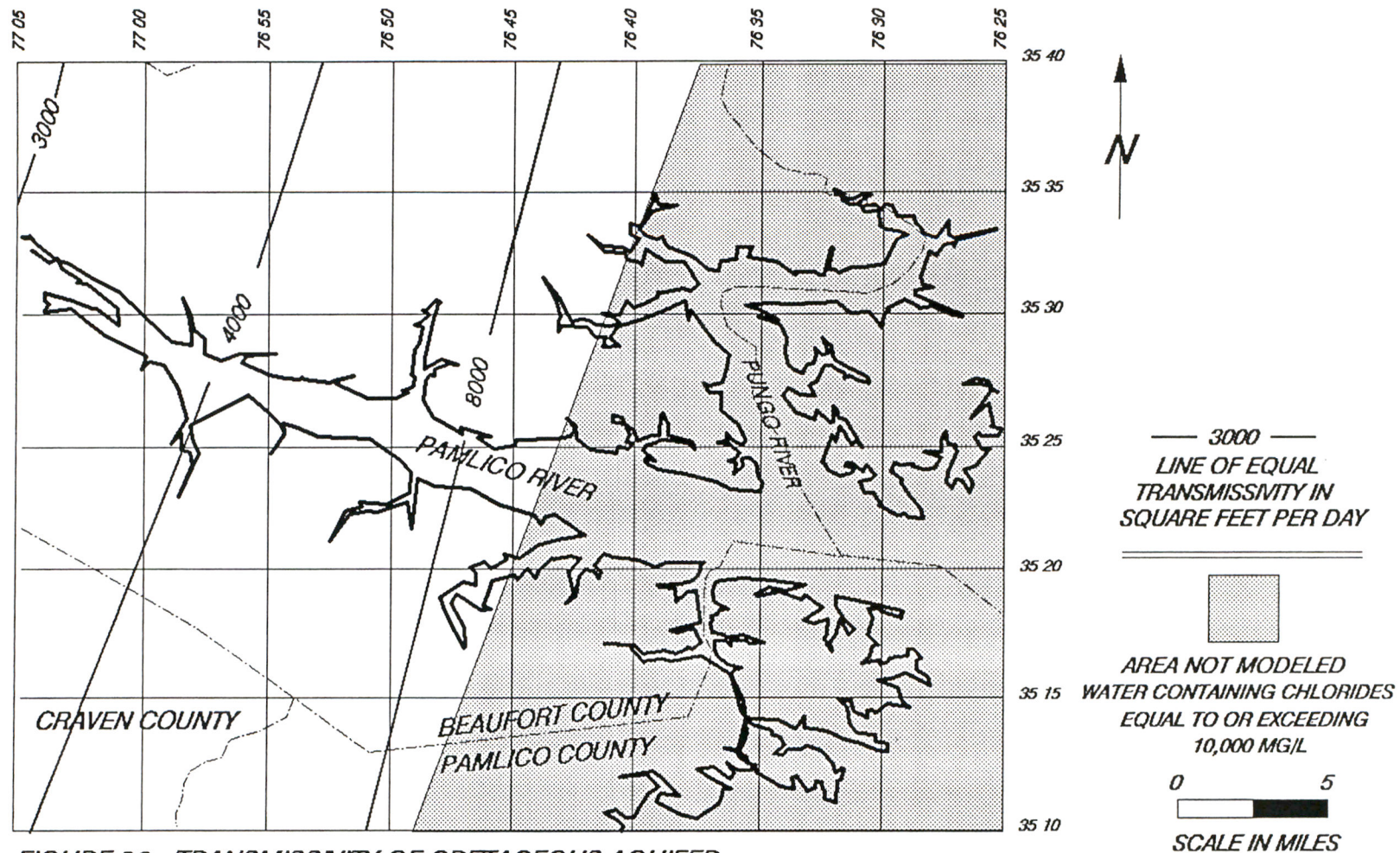


FIGURE 26 - TRANSMISSIVITY OF CRETACEOUS AQUIFER
(LAYER 3) USED IN SIMULATIONS

Vertical Hydraulic Conductivity/Leakance

As previously mentioned, "gaps" present between the bottom of a layer and the top of an underlying layer are considered to be confining layers between the units. Since water movement across confining units is considered to be vertical, a coefficient of vertical leakance (L) must be specified at each node occupied by the confining unit. Leakance is defined as the vertical hydraulic conductivity (K') divided by the thickness (b') of the confining layer resulting in units of day^{-1} .

The variable vertical leakance values assigned to the Yorktown-Pungo River aquitard (confining layer 1) are presented in Figure 27. The leakance value assigned to the entire Peedee aquitard (confining layer 2) is $1.0\text{E-}06 \text{ day}^{-1}$.

Boundary Conditions

Three types of boundary conditions must be considered when describing the hydrogeologic conditions at the boundaries of the grid and in areas of specified head values. Boundary conditions used in this model include constant (specified)-head boundaries, specified-flux boundaries, and no-flow boundaries. Flux is defined as the "volume of fluid crossing a unit cross-sectional area per unit time" (Franke, et al., 1984).

Constant-head boundaries are defined as the coincidence of a boundary surface of an aquifer system with a surface of

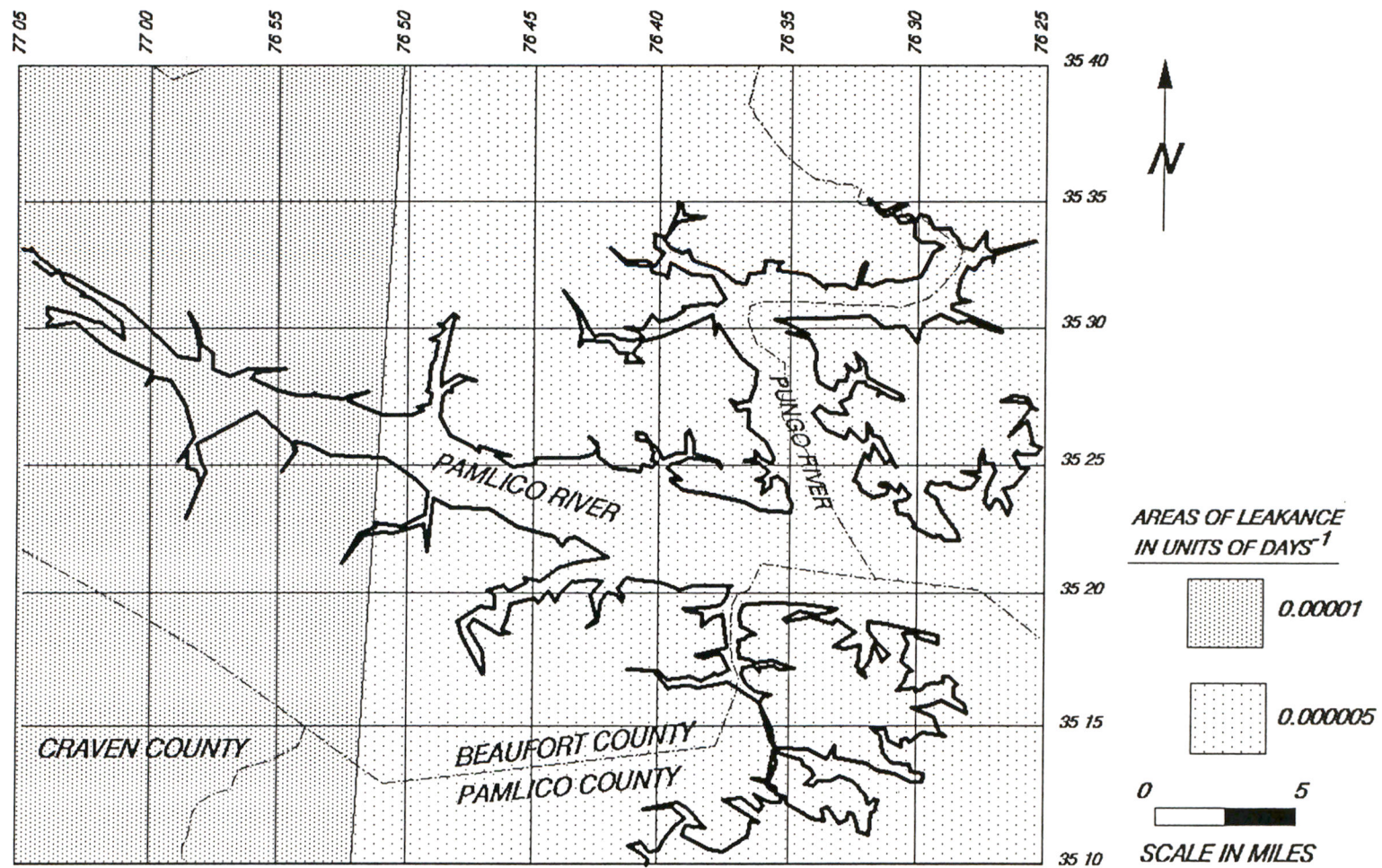


FIGURE 27 - DISTRIBUTION OF VERTICAL LEAKANCE OF YORKTOWN-PUNGO RIVER CONFINING UNIT USED IN SIMULATIONS

essentially constant head (Franke, et al., 1984). For example, since the water level of the Pamlico River remains at sea level, cells affected by the Pamlico River were given a constant head elevation of 0 feet MSL.

Due to the lack of reliable hydrogeologic information on the Cretaceous aquifer system in the model area (i.e. heads and transmissivities); the eastern and western boundaries of the Cretaceous system (layer 3) were also delineated as constant-head boundaries. This designation was important in controlling heads in this layer during transient predictive simulations to evaluate the effects of these head changes on the Castle Hayne aquifer, as described later in this report.

Specified-flux boundaries are defined as boundaries where the flux of water moving across a boundary can be quantified with respect to position and time (Franke, et al., 1984). Specified-flux boundaries were defined for the grid boundaries for layers 1 and 2 (Table 5). The degree of flux crossing the boundary was first calculated using Darcy's Law and modified as necessary during model calibration. The predevelopment water table map (Figure 4) and potentiometric surface map of the Castle Hayne aquifer (Figure 5) were used to estimate fluxes into and out of layers 1 and 2. Positive and negative boundary fluxes were simulated with arrays of recharge and production wells along the boundaries of the model. Since the initial simulation reflects steady-state conditions, positive flux was set to equal negative flux. For layer 2, positive

flux was set to equal negative flux plus the estimated natural discharge to the Pamlico River (± 24 MGD).

Table 5 - Net flux across model boundaries used in computer simulations

Aquifer/Layer	Boundary Flux*, MGD			
	North	South	East	West
Surficial (Layer 1)	+0.63	-0.55	-0.10	+0.02
Castle Hayne (Layer 2)	+9.28	-0.67	-1.73	+14.03
Cretaceous (Layer 3)	--boundary flux not estimated--			

* Negative flux indicates water leaving model area

A **no-flow (impermeable) boundary** is defined as a plane through which streamlines will not cross. Although no earth materials are completely impermeable, a no-flow boundary may exist at the interface of two materials with highly varying hydraulic conductivities (Heath, 1989). Two no-flow boundaries are present in the model system.

One of the no-flow boundaries is the basement rock underlying the coastal plain sediments, corresponding to the bottom of layer 3. Therefore, the relatively small interchange of groundwater between the crystalline basement and the basal section of layer 3 was not considered in this model.

The other no-flow boundary is the interface of freshwater and saltwater containing greater than 10,000 mg/l chloride (Eimers, et al., 1990). Due to the density difference between the saltwater and freshwater, streamlines do not cross this

boundary. The location of the boundary used in the simulation is presented in Figure 28. No withdrawals from the Cretaceous aquifer system (layer 3) were simulated, therefore the position of the saltwater-freshwater interface did not change during the simulations.

Calibration

Calibration of the flow model consists of matching available observed heads in the aquifers with simulated heads calculated by the flow model. A model is calibrated by "modifying the initial parameter estimates within their probable ranges to obtain a better match of computed heads with observed hydraulic heads" (Eimers, et al., 1990).

Calibration of prepumping (steady-state) and pumping (transient) conditions were performed to assess the accuracy of the model. A trial and error method of calibration was used.

Steady-State Calibration

A steady-state calibration was performed to simulate heads in the aquifers prior to pumping. For the Castle Hayne aquifer system (layer 2), "predevelopment" refers to the period prior to pumping at Texasgulf (pre-1965). Heads in the Cretaceous aquifer system (layer 3) were affected by development outside of the model area decades prior to 1965. Therefore, predevelopment for the Cretaceous aquifer actually

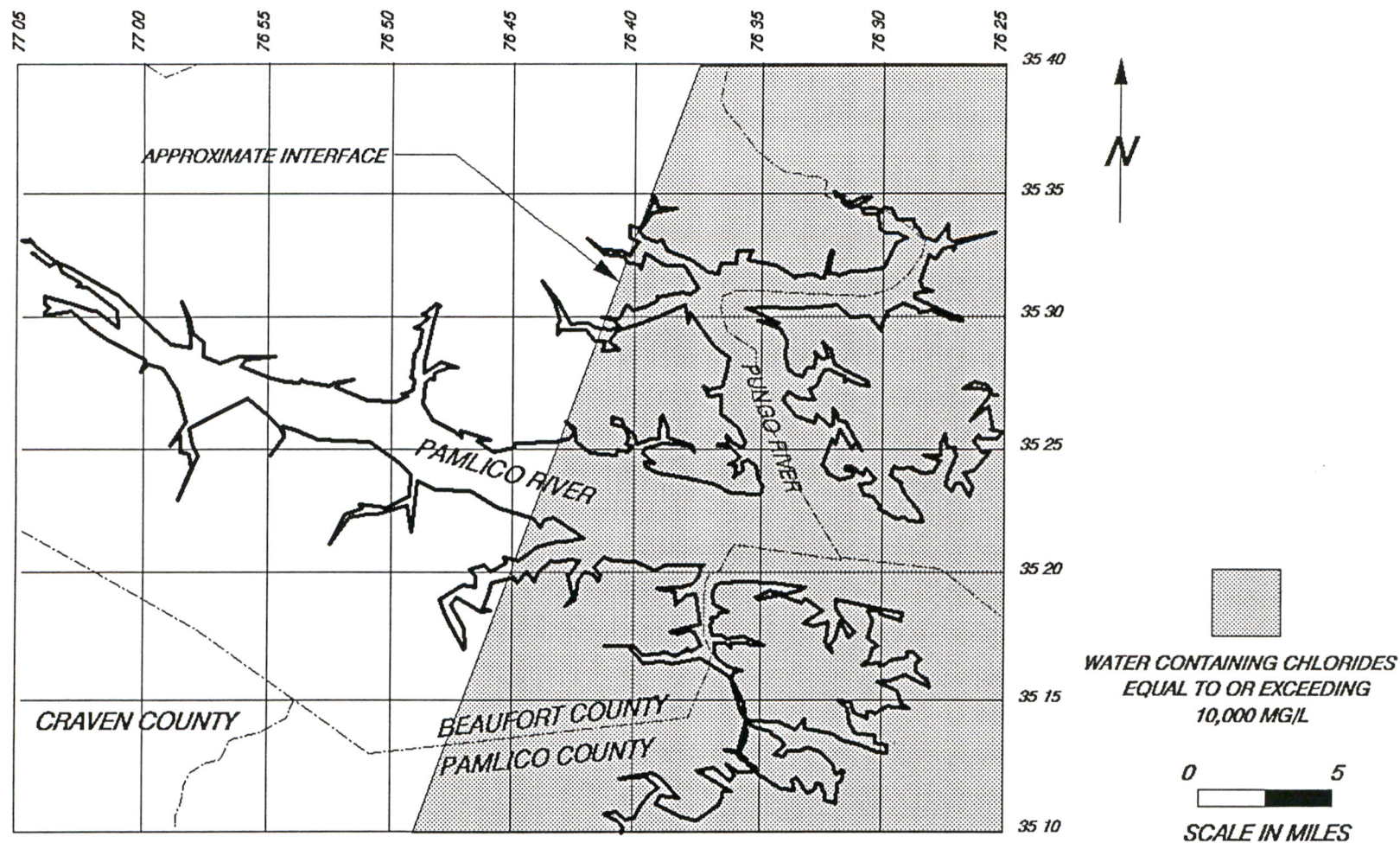


FIGURE 28 - LOCATION OF SALTWATER-FRESHWATER
INTERFACE IN CRETACEOUS AQUIFER (LAYER 3)
USED IN SIMULATIONS

refers to several years prior to 1965. However, exact designation of the term "predevelopment" is not critical to the calibration process.

Since the predevelopment conditions are at steady-state, no groundwater is contributed by storage. Therefore, storage coefficients were not entered for the layers during the steady-state calibration.

The Castle Hayne aquifer (layer 2) is the principal aquifer in the model area. Therefore, the most extensive predevelopment and current water-level data are available for this aquifer. Water-level data for the surficial and Cretaceous aquifers, (layers 1 and 3, respectively) are sparse in the model area for both predeveloped and developed conditions.

The surficial aquifer (layer 1) was calibrated only qualitatively due to the variability and lack of dependable water levels for the surficial aquifer. Hydraulic parameters were adjusted in order to approximate the shape of the water table as presented in Figure 4. The range of observed prepumping heads in the surficial aquifer is from 0 feet MSL at the Pamlico River/Sound to approximately 45 feet above MSL. Simulated heads range from 0 to 43 feet above MSL (Figure 29).

The Castle Hayne aquifer (layer 2) was first qualitatively calibrated by comparing the observed prepumping potentiometric surface map of the Castle Hayne aquifer (Figure 5) to the simulated potentiometric surface map for layer 2

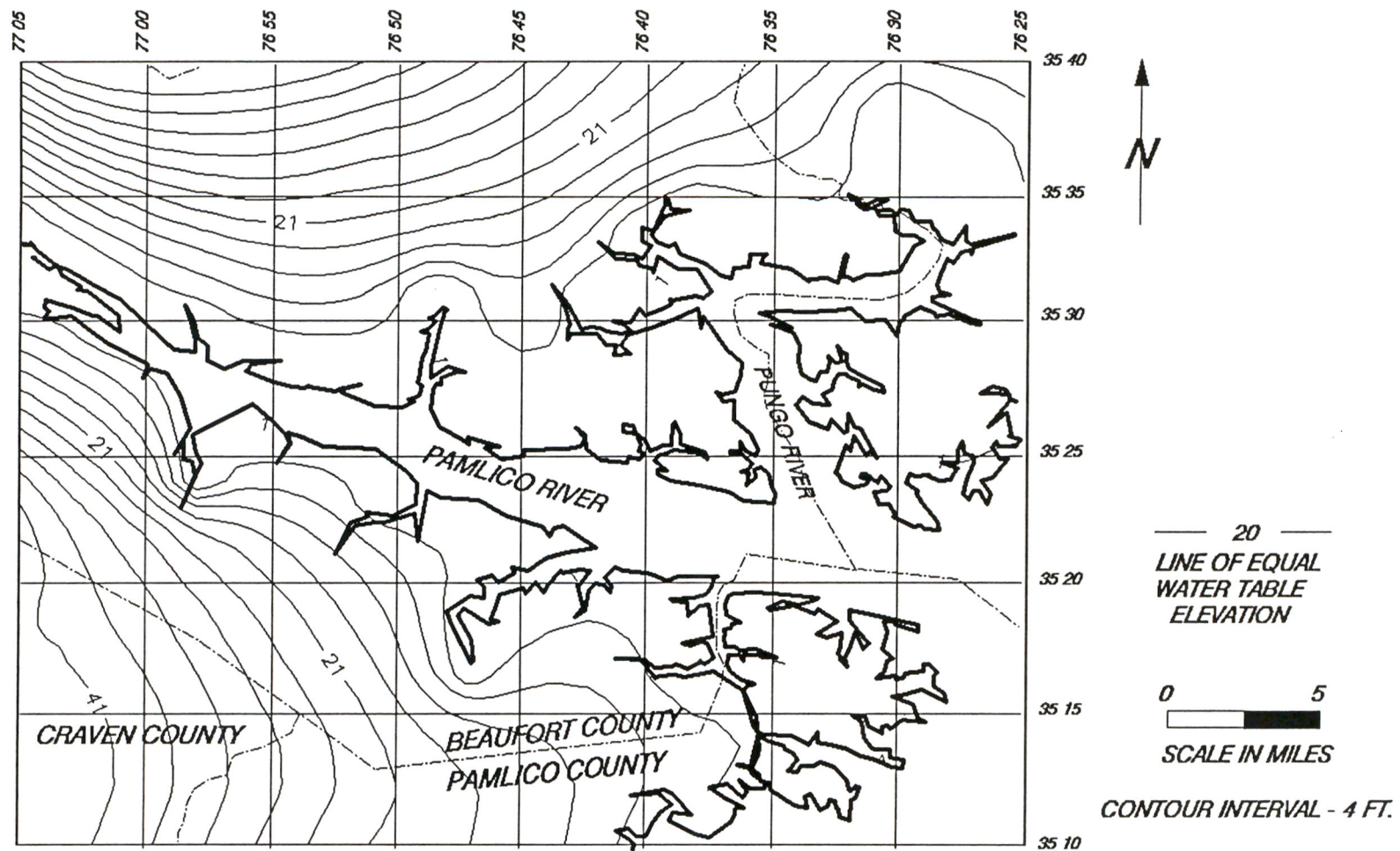


FIGURE 29 - SIMULATED PREDEVELOPMENT (STEADY-STATE)
WATER TABLE MAP (LAYER 1)

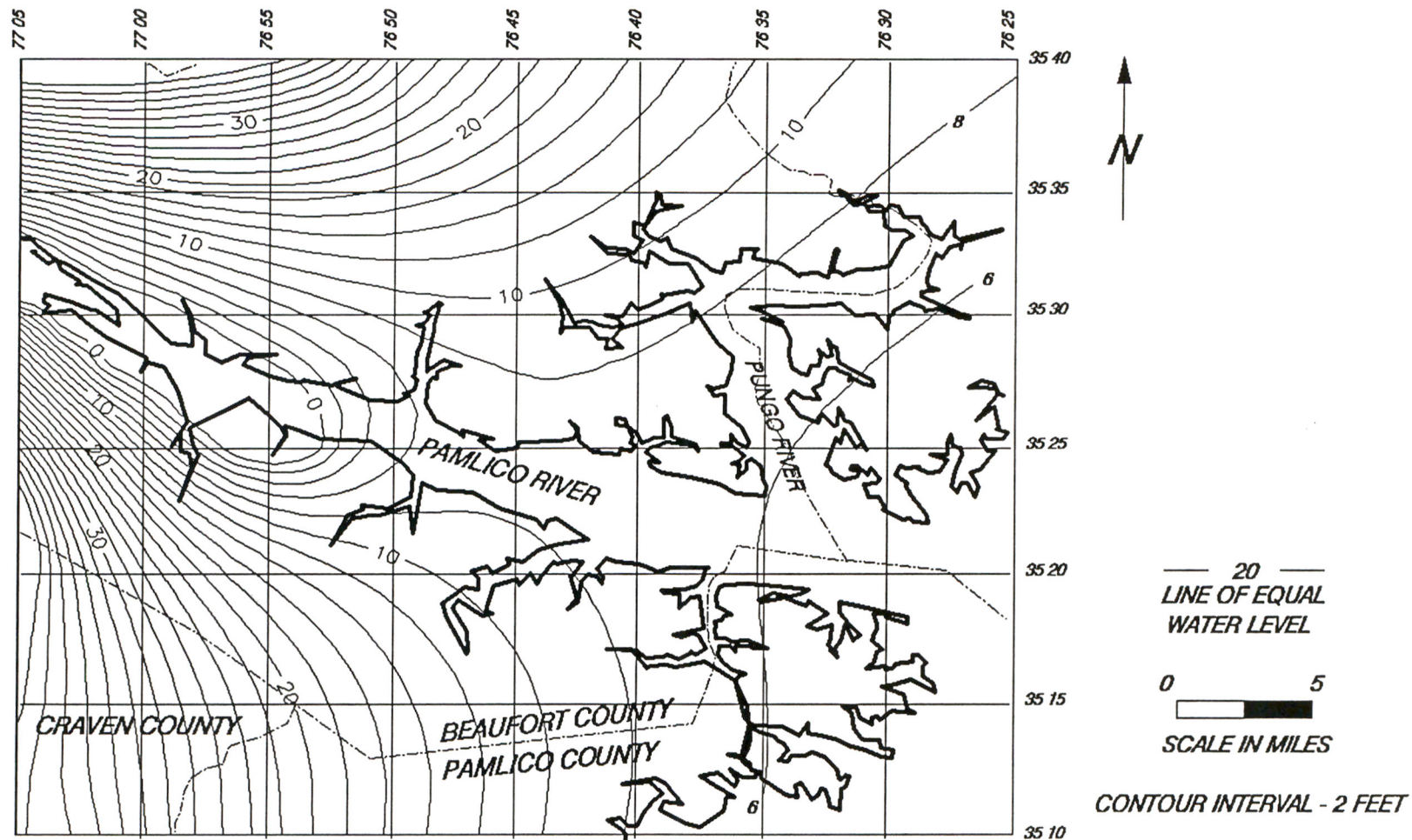


FIGURE 30 - SIMULATED PREDEVELOPMENT (STEADY-STATE) POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2)

(Figure 30). A quantitative evaluation was then performed by comparing 20 head measurements as reported by the NCDNER (1974), to the simulated heads at each appropriate node. The locations of the 20 wells used in the steady-state calibration are presented on Figure 31. A graphical comparison of the observed and simulated heads for the Castle Hayne aquifer (layer 2) is presented on Figure 32.

The mean difference between the observed and simulated heads was 1.35 feet. The root mean squared (RMS) error was also calculated for this calibration. RMS is defined as an average of the squared differences in observed and simulated heads and is considered to be the best measurement of errors if normally distributed (Anderson and Woessner, 1992). RMS is typically used by the U.S. Geological Survey for modeling projects, and generally, an RMS error of under 5 feet is acceptable for a model of this type (Eimers, personal communication, 1992). The RMS error calculated for the steady state calibration was 1.68 feet.

Little or no information exists on the prepumping or current heads for the Cretaceous aquifer (layer 3) in the model area. Therefore, a numerical calibration of the observed versus simulated heads was not possible. Parameters were adjusted in order to simulate heads in layer 3 which are comparable to the estimated predevelopment potentiometric surface configuration of the Black Creek unit. The simulated predevelopment potentiometric surface map for layer 3 is

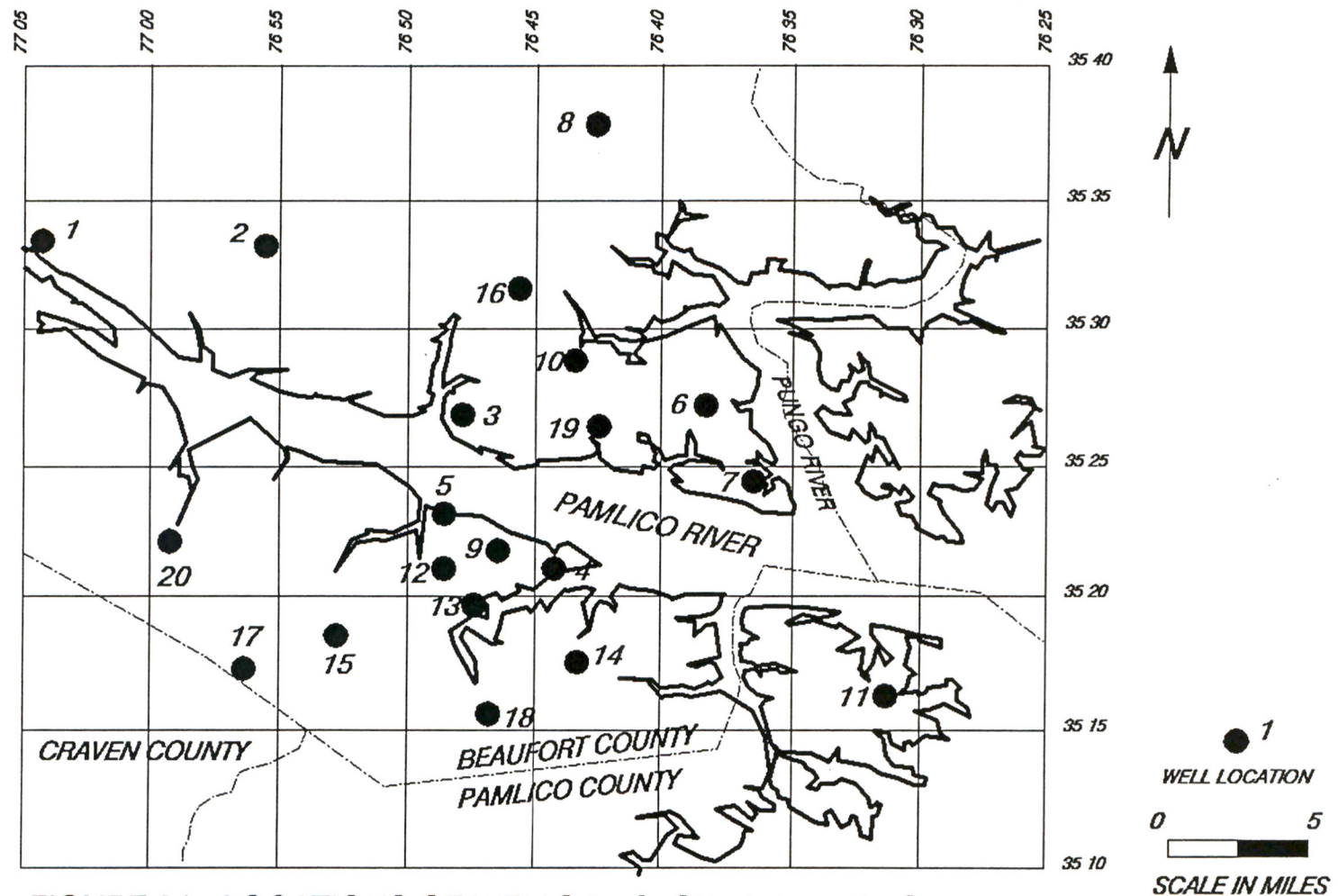
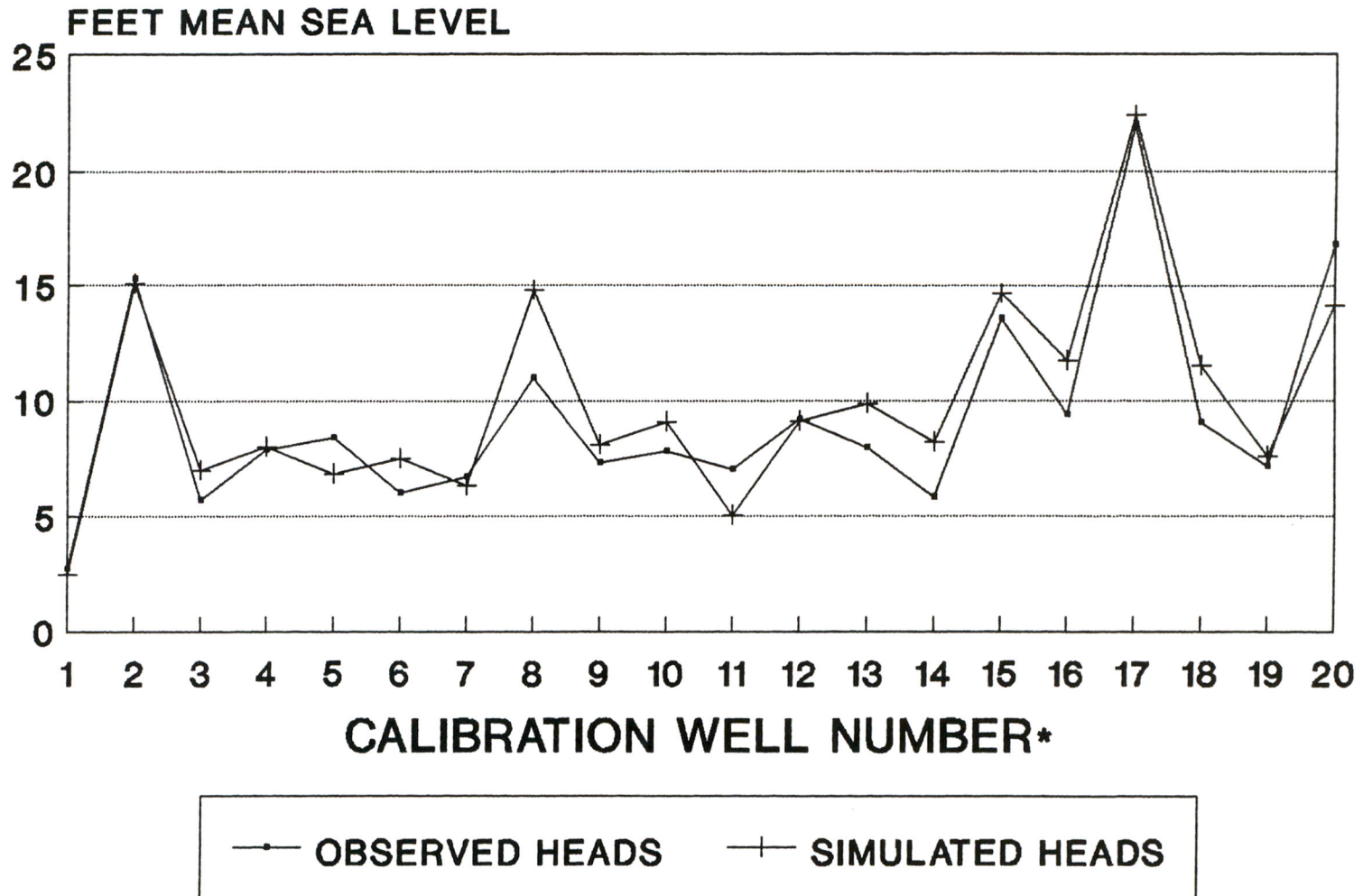


FIGURE 31 - LOCATIONS OF WELLS IN CASTLE HAYNE AQUIFER
(LAYER 2) USED IN STEADY-STATE CALIBRATION

**FIGURE 32 - STEADY STATE CALIBRATION
FOR CASTLE HAYNE SYSTEM (LAYER 2)**



* SEE FIGURE 31 FOR WELL LOCATIONS

presented in Figure 33. The estimated and simulated flow patterns for the Cretaceous aquifer are from west to east with hydraulic gradients of 0.95 and 1.03 feet per mile, respectively.

Transient Calibration

In order to assess the reliability of the calibrated, steady-state model to simulate current and predicted conditions, calibration of transient simulations was also performed.

The heads resulting from depressurization pumping at Texasgulf were simulated from 1965 to present (1992). In transient simulations, pumping stresses are imposed on initial heads calculated during the steady-state simulations and ground water is contributed from aquifer storage. Storage coefficients of 0.15 and $1.0\text{E-}05$ (unitless) were entered for the unconfined unit and confined units, respectively.

The pumping rates and pumping center locations at Texasgulf are variable and depend upon the depth and thickness of the ore, and transmissivity of the Castle Hayne aquifer. Because the Castle Hayne aquifer has been observed to achieve steady-state typically after less than one year of pumping at a new location, short, numerous stress periods were not necessary. The transient simulation therefore utilized 3 arbitrary stress periods of 10, 10, and 8 years, corresponding to 1965-1974, 1975-1984, and 1985-1992. For calibration

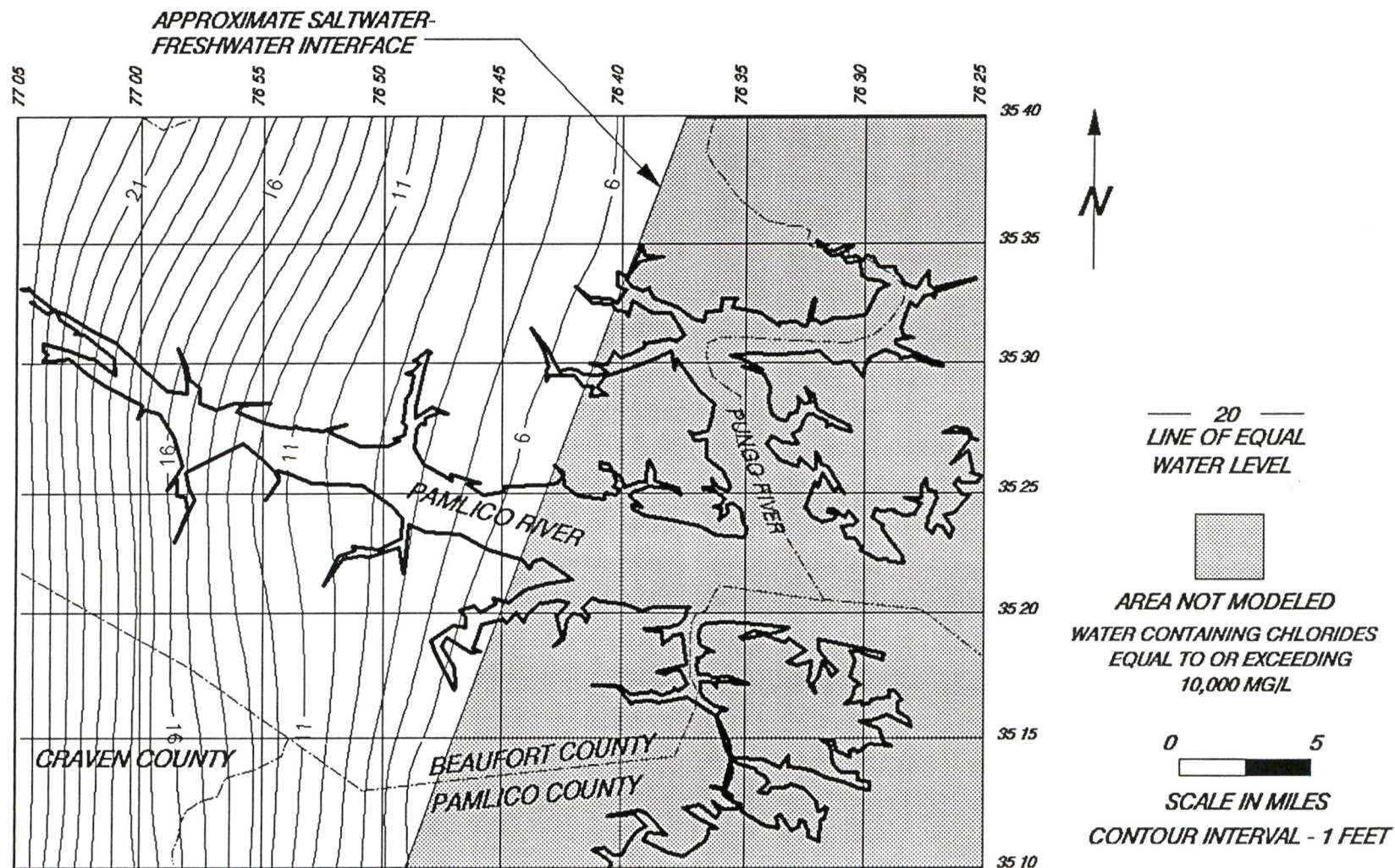


FIGURE 33 - SIMULATED PREDEVELOPMENT (STEADY-STATE) POTENTIOMETRIC SURFACE OF THE CRETACEOUS AQUIFER (LAYER 3)

purposes, the mean pumping rates for these stress periods were used in the simulation. Pumping rates of 56.5, 58.8, and 53.4 MGD were used for the three stress periods, respectively. The average annual depressurization pumpage is presented in Figure 34.

The locations of pumping centers vary depending on the active mining location. The size of the model cells in the mine vicinity (0.82 mi.^2) prevents accurate representation of each individual mine block. Therefore, the pumping cells designated in the model reflect the general vicinity of the active pumping centers during the three stress periods. The locations of these pumping centers are presented in Figure 35.

Two significant adjustments to the model were required for the transient simulations. These adjustments were related to 1) the reduction of natural discharge of the Castle Hayne aquifer to the Pamlico River, and 2) changes in specified-flux boundaries due to the propagation of the cone-of-depression to the grid borders.

The natural discharge to the Pamlico River was estimated using Darcy's Law and predevelopment equipotential lines of the Castle Hayne aquifer in the vicinity of the river near Washington. It was calculated that the Castle Hayne aquifer discharged approximately 24 MGD along a 15 mile stretch of the Pamlico River prior to depressurization pumping. Based on later potentiometric surface maps produced after establishment of a steady-state cone-of-depression, the average natural

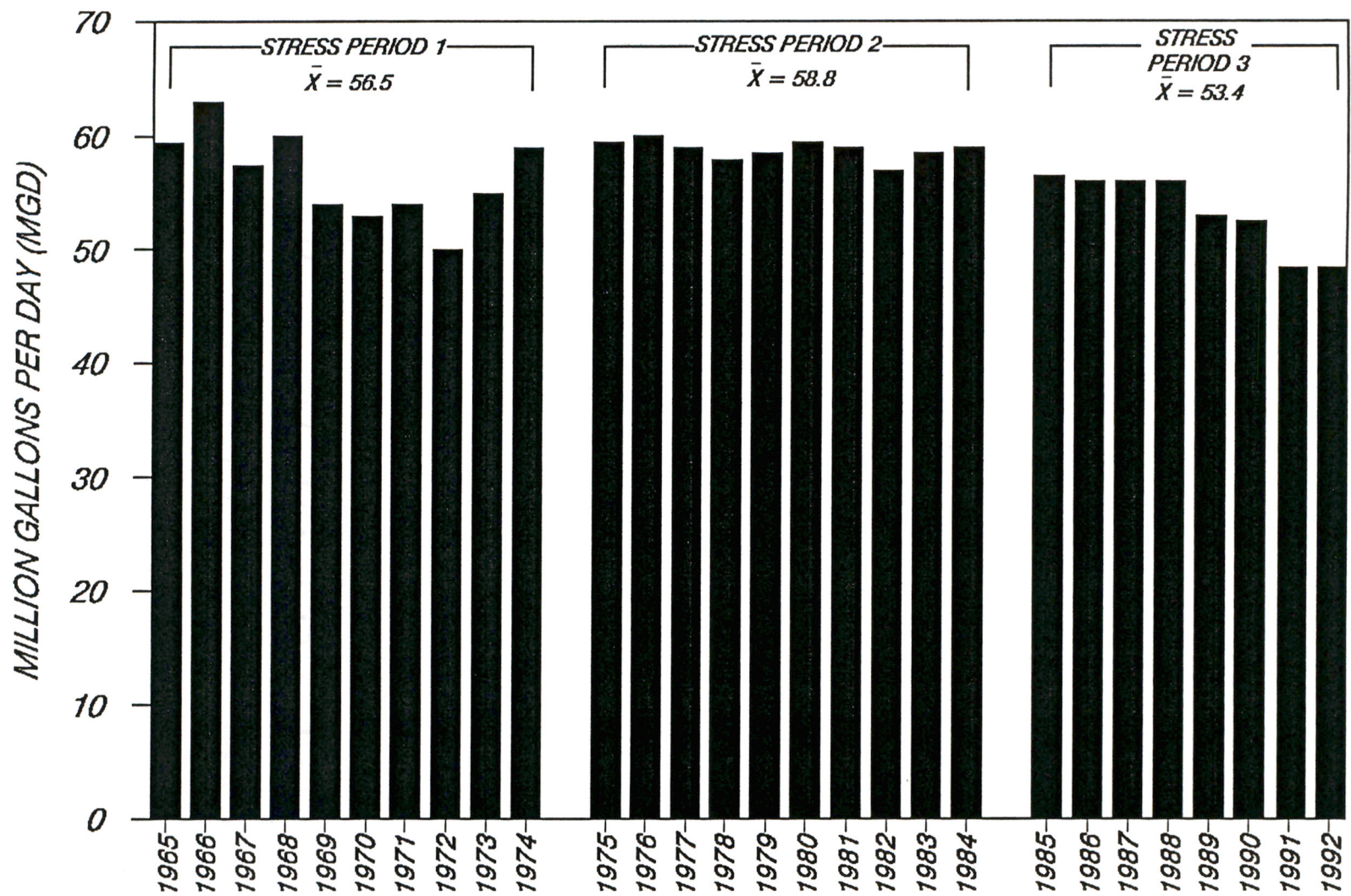


FIGURE 34 - AVERAGE ANNUAL DEPRESSURIZATION PUMPAGE
USED IN TRANSIENT SIMULATIONS

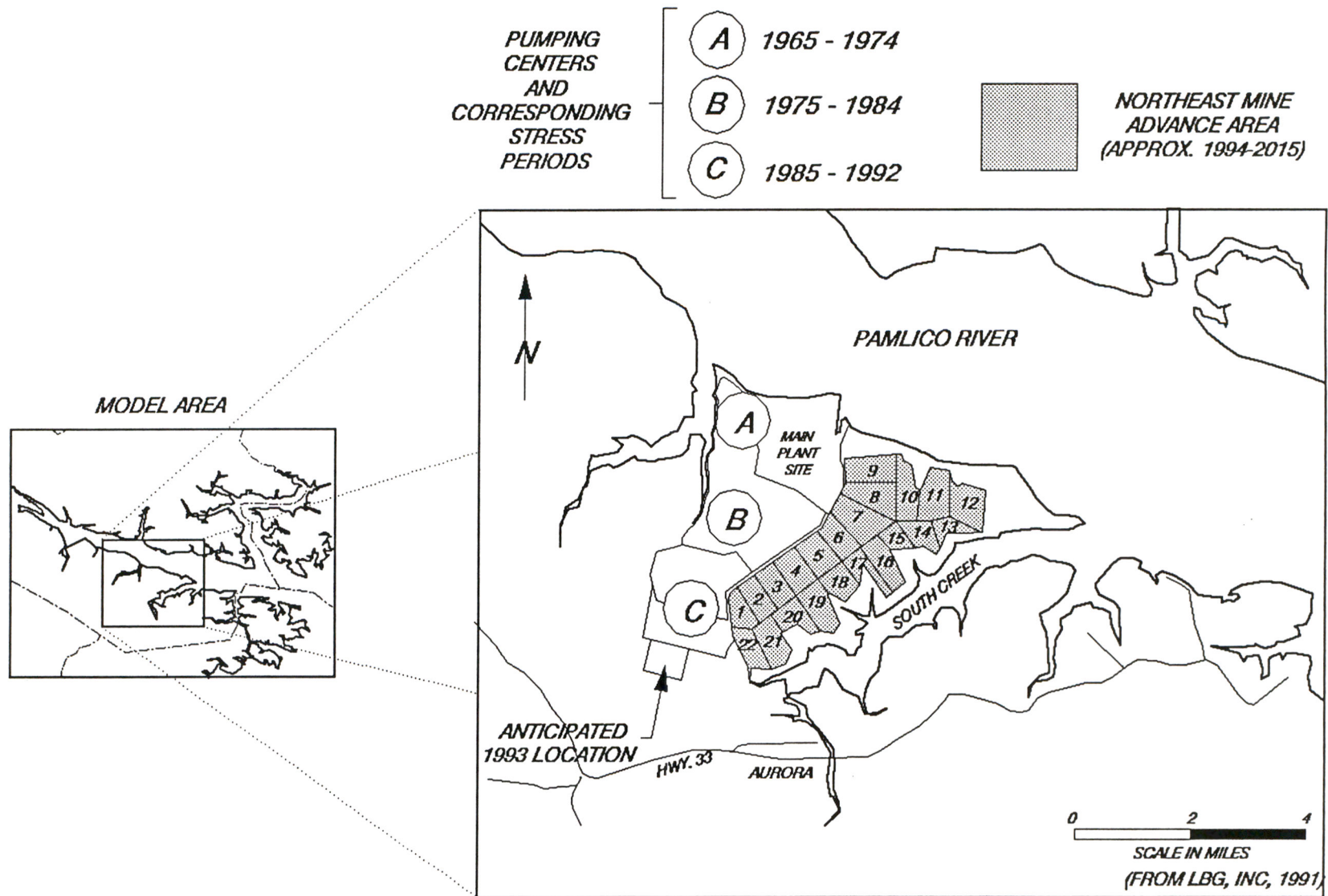
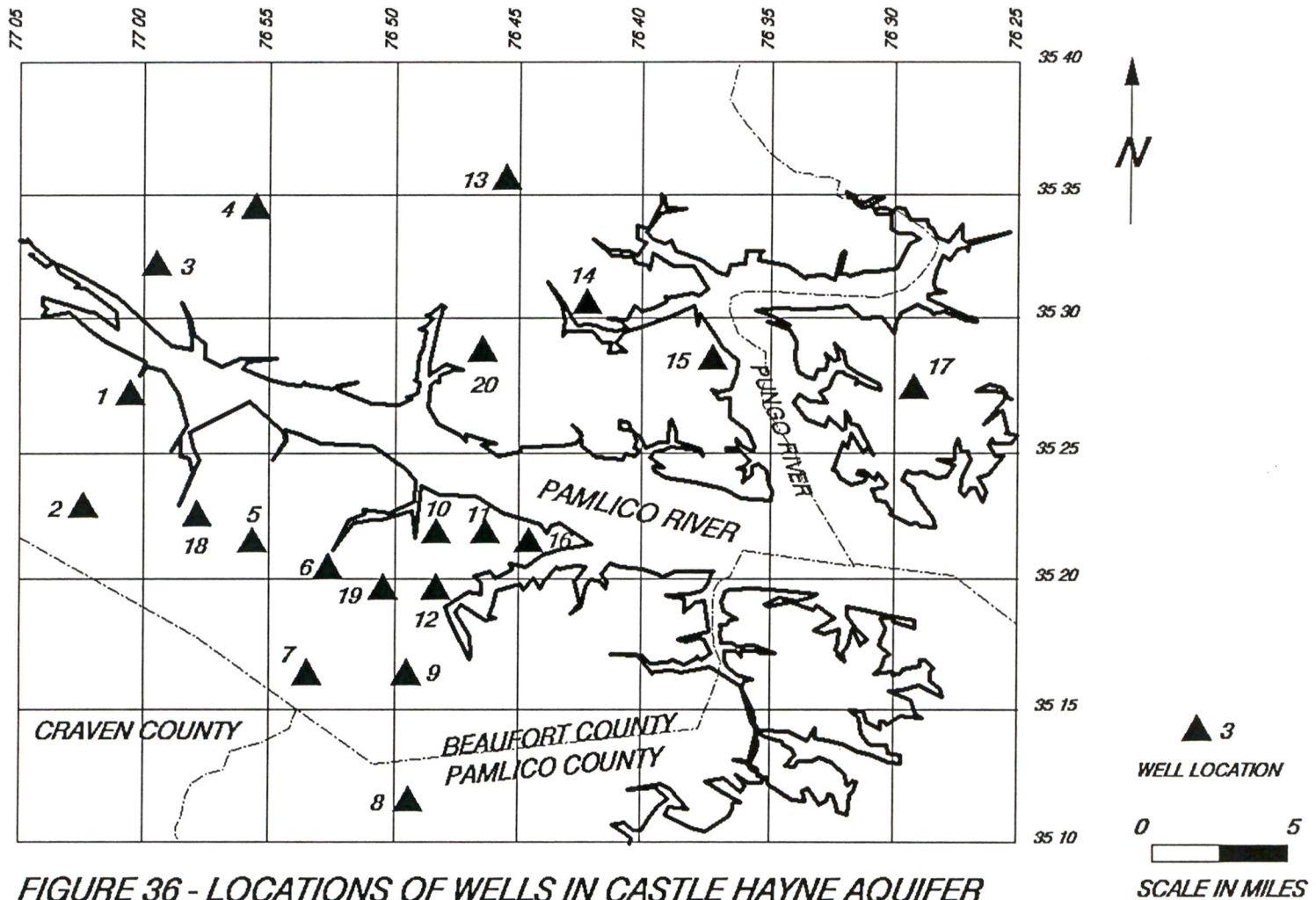


FIGURE 35 - LOCATIONS OF PUMPING CENTERS USED IN TRANSIENT SIMULATIONS

discharge to the Pamlico River was reduced to approximately 7.5 MGD. The model was modified to reflect this change in discharge during the transient simulations by reducing the number and volume of discharge cells in layer 2 in this area.

As shown in Table 5, the specified-flux boundaries for the southern and eastern borders of layer 2 were -0.67 and -1.73 MGD, respectively. The negative numbers indicate a net outward movement of water from the model area during prepumping conditions. After imposition of a large stress on the aquifer such as depressurization pumping, the flow at these boundaries shifted to a net inward flow. Since the degree of net inflow could not realistically be quantified during predictive simulations; the southern, eastern, and a segment of the northern boundaries were given constant head values in order to reduce excessive drawdowns at the grid borders. The constant head values range from +1 to -3 feet MSL, depending upon the extent of the cone-of-depression.

As specified in the steady-state calibration section, reliable heads in the surficial and Cretaceous aquifers were not available, and numerical calibrations of heads in these aquifers were not performed. A numerical calibration was performed only for the Castle Hayne aquifer (layer 2) after the final stress period (1992). The observed heads at 20 well locations (Figure 36) for the Castle Hayne aquifer in 1991-1992 were compared to the corresponding simulated heads. The mean difference and RMS error for the observed and simulated



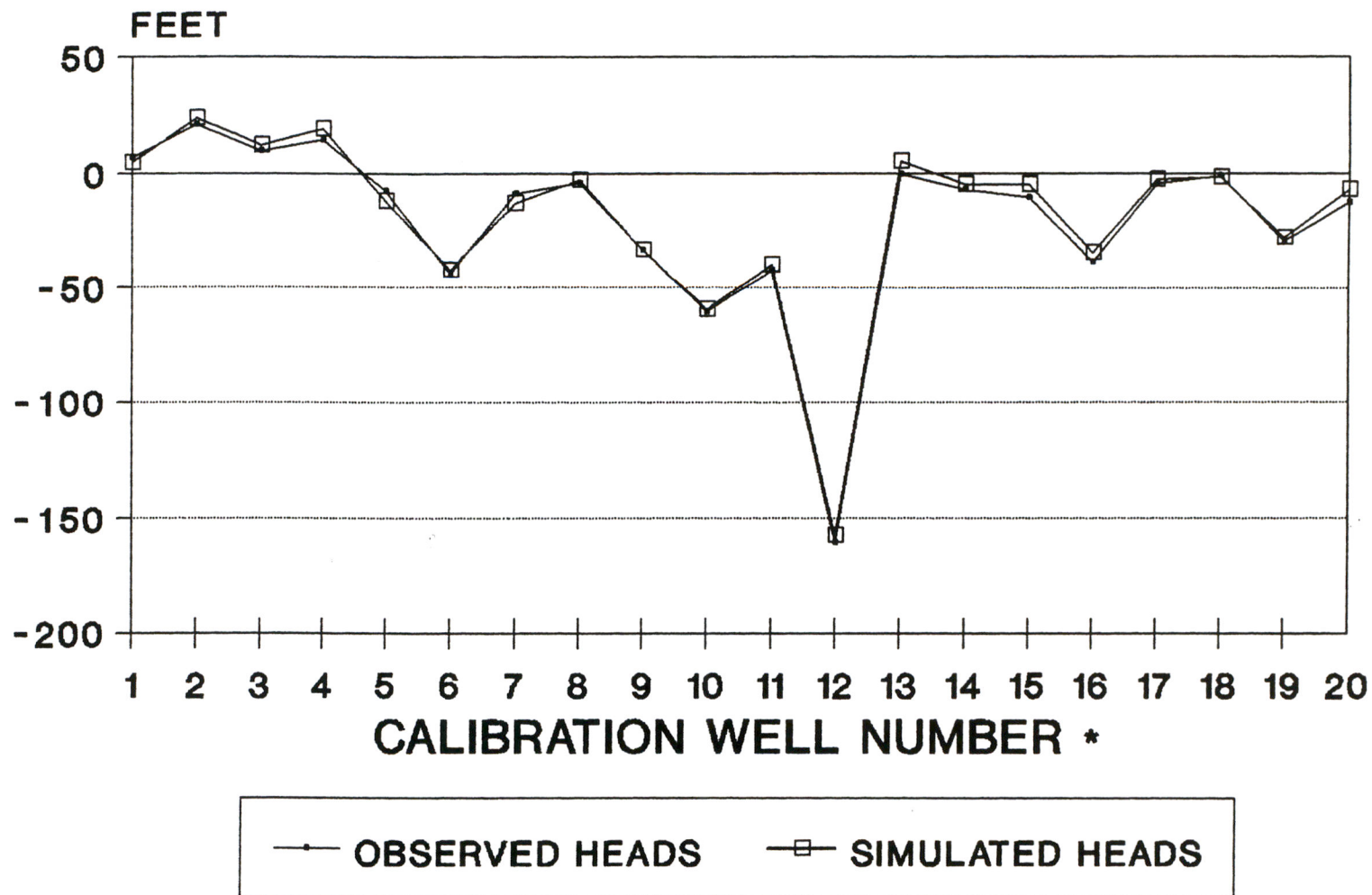
heads during the calibration were 2.62 and 3.17 feet, respectively. A graph illustrating the observed-simulated head differences is presented in Figure 37 and a map of the simulated 1992 potentiometric surface of the Castle Hayne aquifer (layer 2) is presented on Figure 38.

In order to evaluate the accuracy of the model in a specific area for the duration of the stress periods, the hydrograph for a well in the Castle Hayne aquifer that has been monitored continuously since before depressurization pumping was compared to a simulated hydrograph for the model cell corresponding to this well. The well used in this comparison is the U.S. Geological Survey observation well NC-13 located near Aurora, NC. The graphical comparison of the observed/simulated hydrographs is presented in Figure 39. This figure indicates that the observed head change over time was favorably reproduced in the transient simulation.

Sensitivity Evaluation

In order to assess variations in heads caused by errors in estimating hydrologic parameters, a sensitivity evaluation was performed for each of these parameters. This evaluation was performed by modifying (one at a time) each of the parameters (transmissivity, vertical hydraulic conductivity, boundary fluxes, leakance, and storage coefficients) by + and - 50 and 90 percent. The results of the analysis are presented on Table 6.

**FIGURE 37 - TRANSIENT CALIBRATION
FOR CASTLE HAYNE AQUIFER (LAYER 2)**



*Calibration Well Locations on Figure 36

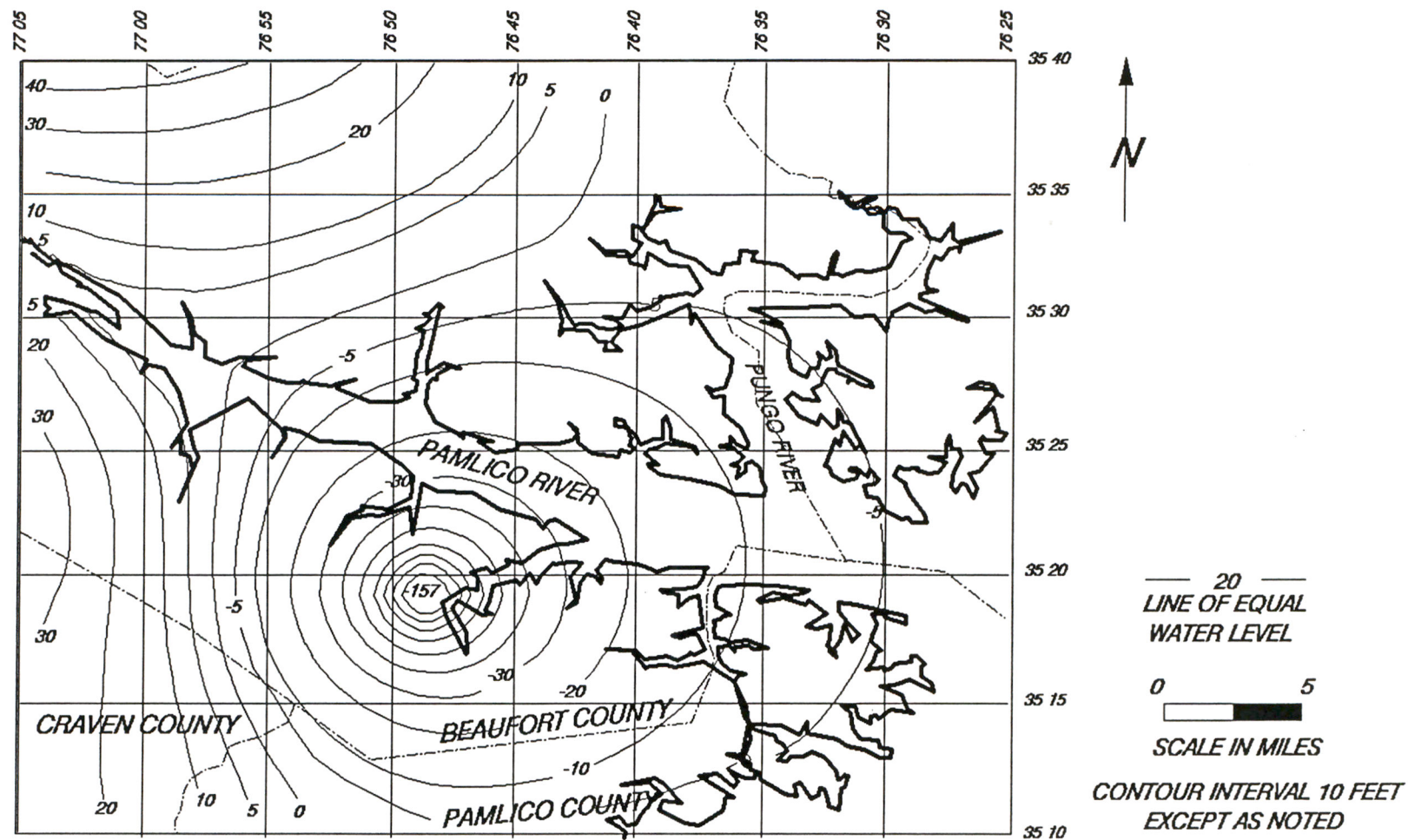
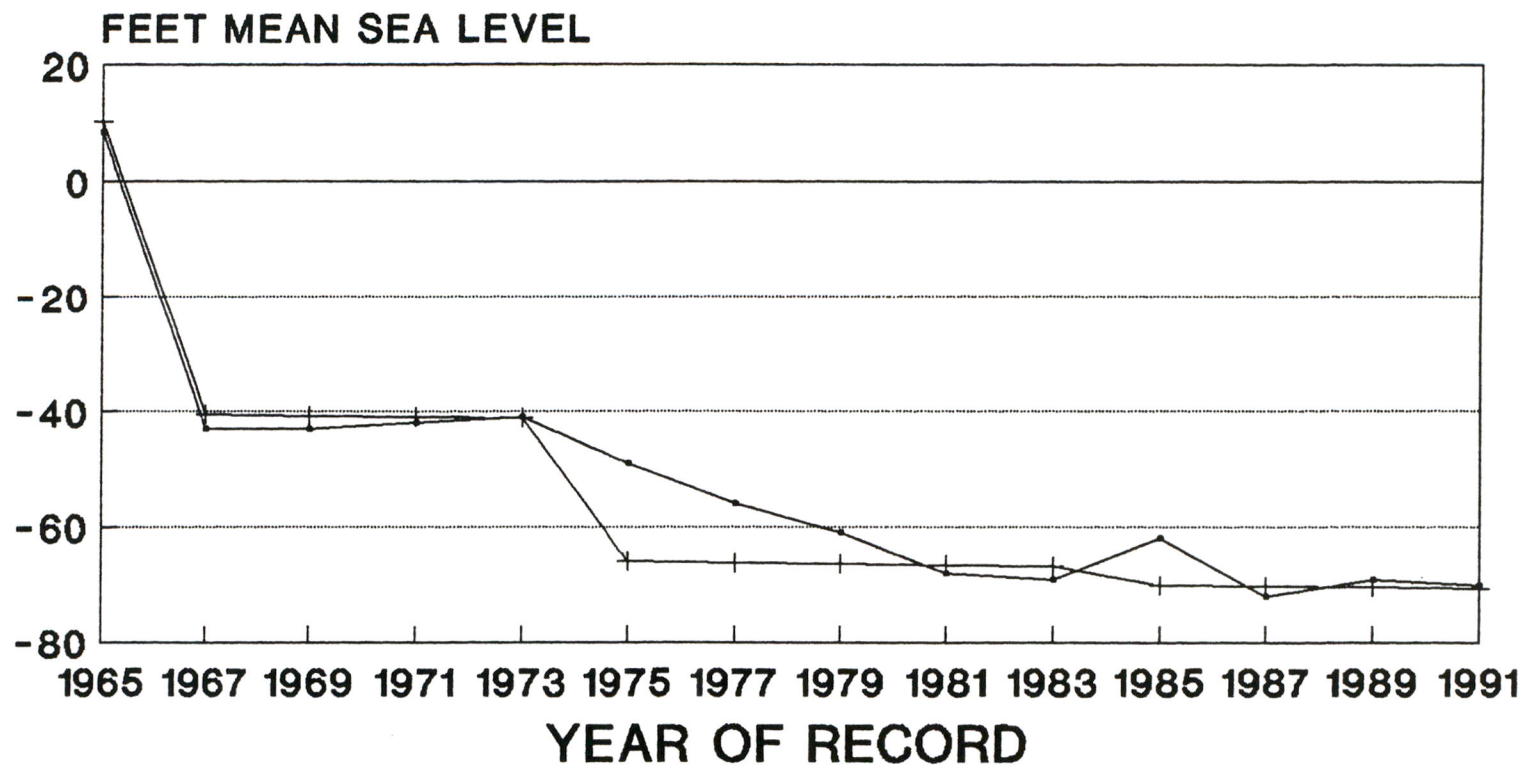


FIGURE 38 - SIMULATED POTENTIOMETRIC SURFACE MAP
OF CASTLE HAYNE AQUIFER (LAYER 2), 1992

**FIGURE 39 - OBSERVED VS. SIMULATED
HYDROGRAPHS - WELL NC-13, AURORA, NC**



EXPLANATION

—•— OBSERVED HEADS

—+— SIMULATED HEADS

TABLE 6 - Results of Sensitivity Evaluation

Aquifer and Varied Parameter	% Change	Resulting Head Changes (mean difference in feet +/-)		
		Layer 1	Layer 2	Layer 3
SURFICIAL AQUIFER (LAYER 1)				
Hydraulic Conductivity	+90	3.78	2.72	2.71
	+50	2.05	1.72	1.71
	-50	3.66	2.95	2.94
	-90	11.98	9.37	9.37
Boundary Flux	+90	0.35	0.29	0.14
	+50	0.20	0.16	0.14
	-50	0.16	0.15	0.12
	-90	0.34	0.28	0.14
Recharge	+90	9.84	9.01	8.78
	+50	5.44	4.98	4.85
	-50	7.02	3.91	4.87
	-90	9.85	9.45	8.77
Specific Yield	+90	2.58	2.06	1.93
	+50	1.77	1.41	1.33
	-50	4.09	3.35	3.03
	-90	15.91	13.67	12.64
YORKTOWN-PUNGO RIVER CONFINING UNIT				
Vertical Leakance	+90	1.93	1.74	1.78
	+50	1.29	1.17	1.18
	-50	2.83	2.68	2.73
	-90	12.74	13.82	13.99
CASTLE HAYNE AQUIFER (LAYER 2)				
Transmissivity	+90	3.06	3.35	3.51
	+50	2.13	2.45	2.44
	-50	5.79	6.27	6.58
	-90	33.84	35.83	37.57
Boundary Flux	+90	3.66	4.01	4.31
	+50	2.14	2.36	2.48
	-50	1.98	2.17	2.50
	-90	3.67	4.03	4.54
Storage	+90	0.008	0.003	0.044
	+50	0.008	0.003	0.044
	-50	0.007	0.003	0.041
	-90	0.005	0.003	0.041

TABLE 6 (Cont'd) - Results of Sensitivity Evaluation

Aquifer and Varied Parameter	% Change	Resulting Head Changes (mean difference in feet +/-)		
		Layer 1	Layer 2	Layer 3
PEEDEE CONFINING UNIT				
Vertical Leakance	+90	0.05	0.06	0.70
	+50	0.03	0.04	0.42
	-50	0.04	0.05	0.54
	-90	0.08	0.10	1.15
CRETACEOUS AQUIFER (LAYER 3)				
Transmissivity	+90	0.05	0.06	1.84
	+50	0.04	0.04	1.25
	-50	0.07	0.08	2.77
	-90	0.20	0.29	8.81
Storage	+90	0.0	0.0	0.01
	+50	0.0	0.0	0.003
	-50	0.0	0.002	0.008
	-90	0.0	0.002	0.008

A review of the results indicates that each of the aquifers are nearly equally sensitive to changes in the parameters of the surficial aquifer (layer 1). Changes in recharge to the surficial aquifer result in the most significant variations in head. Variations in the hydraulic conductivity and specific yield result only in moderate head changes in each layer, with the exception of a -90 percent deviation from accepted hydraulic conductivity and specific yield values. The model layers are only marginally sensitive to changes in the boundary flux for the surficial aquifer. Fortunately, the boundary flux of the surficial aquifer is the least defined of the parameters evaluated and less critical in its estimation.

Variations in the vertical leakance of the Yorktown-Pungo River confining unit result in only minor variations in head, with the exception of the -90 percent deviation, which most likely resulted in the virtual isolation of units above and below the confining unit.

The model layers were moderately sensitive to changes in the transmissivity and boundary flux of the Castle Hayne aquifer (layer 2). However, a -90 percent deviation of the transmissivity of the Castle Hayne aquifer resulted inexplicably in major head variations in all layers. This effect is not especially critical since the transmissivity of the Castle Hayne aquifer system is well-defined and closely replicated in the model. Changes in the storage coefficient of

the Castle Hayne aquifer during the transient sensitivity analysis resulted in practically no effect on the system.

The actual vertical hydraulic conductivity and thickness of the Peedee confining unit are poorly documented. Vertical leakance may therefore only be estimated. However, the system is not especially sensitive to errors in the estimation of leakance for this unit.

Parameters of the Cretaceous aquifer (layer 3) are the most poorly investigated and documented in the area. However, the upper layers of the system are virtually unresponsive to changes in the transmissivity of the Cretaceous aquifer. Only moderate head variations in layer 3 resulted from changes of Cretaceous aquifer parameters.

Model Limitations

As with any type of computer simulation, this flow model is dependent upon the validity of the parameters entered into it. In the model area, most water resources are derived from the prolific Castle Hayne aquifer system. Conversely, the surficial and especially the Cretaceous aquifer units are rarely used for water resources and are therefore sparsely drilled and/or studied. As a result, much of the hydrologic data and predevelopment heads for these aquifers were estimated. Many of the parameters of the Cretaceous aquifer were estimated or interpolated from data presented by the U.S.G.S. in studies of the central coastal plain west of the

model area.

The model was verified by qualitative, and where possible, quantitative calibrations of steady-state and transient runs. One factor to be considered when appraising the validity of the calibration process is that simulated heads at each node are generated as an average for the entire cell. Though the comparison of wells to nodes is a reasonable method of calibration, simulated heads at the exact point of a well site may vary from the computed average for the cell.

The model is also limited in that the exact location of the saltwater-freshwater front in the Cretaceous aquifer is uncertain. The model also does not simulate movement of this front and assumes that the interface is sharp and vertical, whereas, the saltwater front is actually a diffuse transitional zone and is a curved surface due to the higher density of the saltwater.

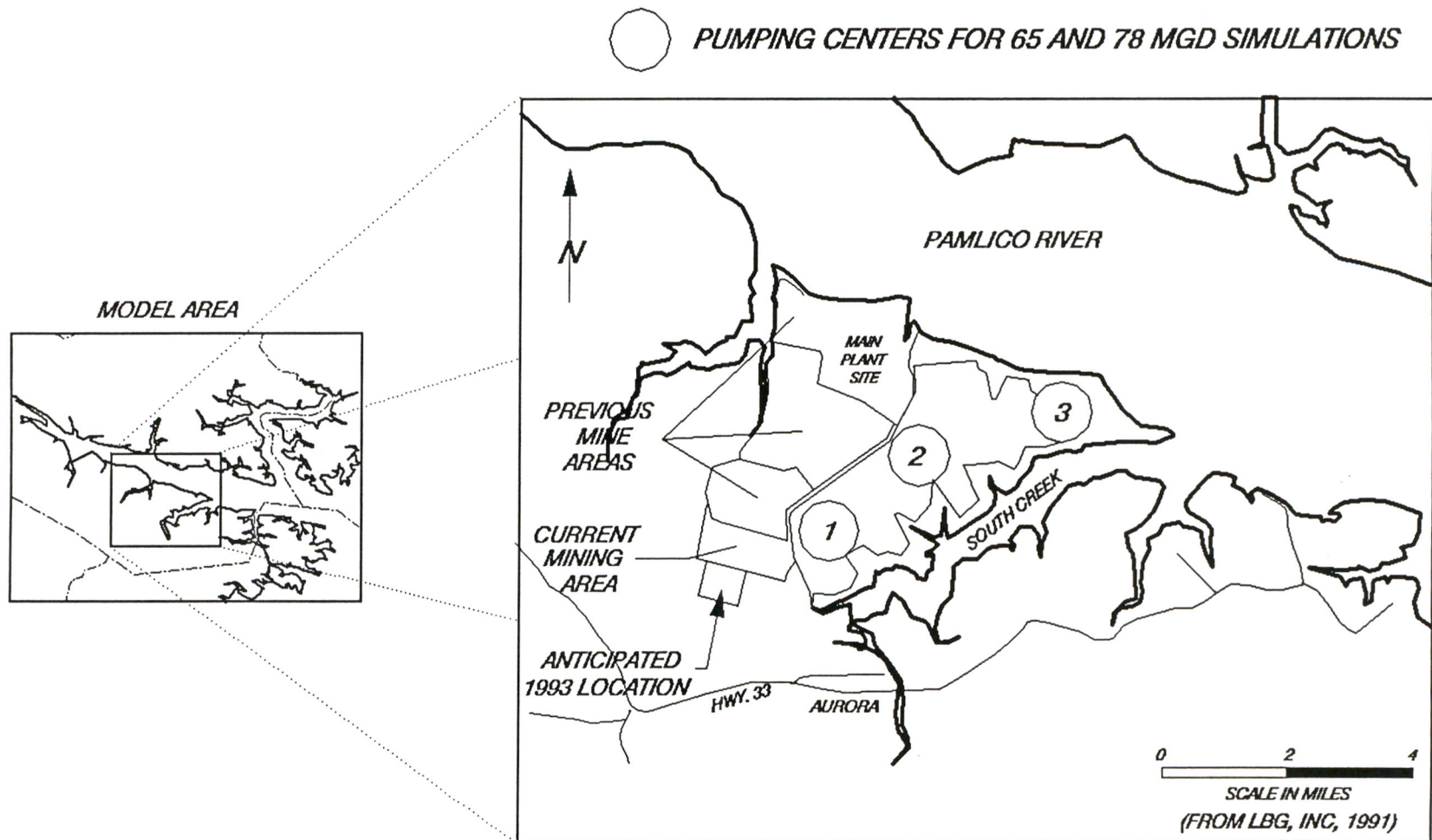
A source of variability in qualitative comparisons of observed and simulated heads is the method of plotting and contouring head values and potentiometric surfaces. Plotting and contouring surfaces manually varies significantly with the experience level of an individual, whereas automated contouring programs produce unbiased and uniform output. However, automated contouring programs often require modification at the grid boundaries.

RESPONSE OF CASTLE HAYNE AQUIFER TO INCREASED PUMPAGE

Texasgulf has planned a northeastern mine advance to begin in 1994. Due to the eastward movement of the active mining areas, it is anticipated that the ore will be deeper and the Castle Hayne aquifer more transmissive, resulting in a projected increase in depressurization pumping rates (LBG, Inc., 1991). The calibrated flow model was used to predict the effects of the increased pumpage on the Castle Hayne aquifer system.

Anticipated Pumping Rates and Locations

Based on Capacity Use Area permit applications, the anticipated withdrawal rates range from 61 to 78 MGD, depending upon the presence and thickness of a less permeable section of the Pungo River unit referred to as the "lean ore" (LBG, Inc., 1991). The northeast mine advance is divided into 22, 1-year mine blocks (Figure 35). Beginning with mine block 1, approximately one-half of the tract will be mined in a northeast advance, with the remainder mined with a southwest return advance. Due to the size of the model cells in the mine area (0.82 mi.^2), simulations of pumping from each individual mine block were not possible. In addition, the mine locations of the southwest return advance simulations duplicate cell locations of the northeast advance simulations. The simulations were therefore divided into three, 4-year pumping centers (Figure 40). Each of the corresponding cells were



**FIGURE 40 - LOCATIONS OF PUMPING CENTERS
USED IN SIMULATIONS
OF NORTHEAST MINE ADVANCE**

stressed at a rate of both 65 and 78 MGD in an attempt to approximate maximum and minimum impacts of the advance.

Results of Increased Pumpage

Simulated potentiometric surface maps were created for each pumping rate and location at the end of each four-year pumping period. In addition, water level changes over each four-year stress period were reported for specific localities in the model area (Figure 41). The simulated head changes in wells located near the east Washington (A), Aurora (B), Texasgulf mine plant (C), Yeatesville (D), Belhaven (E), and the east Bath (F) areas, at pumping rates of 65 and 78 MGD are illustrated on Figure 42.

The simulated potentiometric surface maps for a pumping rate of 65 MGD at the three mine locations are presented on Figures 43, 44, and 45. As shown on these figures, the simulated cones-of-depression shifted to the northeast with each advance. As expected, wells to the north and east experienced decreasing water levels with each advance, and water levels south and west of the pumping center increased with each advance. For instance, wells A, B, and C on Figure 42 are located west of the mine locations. The simulated hydrographs for wells in these areas indicate head increases with each advance. Conversely, hydrographs for wells east of the pumping centers (D, E, and F) indicate decreasing heads with each advance. The hydrograph for well A (east Washington

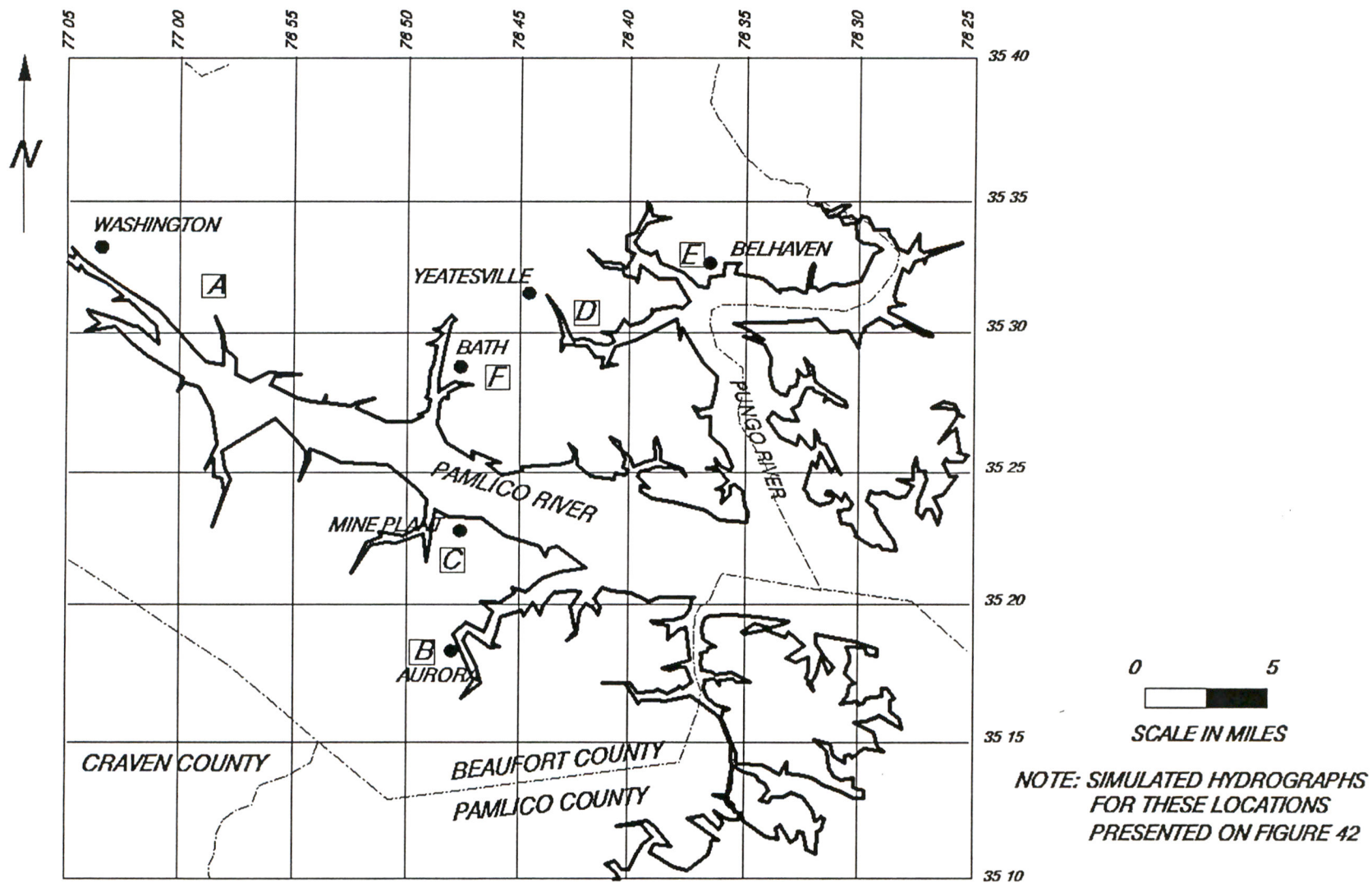


FIGURE 41 - LOCATIONS OF SELECTED WELLSITES MONITORED DURING NORTHEAST MINE ADVANCE SIMULATIONS

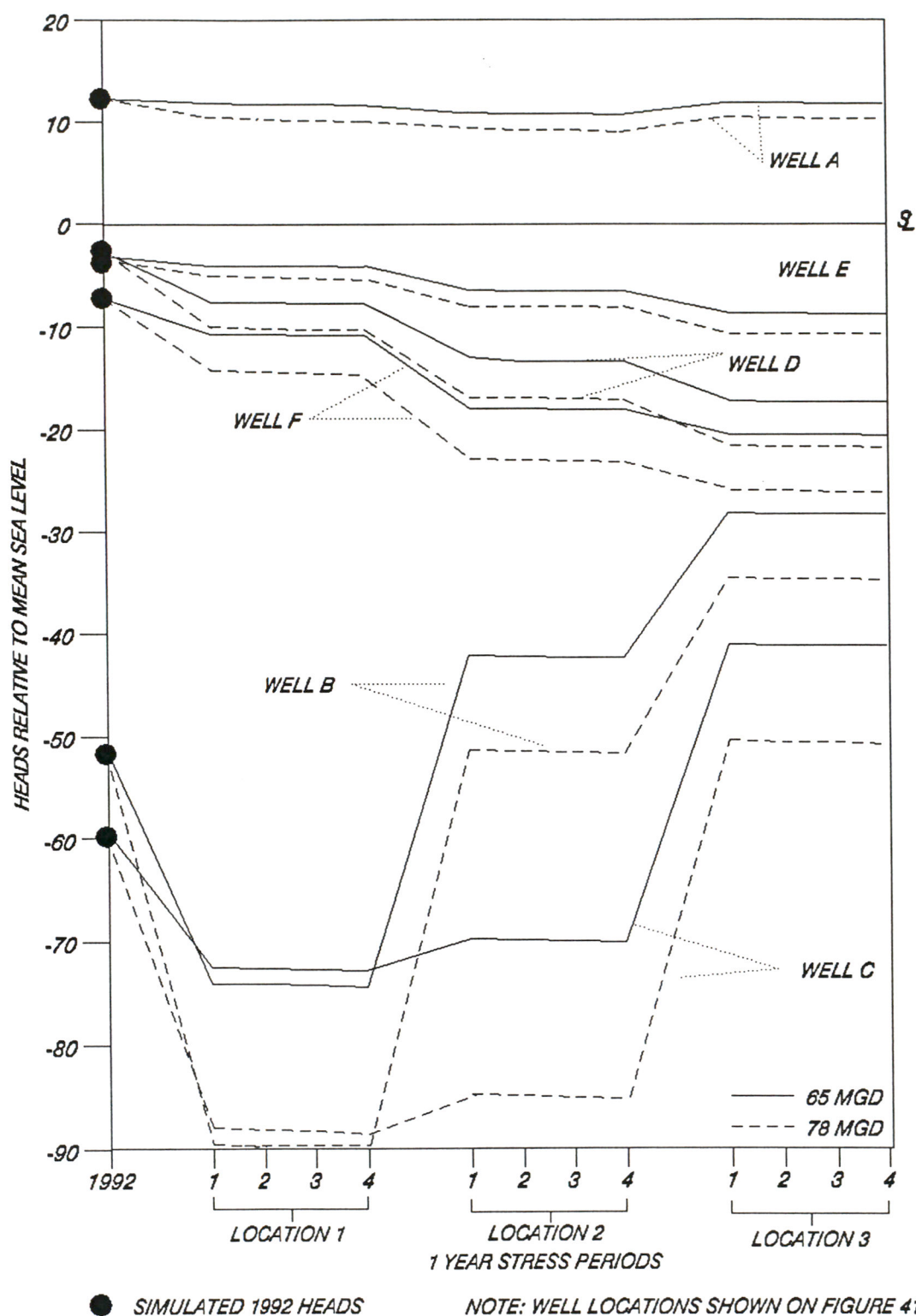


FIGURE 42 - SIMULATED HYDROGRAPHS OF SELECTED WELLSITES
NORTHEAST MINE ADVANCE, 65 AND 78 MGD

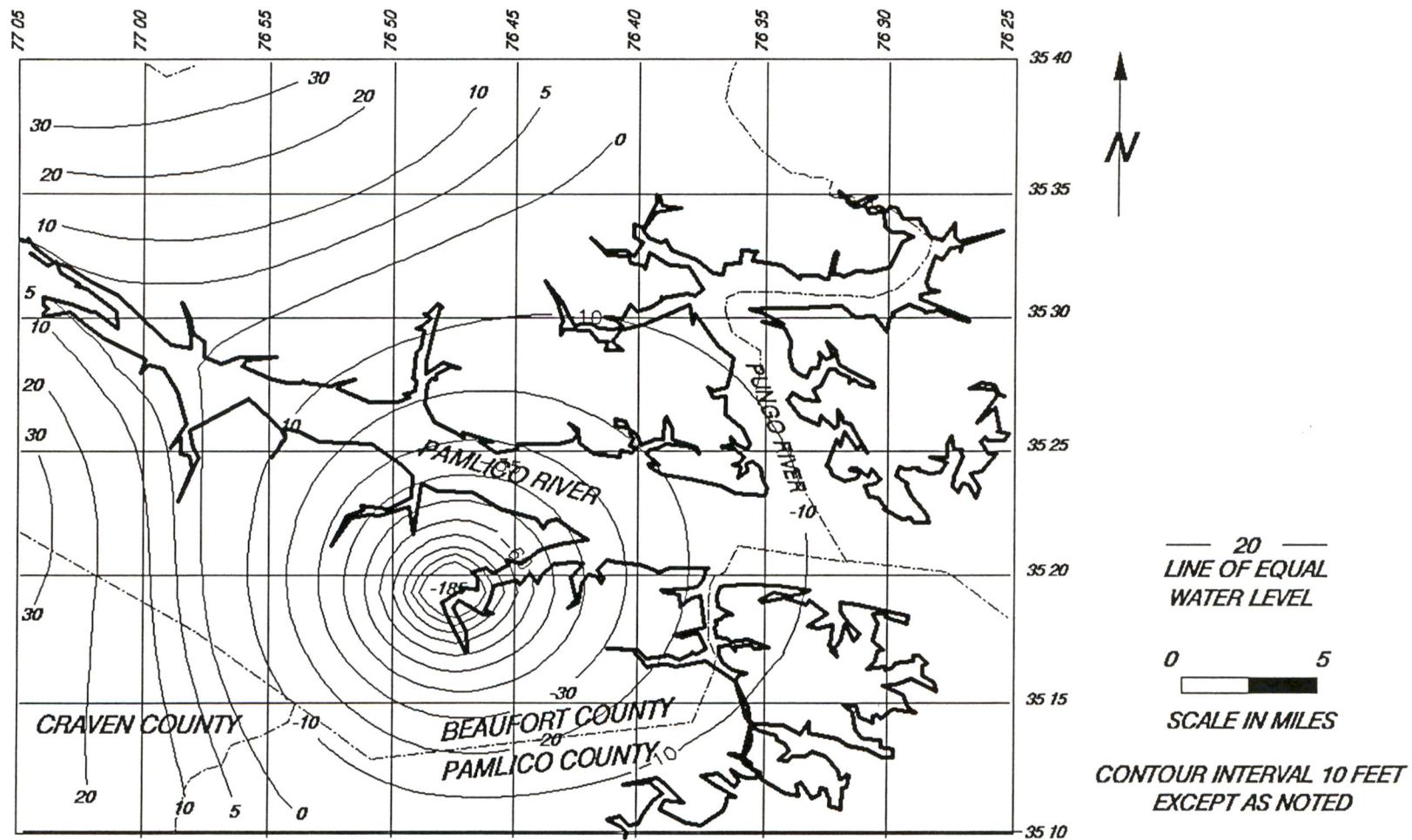


FIGURE 43 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 65 MGD, NORTHEAST MINE ADVANCE LOCATION 1

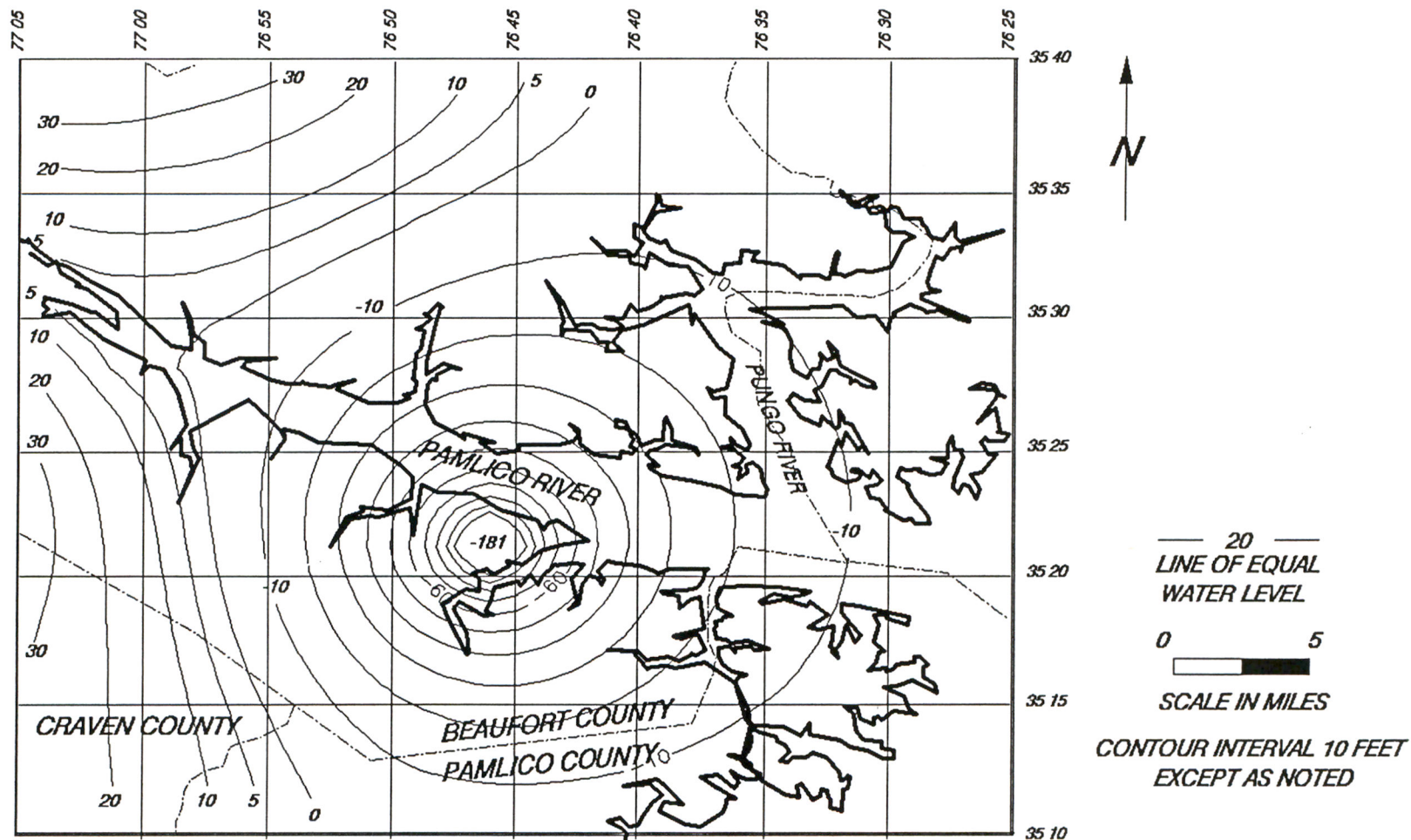


FIGURE 44 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE
AQUIFER (LAYER 2), 65 MGD, NORTHEAST MINE ADVANCE LOCATION 2

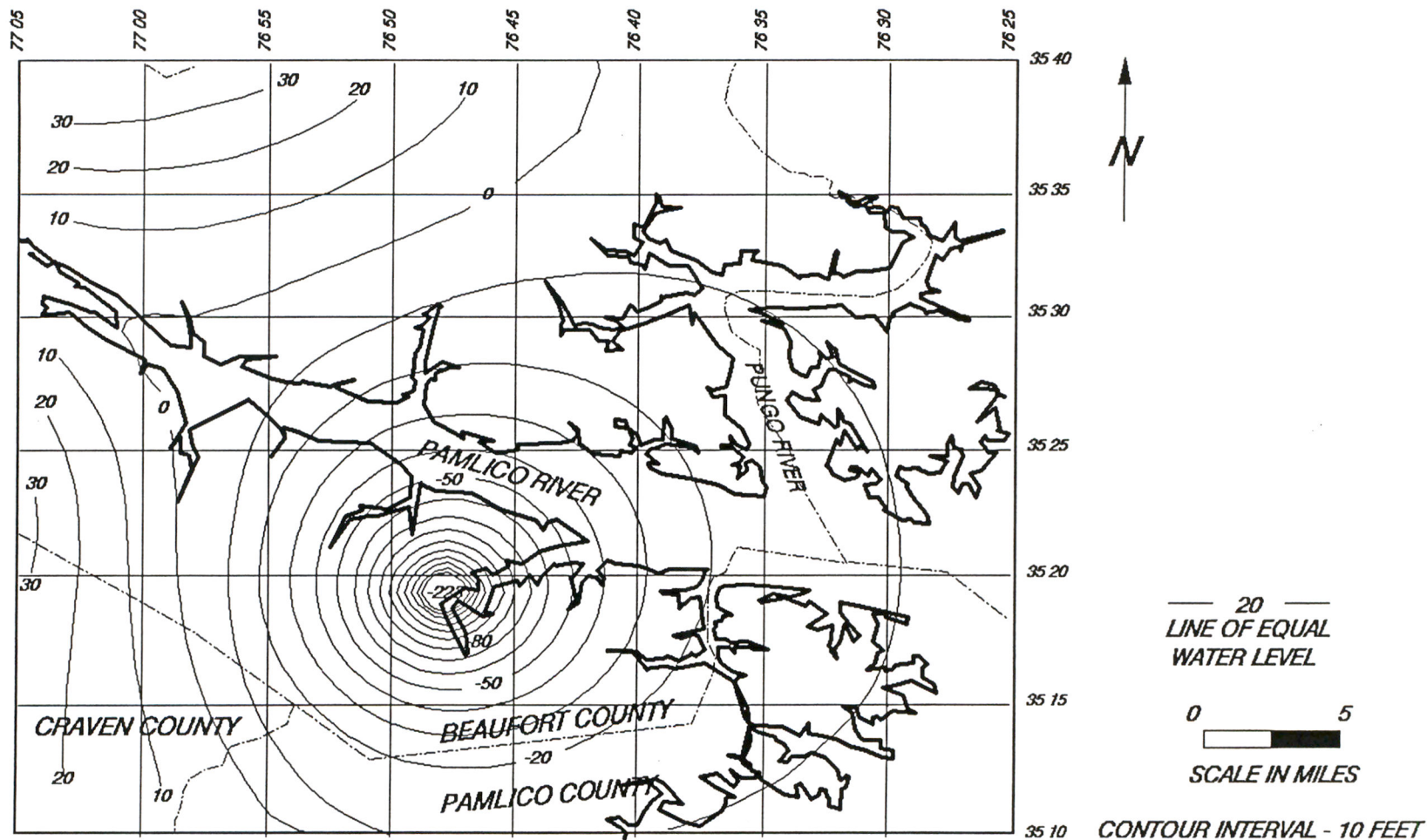
area) shows very little effect related to the increased pumping.

The simulated potentiometric surface maps for pumping rates of 78 MGD at pumping centers 1, 2, and 3 are presented on Figures 46, 47, and 48, respectively. These simulations produced cones-of-depression which also shifted to the northeast with each advance. As expected, wells to the north and east experienced decreasing water levels with each advance and water levels south and west of the pumping center increased with each advance (Figure 42).

The simulated heads at the end of each four-year stress period at mine locations 1, 2, and 3 at 65 and 78 MGD are presented on Table 7. The increasing head values at each mine location illustrate that the required depressurization pumpage will in fact have to be increased as the mine centers move northeast. This is due to the increased transmissivity of the aquifer in the direction of the advance.

It should be noted that the volumes of the discharging cells in the upper reaches of the Pamlico River were not automatically reduced with a corresponding decrease in head in that area. Therefore, the flow volume specified for discharging cells in this area was unchanged during each of the simulations. As a result, actual increases/decreases in natural discharge to the Pamlico River could not be realistically calculated.

There was little difference in the configuration of the



**FIGURE 46 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE
AQUIFER (LAYER 2), 78 MGD, NORTHEAST MINE ADVANCE LOCATION 1**

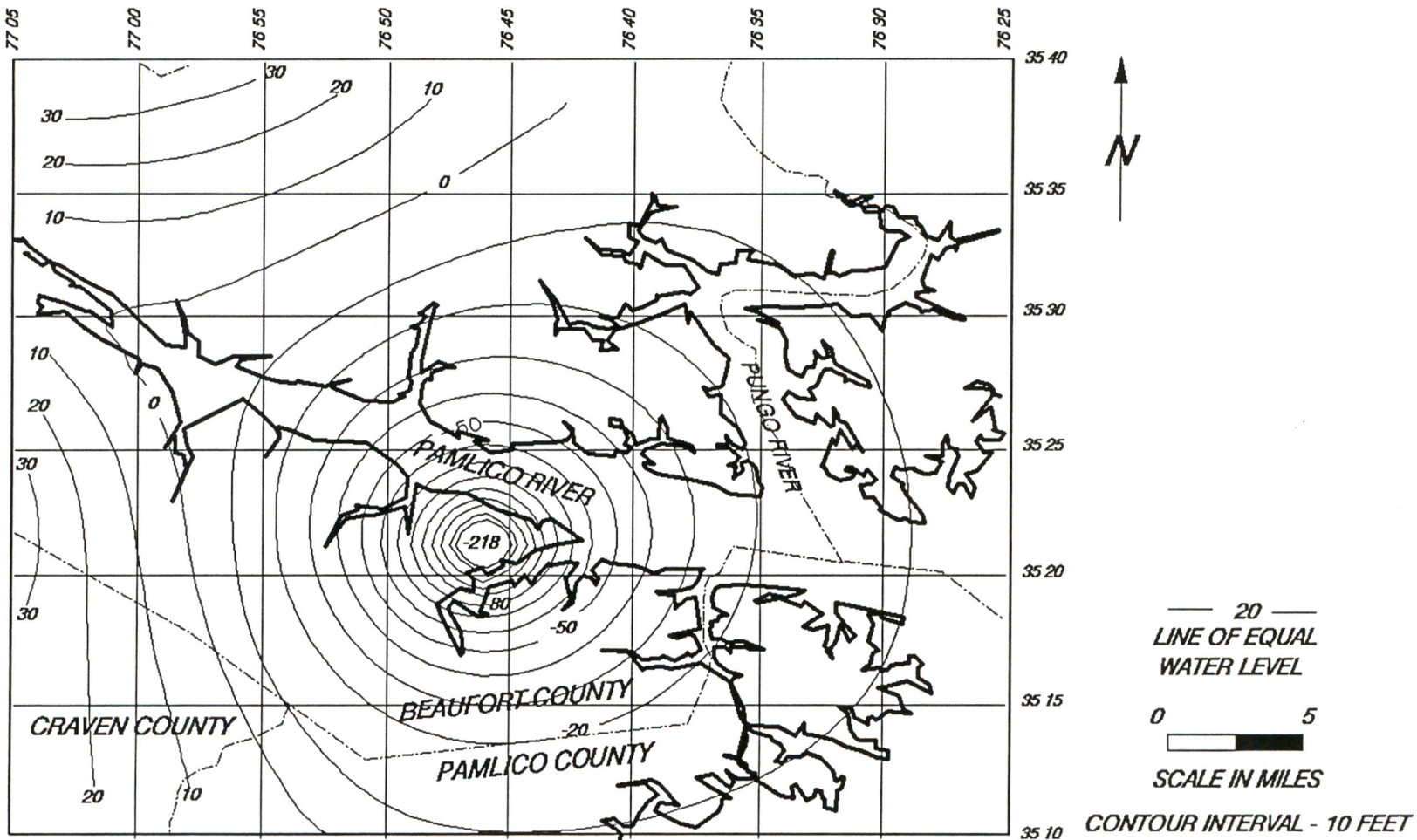


FIGURE 47 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 78 MGD, NORTHEAST MINE ADVANCE LOCATION 2

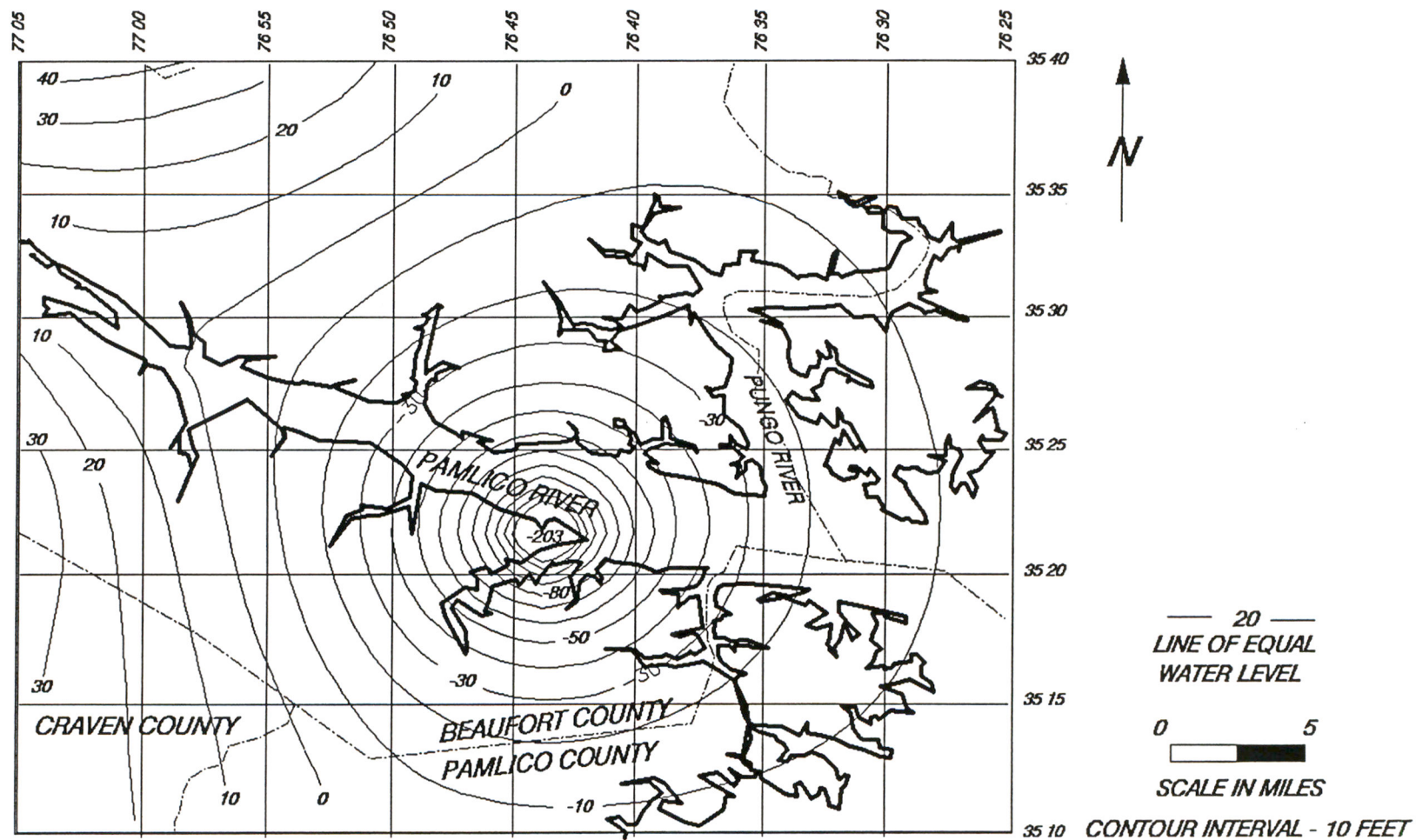


FIGURE 48 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE
AQUIFER (LAYER 2), 78 MGD, NORTHEAST MINE ADVANCE LOCATION 3

Table 7 - Simulated heads for layer 2 at pumping centers of northeast mine advance, 65 and 78 MGD

Mine Location	<u>Pumping Rates</u>	
	65 MGD	78 MGD
1	-184.8	-222.7
2	-181.0	-218.1
3	-168.3	-202.6

**Note: Heads are referenced to mean sea level
Refer to Figure 40 for mine locations**

potentiometric lines of the Castle Hayne aquifer (layer 2) in the area of the upper reaches of the Pamlico River near Washington during the 65 MGD simulations. However, a reduction in the potentiometric surface of layer 2 during the 78 MGD simulations at locations 1 and 2 indicates a reduction in natural discharge to the Pamlico River from the Castle Hayne aquifer.

ESTIMATION OF REQUIRED PUMPING RATES FOR MINE ADVANCE

The previous section described the predicted effects on the Castle Hayne aquifer resulting from the increased maximum depressurization pumping rates estimated by consultants for Texasgulf (65 to 78 MGD). These pumping rates were compared to rates estimated using the flow model developed for this study.

In order to estimate the pumpage required at a specific mining area, it was first necessary to:

- 1) establish the basal elevation of the ore unit at mining locations 1, 2, and 3;

- 2) estimate the drawdown required for mining at the specific location based on the ore depth and presence of the "lean ore";
- 3) determine the pumping rate necessary to achieve the required drawdowns.

Mining requires lowering of the potentiometric surface of the Castle Hayne aquifer below the bottom of the ore section. The elevation of the bottom of the ore unit is presented in Figure 49. Based on the contours presented in this figure, the bottom of the ore structure at mine locations 1, 2, and 3 are -135, -150, and -165 feet MSL, respectively. In order to maintain safe mining conditions, the potentiometric surface must be lowered approximately five feet below the base of the ore unit, if the lean ore is in place (Gilmore, personal comm.). Therefore, pumping rates were modified to result in heads of -140, -155, and -170 feet MSL at the pumping centers of mine locations 1, 2, and 3, respectively.

The pumping rates required to achieve the specified heads at the mine locations were calculated using specific capacities at each mine location determined from earlier simulations and modified as required. **The estimated required pumping rates at locations 1, 2, and 3 were approximately 50.08, 56.08, and 65.63 MGD, respectively, if the lean ore is in place.** The potentiometric surface resulting from these pumping rates are presented on Figures 50, 51, and 52.

As described earlier, the required depressurization pumping rate for the northeast mine advance is also dependent

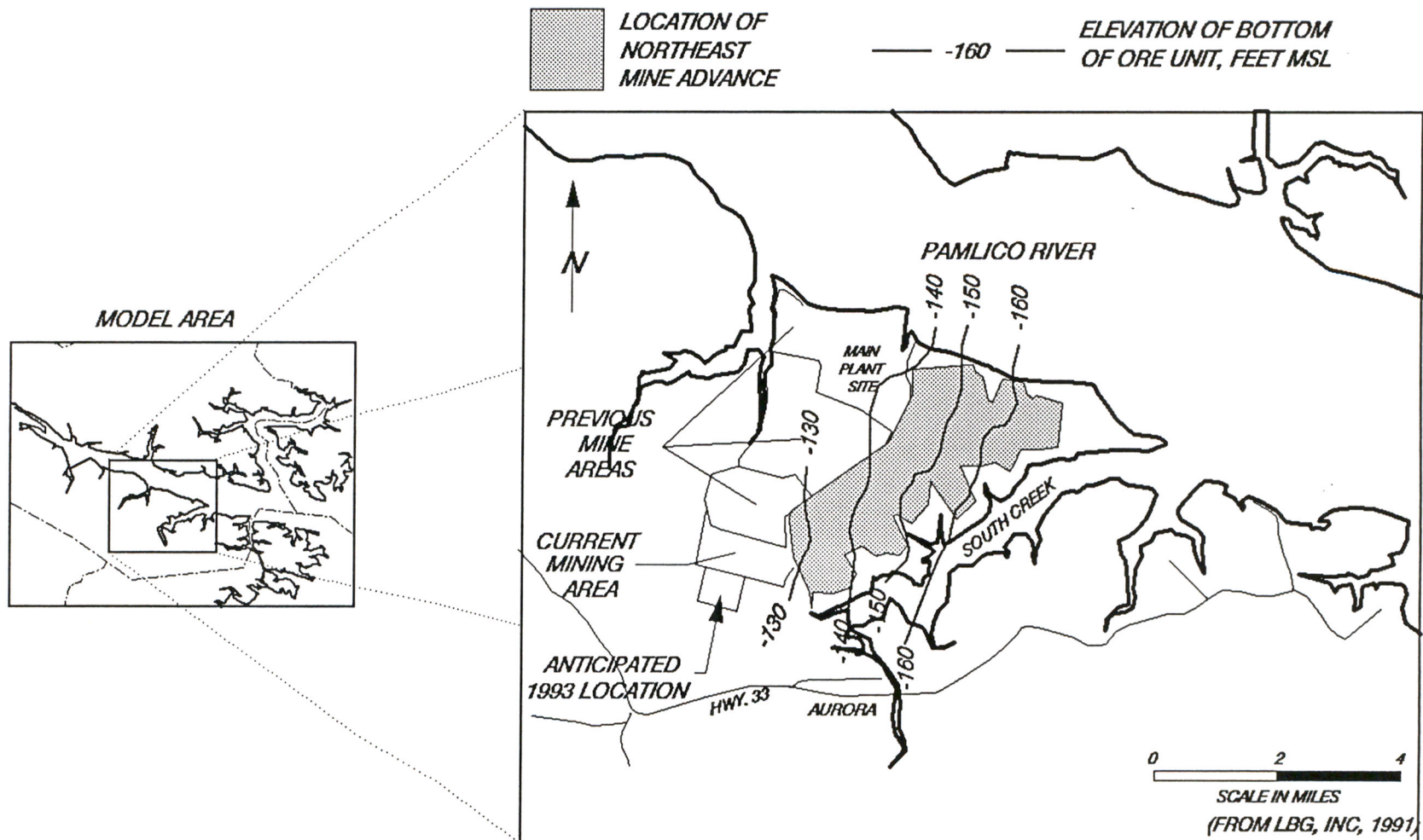


FIGURE 49 - BASAL ELEVATION OF ORE UNIT IN
AREA OF NORTHEAST MINE ADVANCE

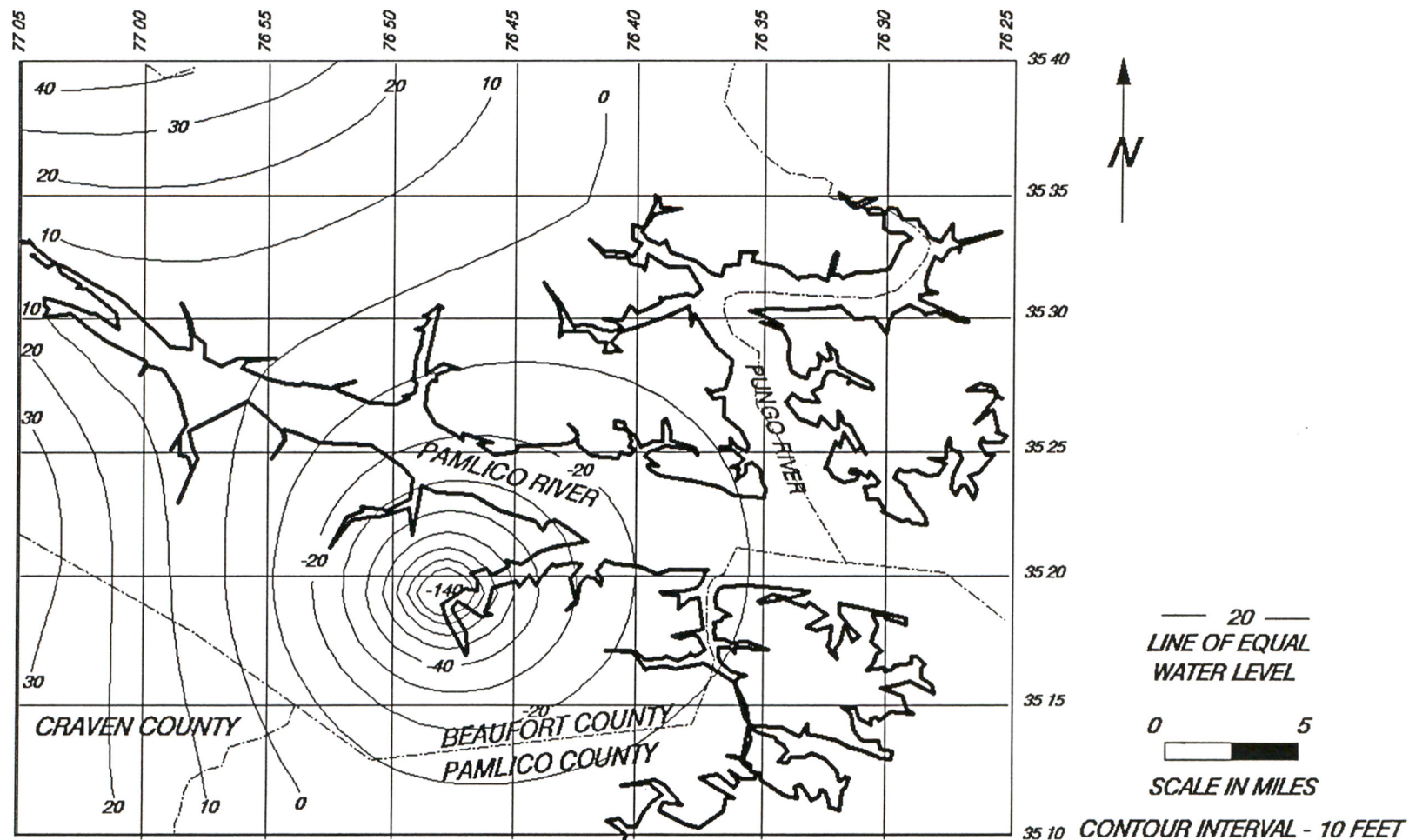


FIGURE 50 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 50.08 MGD, NORTHEAST MINE ADVANCE LOCATION 1 (LEAN ORE PRESENT)

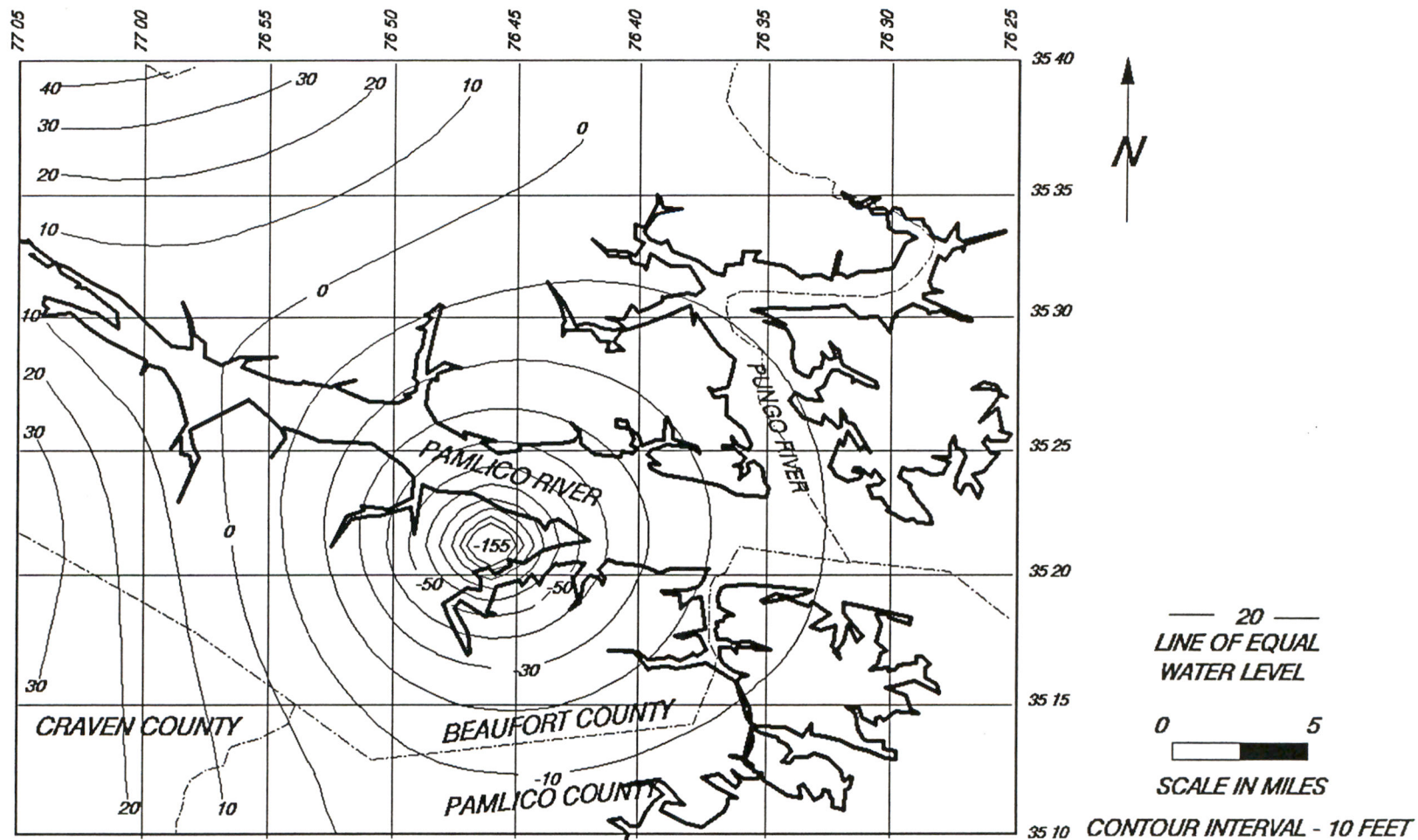


FIGURE 51 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 56.08 MGD, NORTHEAST MINE ADVANCE LOCATION 2 (LEAN ORE PRESENT)

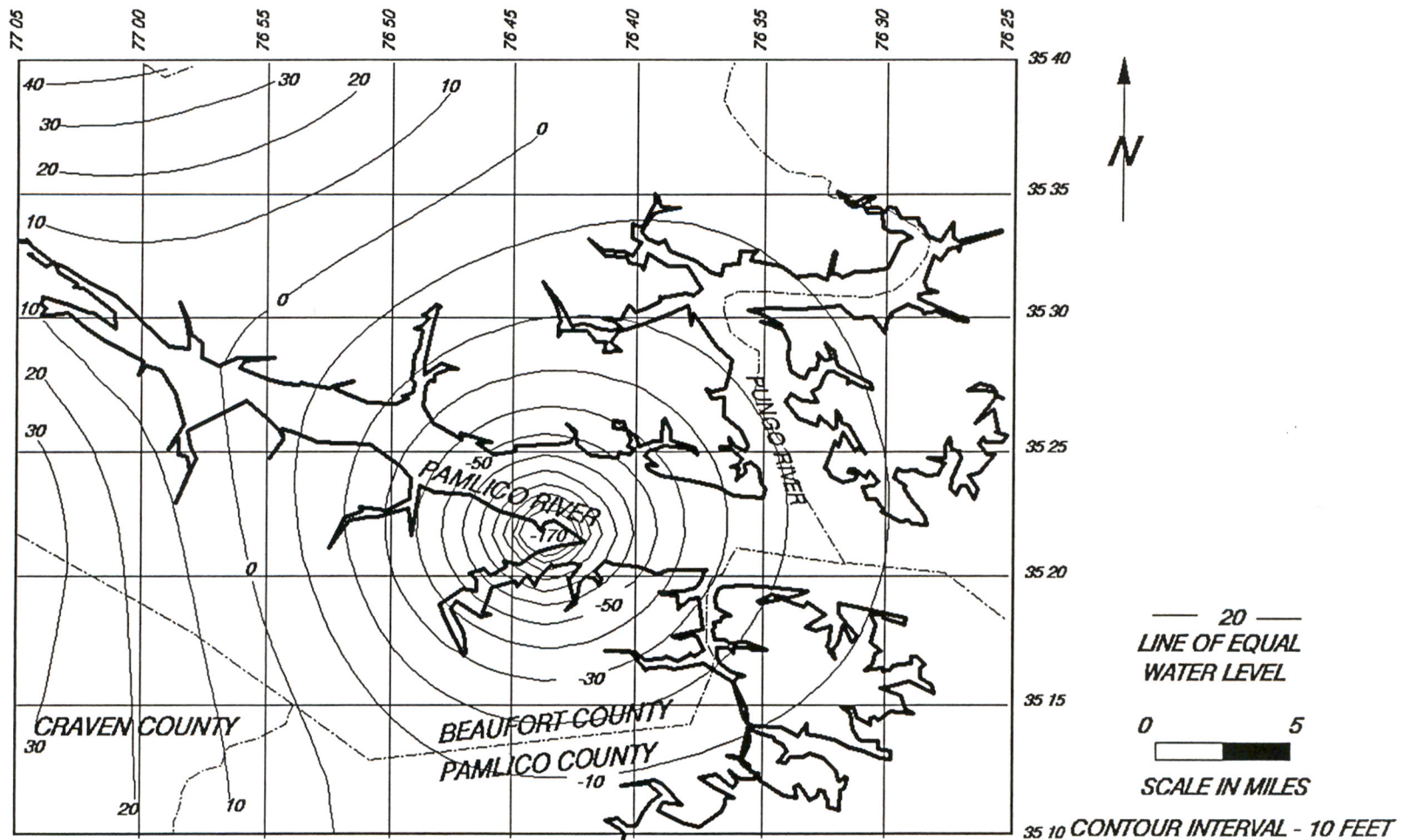


FIGURE 52 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 65.63 MGD, NORTHEAST MINE ADVANCE LOCATION 3 (LEAN ORE PRESENT)

upon the presence or absence of a less permeable zone of the Pungo River Formation referred to as the lean ore. Due to its low permeability, it is estimated that an additional 10 feet of drawdown will be required at the pumping center if the lean ore is not in place (Gilmore, personal comm.). This results in required drawdowns of -150, -165, and -180 feet MSL at mine locations 1, 2, and 3, respectively. Again, the pumping rates required to achieve the specified heads at the mine locations were calculated using specific capacities at each mine location. **Pumping rates used to maintain the specified heads at locations 1, 2, and 3 were 53.40, 59.52, and 69.35 MGD, respectively, if the lean ore is not in place.** The potentiometric surface resulting from these pumping rates are presented on Figures 53, 54, and 55.

POTENTIAL STRATEGIES FOR REDUCTION OF IMPACTS

The calibrated flow model was used where appropriate to evaluate potential strategies for reducing hydrogeologic impacts described earlier in this report. These potential strategies are described in the following sections.

Pumping Adjustment due to Reduced Upward Leakage

With reference to the concept of vertical groundwater movement depending upon head differentials (Figure 7), it is believed that Cretaceous aquifer units contribute water to the Castle Hayne aquifer by upward leakage.

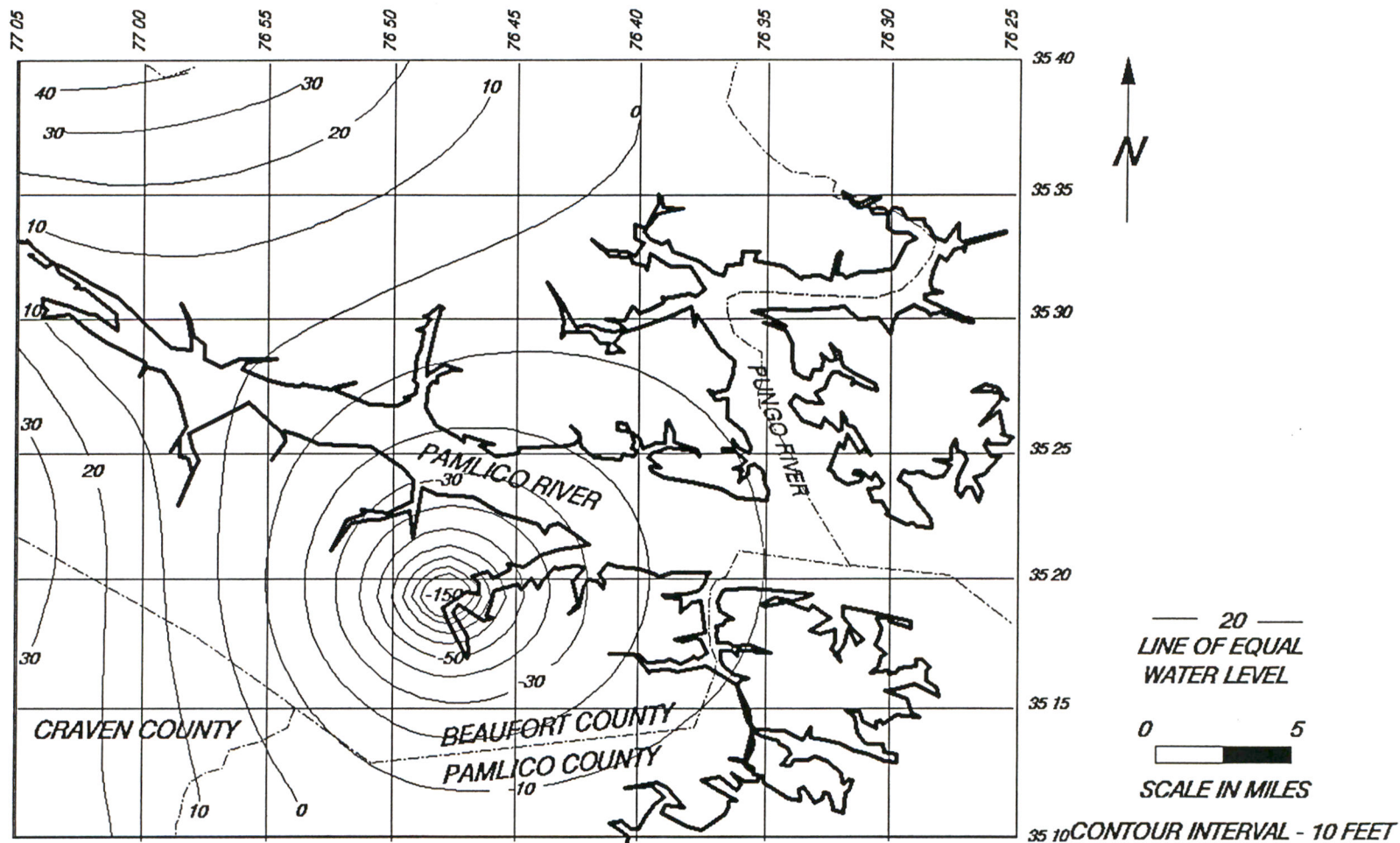


FIGURE 53 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER
(LAYER 2), 53.40 MGD, NORTHEAST MINE ADVANCE LOCATION 1 (NO LEAN ORE PRESENT)

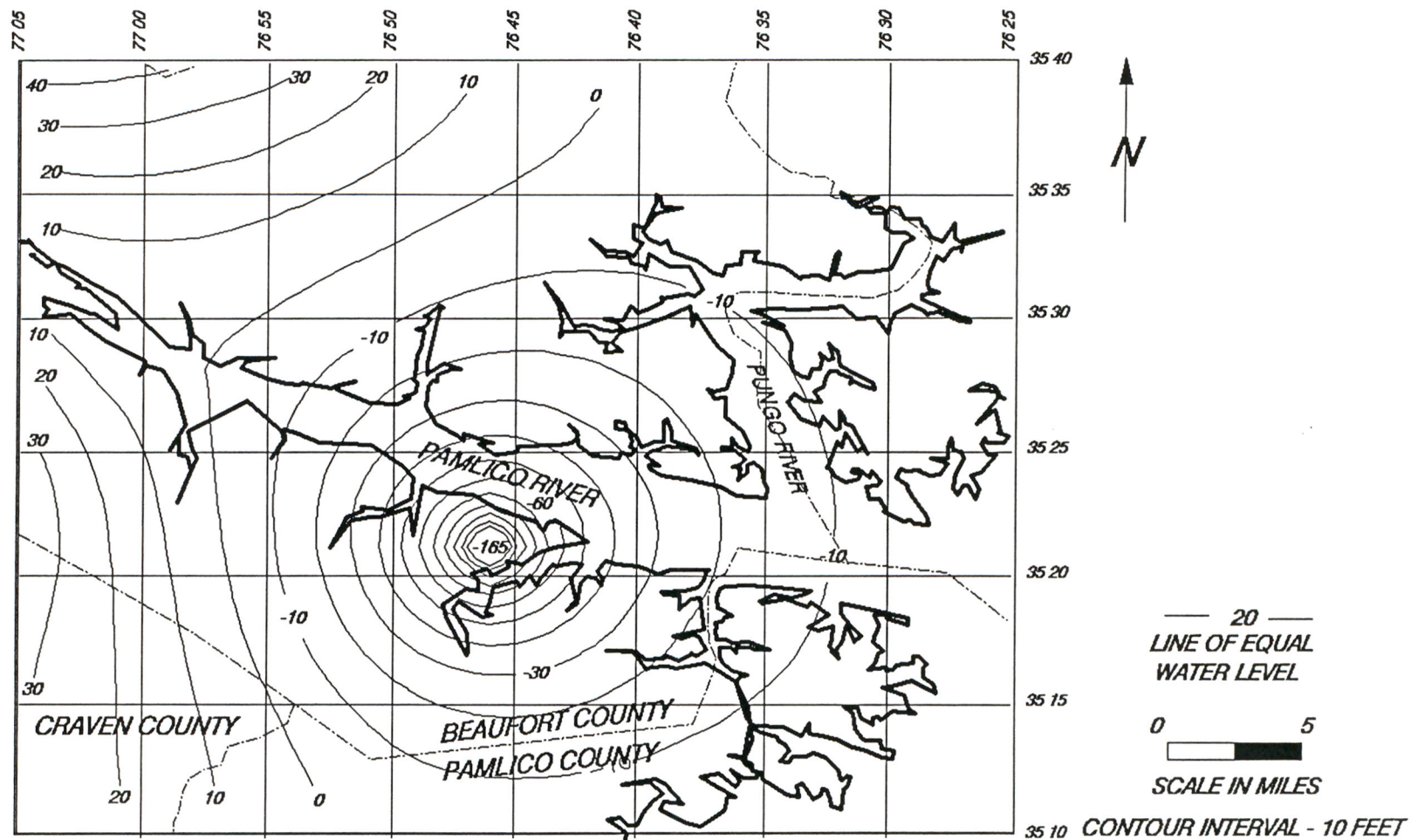


FIGURE 54 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 59.52 MGD, NORTHEAST MINE ADVANCE LOCATION 2 (NO LEAN ORE PRESENT)

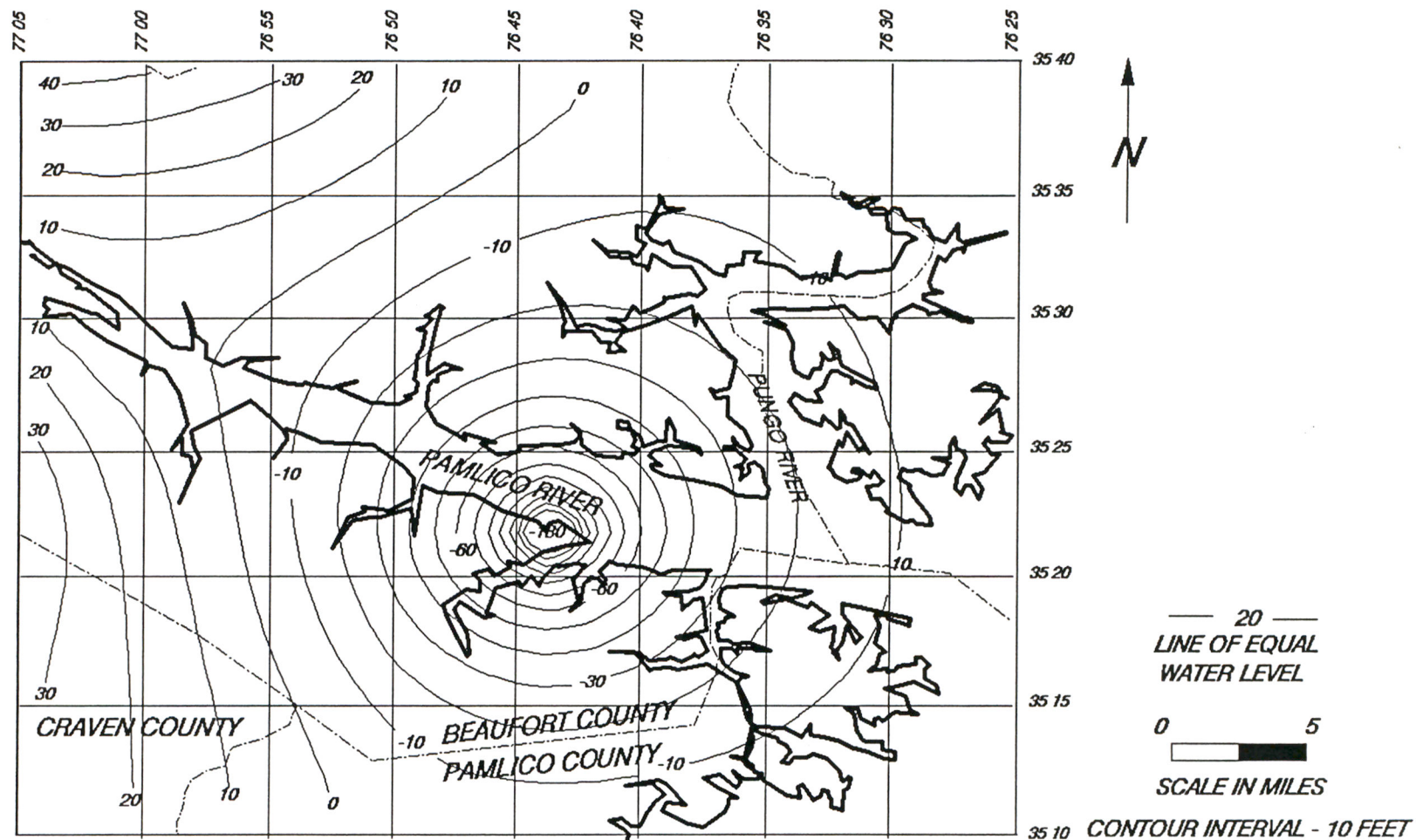


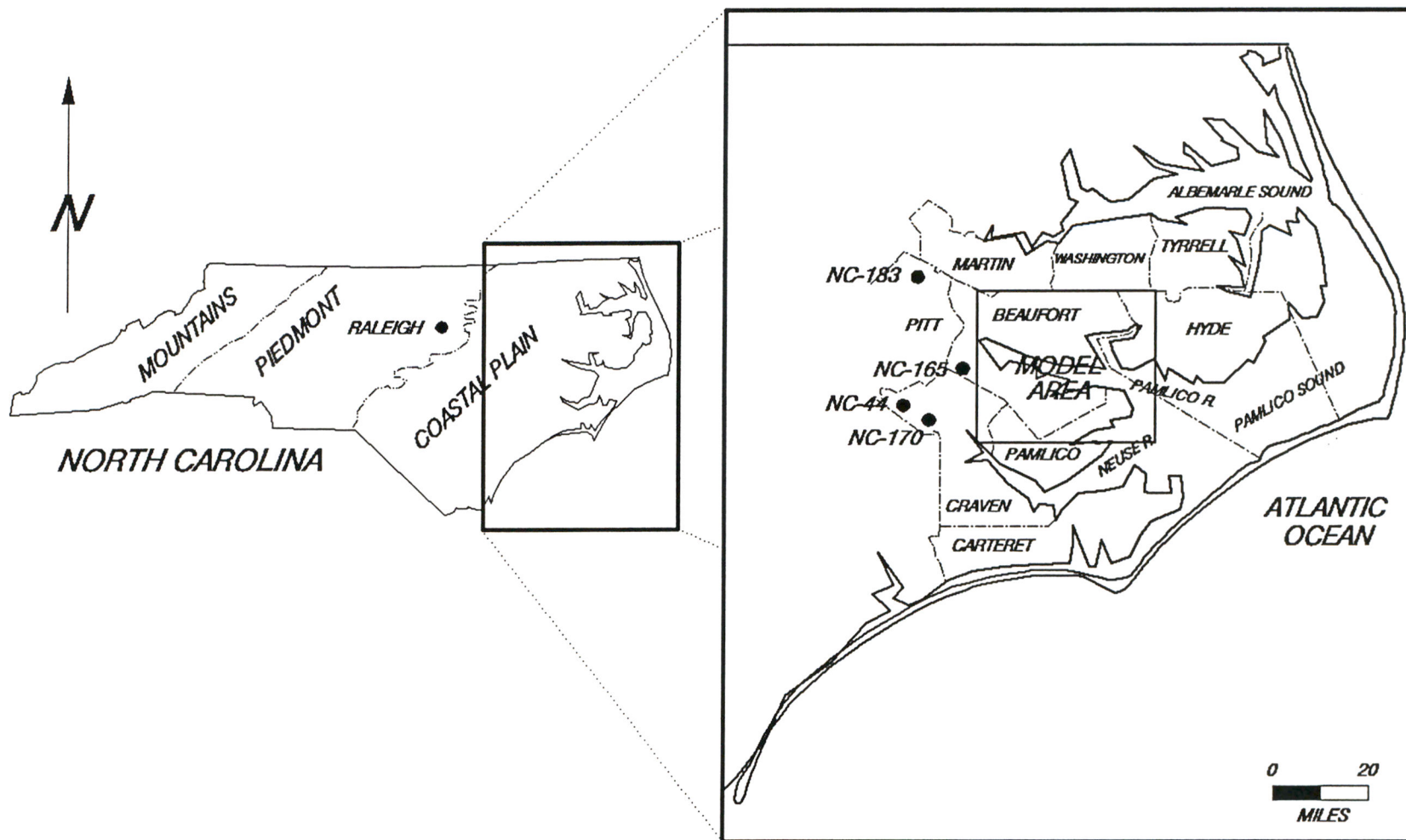
FIGURE 55 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2) 69.35 MGD, NORTHEAST MINE ADVANCE LOCATION 3 (NO LEAN ORE PRESENT)

Due to excessive pumping from the Cretaceous units in the central coastal plain (west of the model area), heads in those units have steadily declined for the last several decades. As a result, it was anticipated that a continued decrease in upward leakage from the underlying Cretaceous units would reduce the amount of water contributed to the Castle Hayne aquifer and therefore reduce the depressurization pumping required at the mine. The effects of the Cretaceous head decline on the Castle Hayne aquifer and the potential for reduction of depressurization pumping are addressed in this section.

Rate of Cretaceous Head Decline

Information on wells penetrating the Cretaceous aquifer is sparse and available only in areas outside of the model area. Hydrographs from wells in Cretaceous aquifers (Black Creek and upper Cape Fear units) in the central coastal plain nearest to the model area (Figure 56) were used to calculate the rate of head reductions in the Cretaceous aquifer. Hydrographs for observation wells at Cove City (NC-44), Wilmar (NC-165), Clarks (NC-170), and Bethel (NC-183) are presented on Figures 57 to 60, respectively. The mean rate of head decline for these wells was determined to be about 2.5 feet per year.

The head decline is more distinct in the western regions of the model area due to the large cones-of-depression being



**FIGURE 56 - LOCATIONS OF OBSERVATION WELLS
IN CRETACEOUS AQUIFERS**

**NOTE: HYDROGRAPHS FOR ABOVE WELLS
IN FIGURES 57,58,59,60**

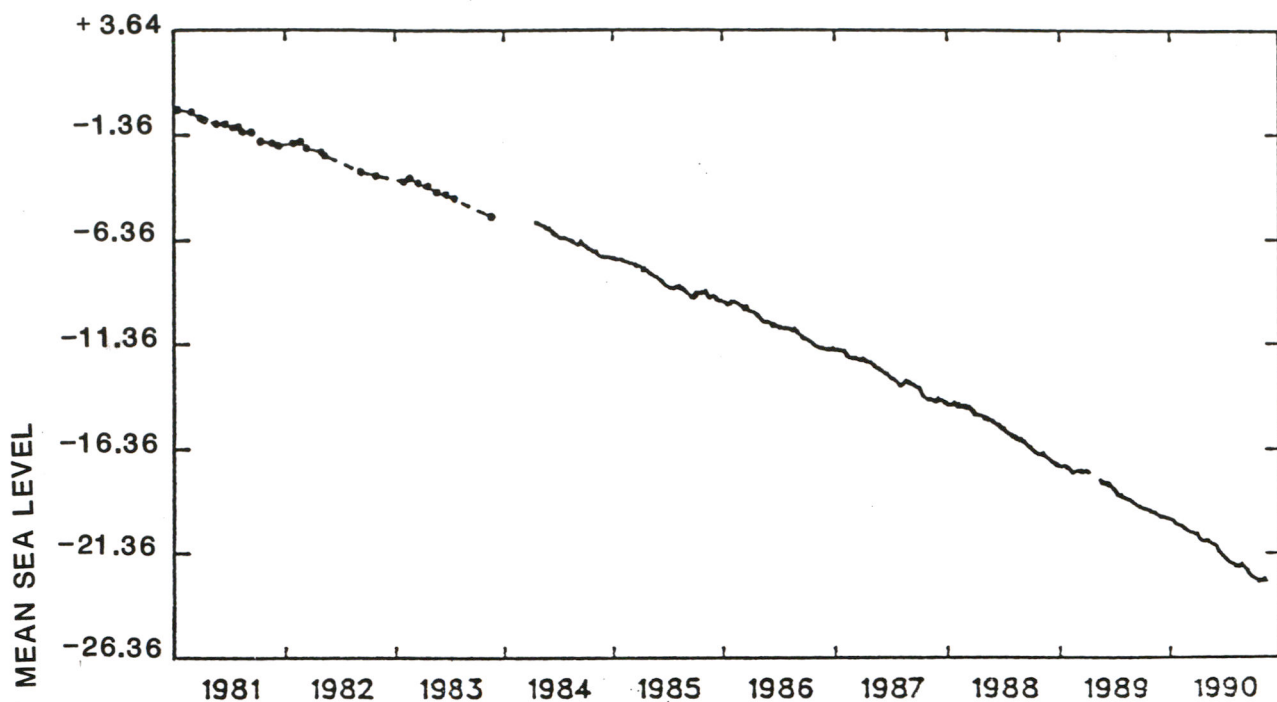


FIGURE 59- HYDROGRAPH FOR CLARKS WELL (NC-170)

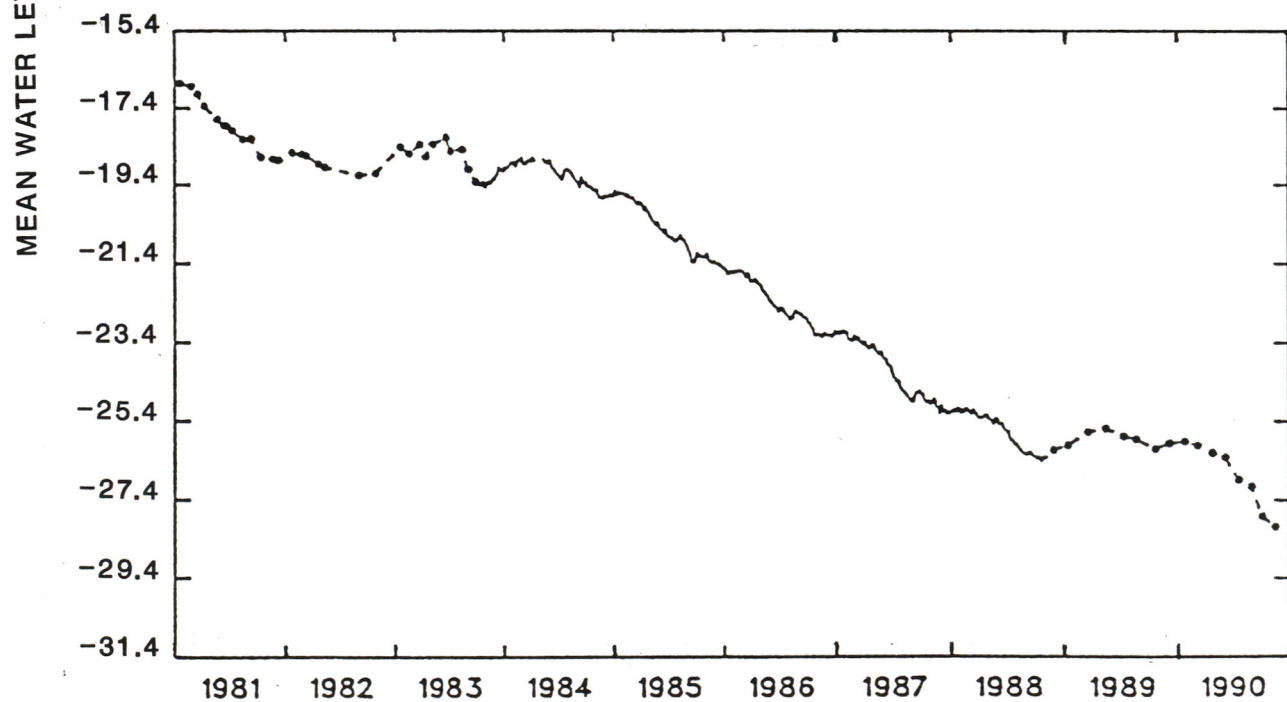


FIGURE 60- HYDROGRAPH FOR BETHEL WELL (NC-183)

NOTE: SEE FIGURE 56 FOR WELL LOCATIONS

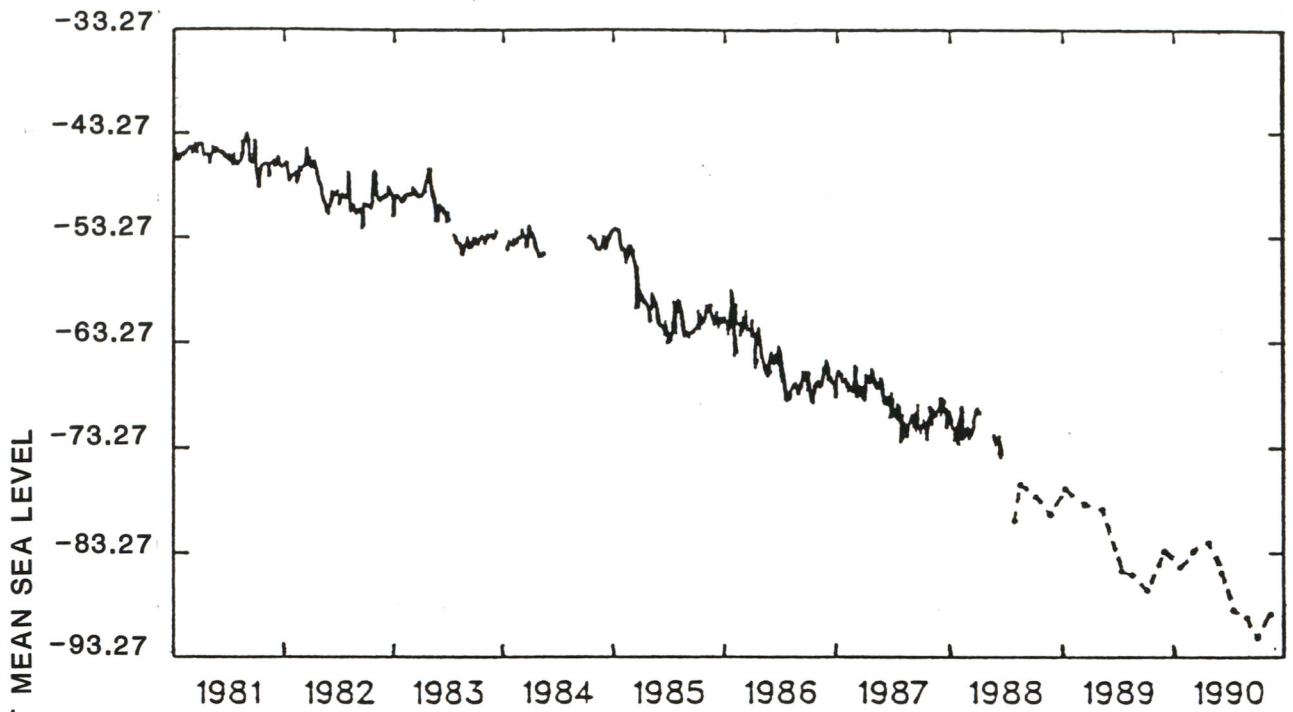


FIGURE 57 - HYDROGRAPH FOR COVE CITY WELL (NC-44)

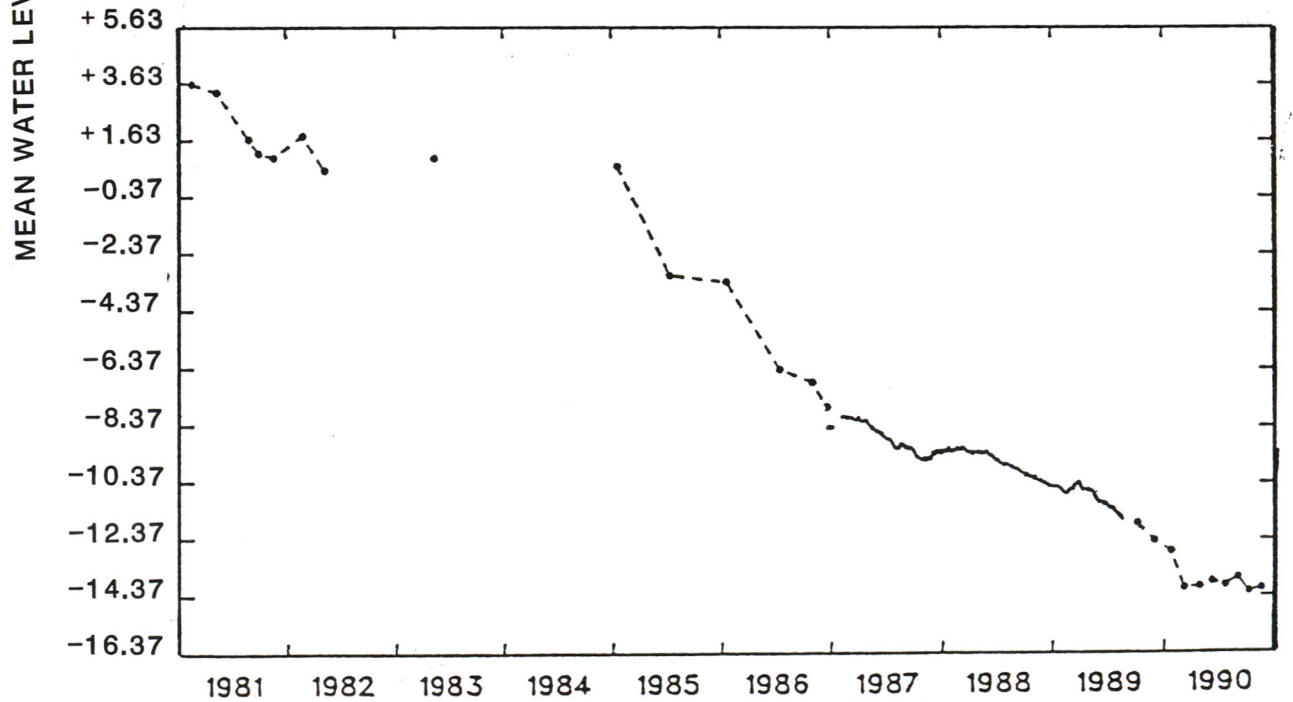


FIGURE 58- HYDROGRAPH FOR WILMAR WELL (NC-165)

NOTE: SEE FIGURE 56 FOR WELL LOCATIONS

produced in the central coastal plain, west of the model area. This results in the most significant lowering of heads in the west, slowly shifting the initial west-east hydraulic gradient of the potentiometric surface of the Cretaceous aquifer (layer 3) to east-west. This condition was reproduced for the simulations.

Effects on Castle Hayne Aquifer

The 1965 to 1992 simulations described in the transient calibration section of this report were reiterated from 1975 to 1992. The previously described trend was implemented in order to evaluate the effects of the head declines on the Castle Hayne aquifer. Since the Cretaceous heads have in fact been declining during this period, it was expected that the revised 1992 potentiometric surface map would be slightly more realistic than the map presented in the transient calibration section of this report. A comparison of 1992 observed and simulated heads for the Castle Hayne aquifer (layer 2) was repeated using the 20 well locations in Figure 36. The mean difference between the observed 1992 and the revised simulated 1992 heads is 2.59 feet. The RMS error was determined to be 3.11 feet. These values indicate a somewhat more realistic 1992 potentiometric surface configuration, compared to the simulations for the transient calibration.

The trend of decreasing heads in layer 3 was continued in simulations of the northeast mine advance. The evaluation was

simplified by using only one pumping rate, 65 MGD at locations 1, 2, and 3 (Figure 35). There is almost no difference between the potentiometric surface maps of these and the prior 65 MGD simulations. The effects of the decreasing heads in layer 3 on layer 2 at the mine locations are addressed in the following section.

Potential for Reduction of Pumping Rates

Simulated heads for layer 2 at northeast advance mine locations computed during previous simulations were compared to those implementing the layer 3 head decline (Table 8).

Table 8 illustrates that simulated heads at the pumping centers do decrease slightly as a result of the decreasing heads in layer 3. At the completion of the 1992 time step, the head at the pumping center (-158.2 ft MSL) is closer to the observed head than the initial simulations.

During the northeast mine advance simulations, the additional head decline at each pumping center is approximately 1.2 feet. **Therefore, it is anticipated that the earlier estimations of required depressurization pumping rates for the northeast mine advance could potentially be reduced by approximately 0.7 percent as a result of the decreasing Cretaceous heads.**

The differences in the mean annual head decrease for layer 2 were insignificant. As a result, it is not anticipated that pumping rates will be able to be continually reduced each

**TABLE 8 - COMPARISON OF HEADS AT PUMPING CENTERS
WITH AND WITHOUT LAYER 3 HEAD DECLINE**

PUMPING CENTER LOCATION	ONE-YEAR TIME STEP	HEADS AT PUMPING CENTER, FEET MSL	
		NO CRETACEOUS HEAD DECLINE	CRETACEOUS HEAD DECLINE
1975 TO 1992 SIMULATIONS	B	1975	-174.0
		1976	-174.1
		1977	-174.2
		1978	-174.3
		1979	-174.4
		1980	-174.6
		1981	-174.7
		1982	-174.8
		1983	-174.9
		1984	-175.0
	C	1985	-156.4
		1986	-156.5
		1987	-156.7
		1988	-156.8
		1989	-156.9
		1990	-157.0
		1991	-157.1
		1992	-157.2
	MEAN ANNUAL HEAD DECLINE		0.113
			0.119
NORTHEAST MINE ADVANCE	1	1	-184.5
		2	-184.6
		3	-184.7
		4	-184.8
	2	1	-180.8
		2	-180.9
		3	-181.0
		4	-181.0
	3	1	-168.2
		2	-168.2
		3	-168.2
		4	-168.3
	MEAN ANNUAL HEAD DECLINE		0.067
			0.078

NOTES: PUMPING CENTER LOCATIONS FOR 1975 TO 1992 SIMULATIONS
PRESENTED ON FIGURE 35
PUMPING CENTER LOCATIONS FOR NORTHEAST MINE ADVANCE
PRESENTED ON FIGURE 40
65 MGD PUMPING RATE FOR NORTHEAST MINE ADVANCE

year as a result of the decreasing Cretaceous heads.

Pumping Adjustment due to Nearby Withdrawals

The City of Washington, NC is in the process of converting from surface water to ground water as a municipal supply source. The pumping rate for the system is anticipated to be on the order of approximately 4.2 MGD, therefore requiring a Capacity Use Area permit. During the permitting process, concern was expressed that the effects of the groundwater withdrawals associated with this system, combined with the anticipated pumping increases at Texasgulf (or vice versa) may produce deleterious effects on the Castle Hayne aquifer system. The flow model was used to estimate the conjunctive effects of the withdrawals on the aquifer system. In addition, the model was used to investigate the possibility that head reductions resulting from the Washington wellfield could reduce the required depressurization pumping rate at Texasgulf.

Description and Predicted Effects

The location of the wellfield used in the simulations is presented in Figure 61. A pumping rate of 4.5 MGD was imposed on the simulated 1992 potentiometric surface of the Castle Hayne aquifer (layer 2), at the appropriate cell location. The estimated required pumping rates for the northeast mine advance (50.08, 56.08, and 65.63 MGD at locations 1, 2, and 3,

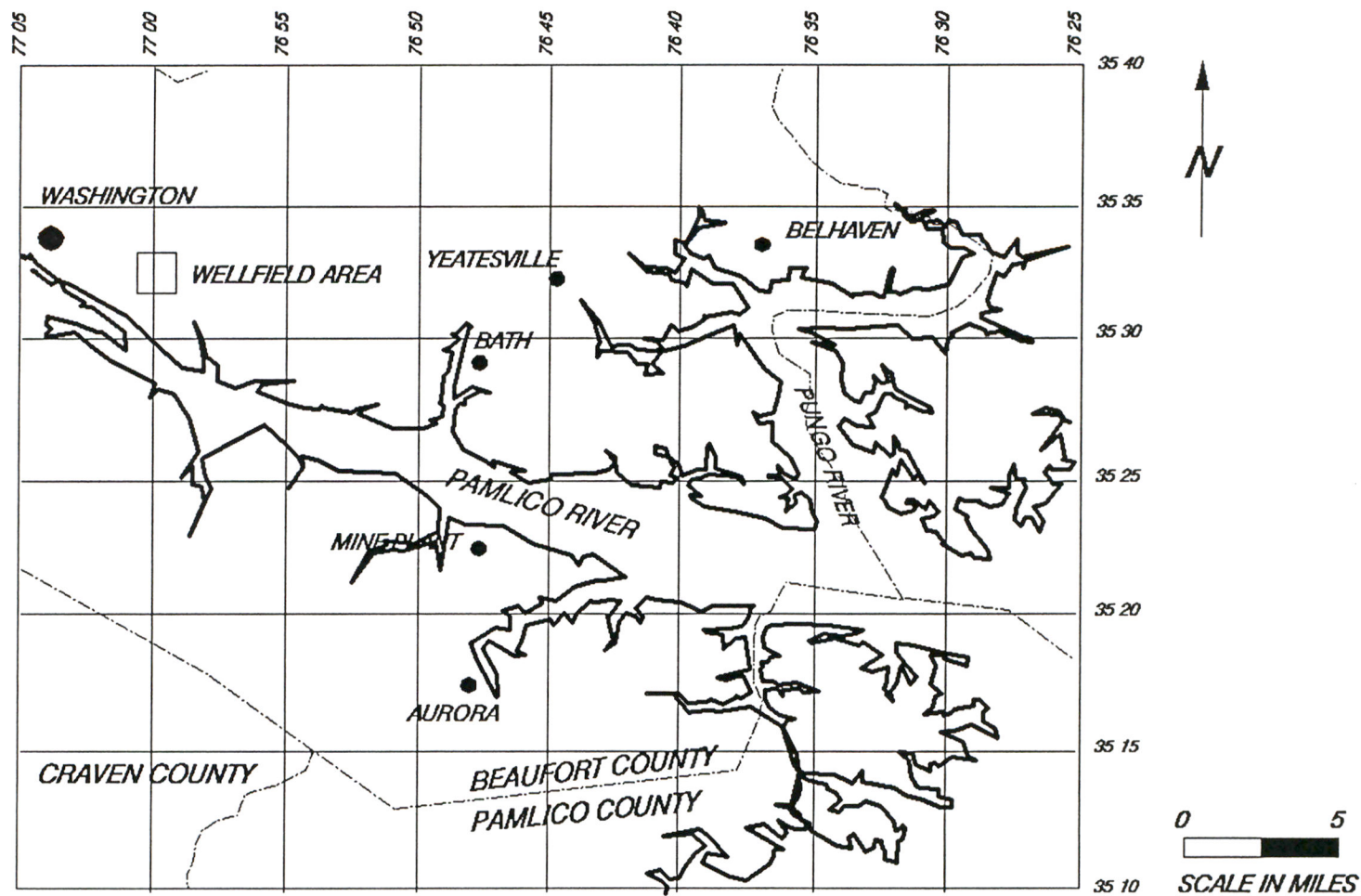


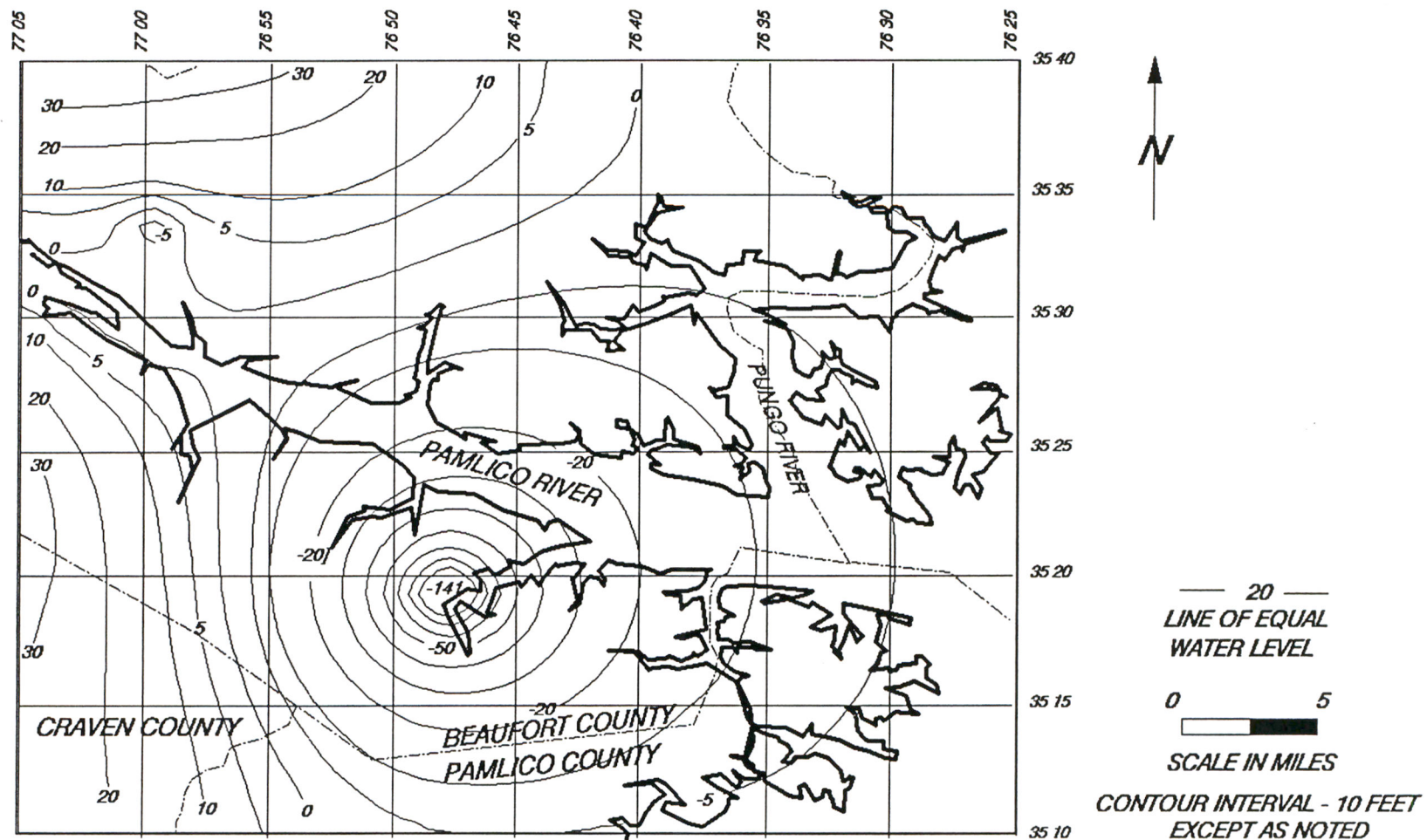
FIGURE 61 - LOCATION OF WASHINGTON WELLFIELD
USED IN SIMULATIONS

respectively) were performed concurrently with the wellfield withdrawals. These conditions were simulated for four years at each mining location, for a total of twelve years. Since the simulations were intended to illustrate relative head changes at the mine locations as a result of the wellfield, the impact of decreasing Cretaceous heads was not considered in this section.

The potentiometric surface maps produced during the simulations are presented on Figures 62, 63, and 64.

Potential for Reduction of Pumping Rates

In order to determine if withdrawals associated with the wellfield could reduce the depressurization pumping volumes required at the mine centers, the simulated heads at each pumping center (calculated concurrently with wellfield withdrawals) were compared to the previously simulated heads at the pumping centers. The comparisons are presented on Table 9. Table 9 indicates that the simulated heads at the end of the four-year stress periods at each pumping center were lowered slightly due to the wellfield withdrawals. Using the previously calculated specific capacities for each mine location and a resulting reduction in head of about 0.7 feet, the potential reduction in depressurization pumping was estimated for each mine location. **Therefore, it is estimated that the depressurization pumping rate may potentially be reduced only slightly once pumping at the Washington wellfield**



**FIGURE 62 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER
50.08 MGD AT MINE LOCATION 1 WITH WASHINGTON WELLFIELD**

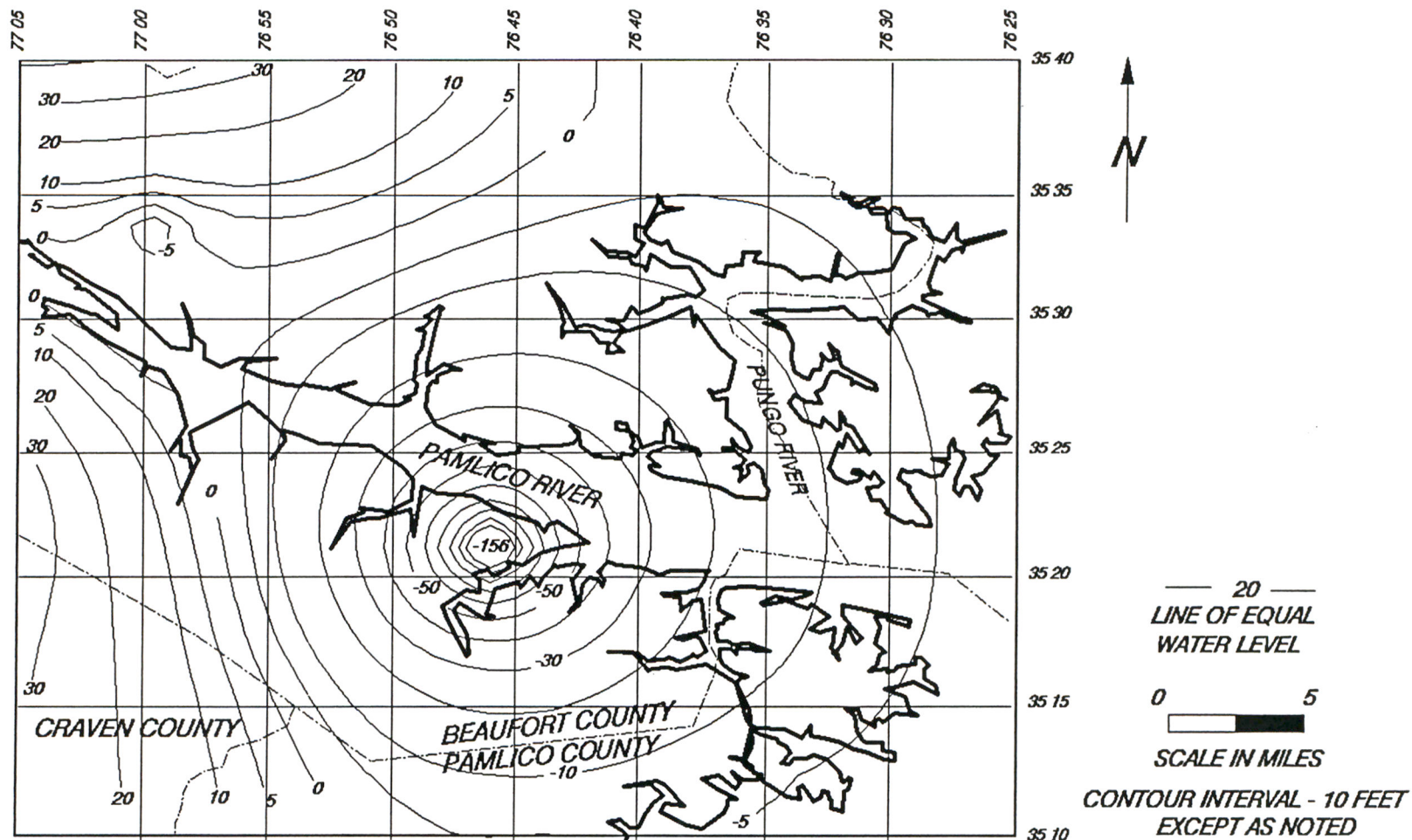


FIGURE 63 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 56.08 MGD, MINE LOCATION 2 WITH WASHINGTON WELLFIELD

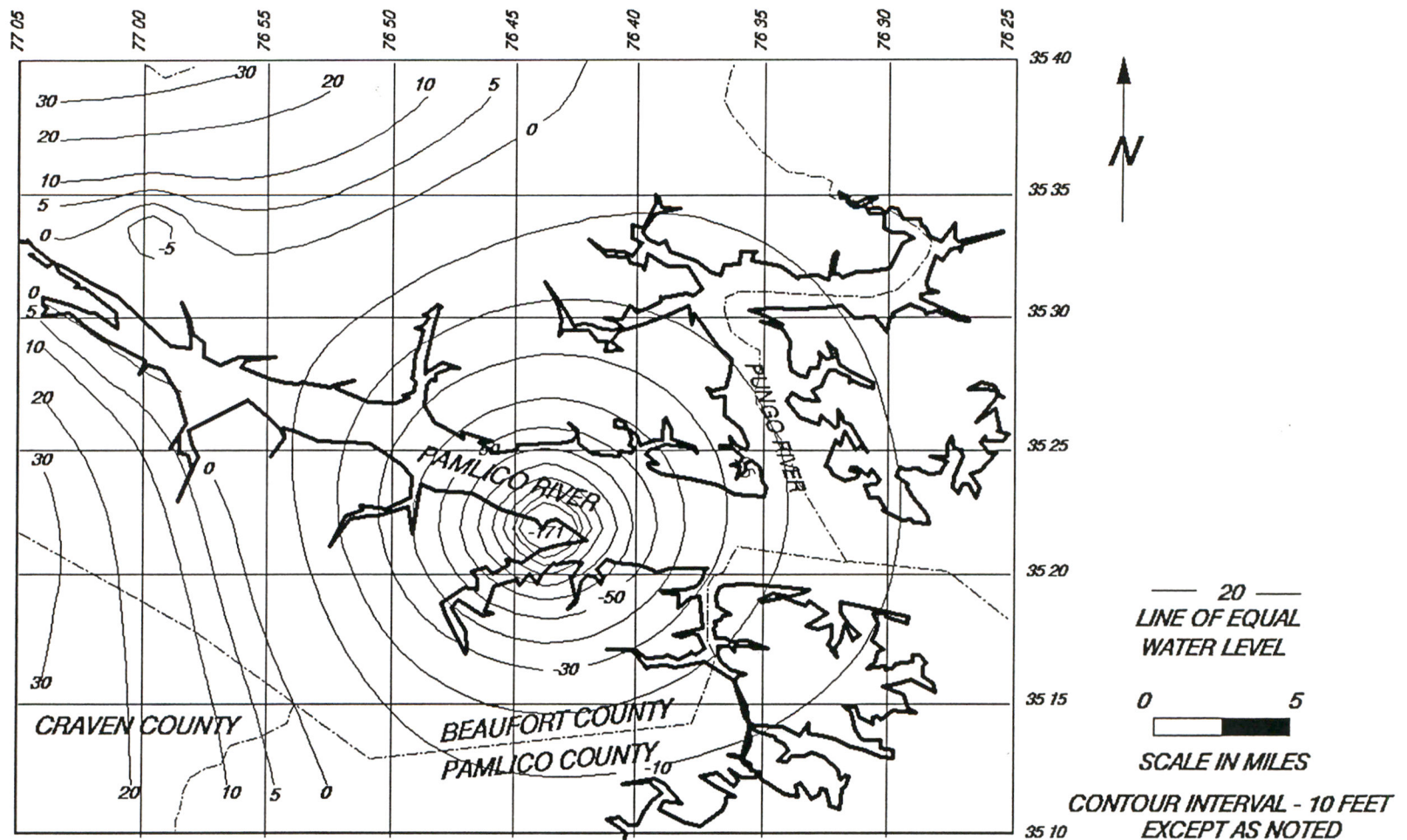


FIGURE 64 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 65.63 MGD, MINE LOCATION 3 WITH WASHINGTON WELLFIELD

commences. The estimated required pumping rates for the northeast mine advance were reduced by approximately 0.4 percent.

Table 9 - Comparison of simulated heads at pumping centers, layer 2, northeast mine advance and Washington wellfield

Mine Location	1-yr. Stress Periods	Previous Simulations	Washington Wellfield	Head Decline
1	1	-140.4	-141.1	0.7
	2	-140.5	-141.1	0.6
	3	-140.6	-141.2	0.6
	4	-140.6	-141.3	0.7
2	1	-155.1	-155.8	0.7
	2	-155.1	-155.9	0.8
	3	-155.2	-156.0	0.8
	4	-155.3	-156.0	0.7
3	1	-169.8	-170.4	0.6
	2	-169.9	-170.5	0.6
	3	-169.9	-170.6	0.7
	4	-169.9	-170.6	0.7

**Note: Heads are referenced to mean sea level
Refer to Figure 40 for mine locations**

Aquifer Response to Artificial Recharge

The most effective method of mitigating the hydrologic impacts resulting from depressurization of the Castle Hayne aquifer is through artificial recharge of the aquifer using injection wells. Injection, or recharge wells are not widely utilized in North Carolina. However, it is believed that as

water demands in this region increase, recharge augmentation via artificial means may require further consideration. Therefore, the flow model developed in this study is expected to provide insight into the efficiency of injection wells on the groundwater system.

Description of Injection Well System

Many elements must be considered when evaluating the use of injection wells including: water supply and quality, land availability, optimum well location(s), aquifer capacity for recharge, and costs associated with the project. For purposes of this study, assumptions include the availability of 1) an ample supply of good quality water (most likely from the depressurization pumping at Texasgulf), 2) land required for the well site(s), and 3) sufficient funding for the project. Therefore, the factors considered when modeling the effects of the artificial recharge include 1) the recharge capacity of the injection wells, and 2) optimum well locations.

The operation of the injection wells used in the flow model entails pumping water into a well in a quantity which maintains a head differential sufficient to force water into the aquifer. When water is pumped into an injection well, its movement into the aquifer forms a cone-of-impression similar in shape, but reverse of the cone-of-depression formed when pumped from a production well. The estimated maximum rate of injection required to maintain a sufficient head differential

was determined using a modification of the Jacob equation as shown below:

$$Q = \frac{hT}{264 \log \frac{0.3Tt}{r^2S}}$$

where:

- Q = injection flow rate, gpm
 - h = height of the water column above prepumping potentiometric surface, feet
 - T = transmissivity, gpd/ft
 - t = time of pumping, days
 - r = radius of the well, feet
 - S = storage coefficient of aquifer, unitless
- (Driscoll, 1986)

Assumptive default values for the pumping time, well radius, and storage coefficient of 1 day, 0.0833 feet and 1.0E-05, respectively, were used in the equation. The values for height of the water column and transmissivity are dependent upon the well location, and were determined for each injection well.

Use of this formula must be done judiciously because some of the assumptions governing the Jacob equation (i.e. a homogeneous, isotropic aquifer of infinite areal extent, initially horizontal potentiometric surface, etc.) are unrealistic; and problems associated with water quality, air entrainment, and water temperature, result in recharge rates rarely equalling pumping rates (Driscoll, 1986). Therefore, the potential recharge rate calculated for each location was reduced by one-half for the simulations. The flow rates used

for each injection well are presented on Figure 65.

Due to the natural eastward gradient of the potentiometric surface of the Castle Hayne aquifer, and since transporting water from the mine area across the Pamlico River would be highly impractical, the injection wells were positioned west and south of the active mine location in a semi-circular arrangement (Figure 65).

Two four-year simulations were performed, the first with five wells at a five-mile radius from mine location 2, and the second with ten wells at a ten-mile radius from the mine location. A pumping rate of 56.1 MGD was imposed on mine location 2 during the simulations. Since the simulations were intended to indicate relative impacts of the injection wells on the aquifer, neither the effects of the decreasing Cretaceous heads nor the Washington wellfield were evaluated in the simulations.

Results of Artificial Recharge Simulations

The potentiometric surface maps produced during the simulations utilizing the five and ten injection wells are presented on Figures 66 and 67, respectively. These maps indicate that the cones-of-depression were visibly steepened at the mine area and the expanse of large drawdowns in the vicinity of the mine was reduced.

In an attempt to evaluate the effects of the artificial recharge on specific areas in the mine vicinity, simulated

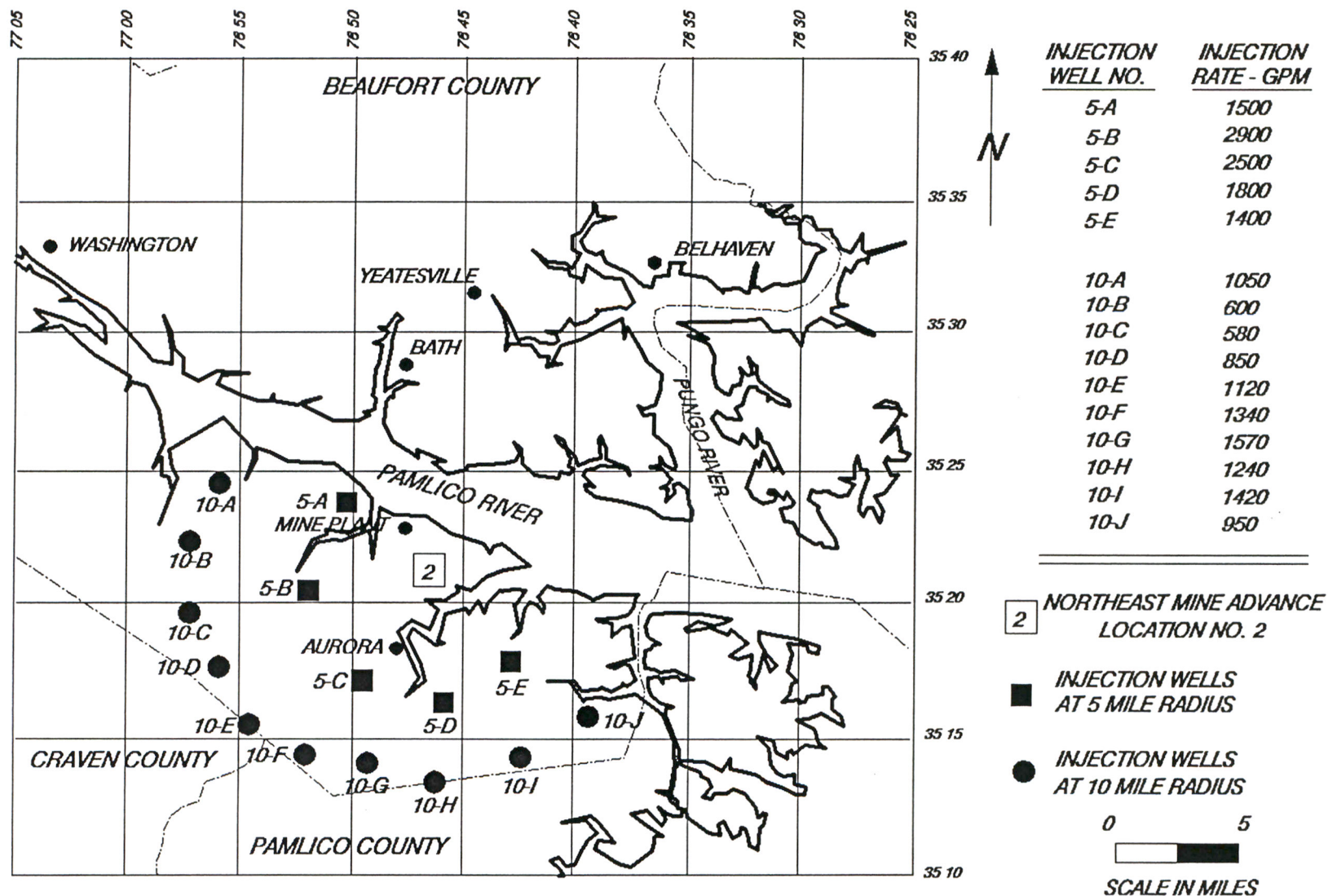


FIGURE 65 - LOCATIONS OF INJECTION WELLS AND CORRESPONDING INJECTION RATES USED IN ARTIFICIAL RECHARGE SIMULATIONS

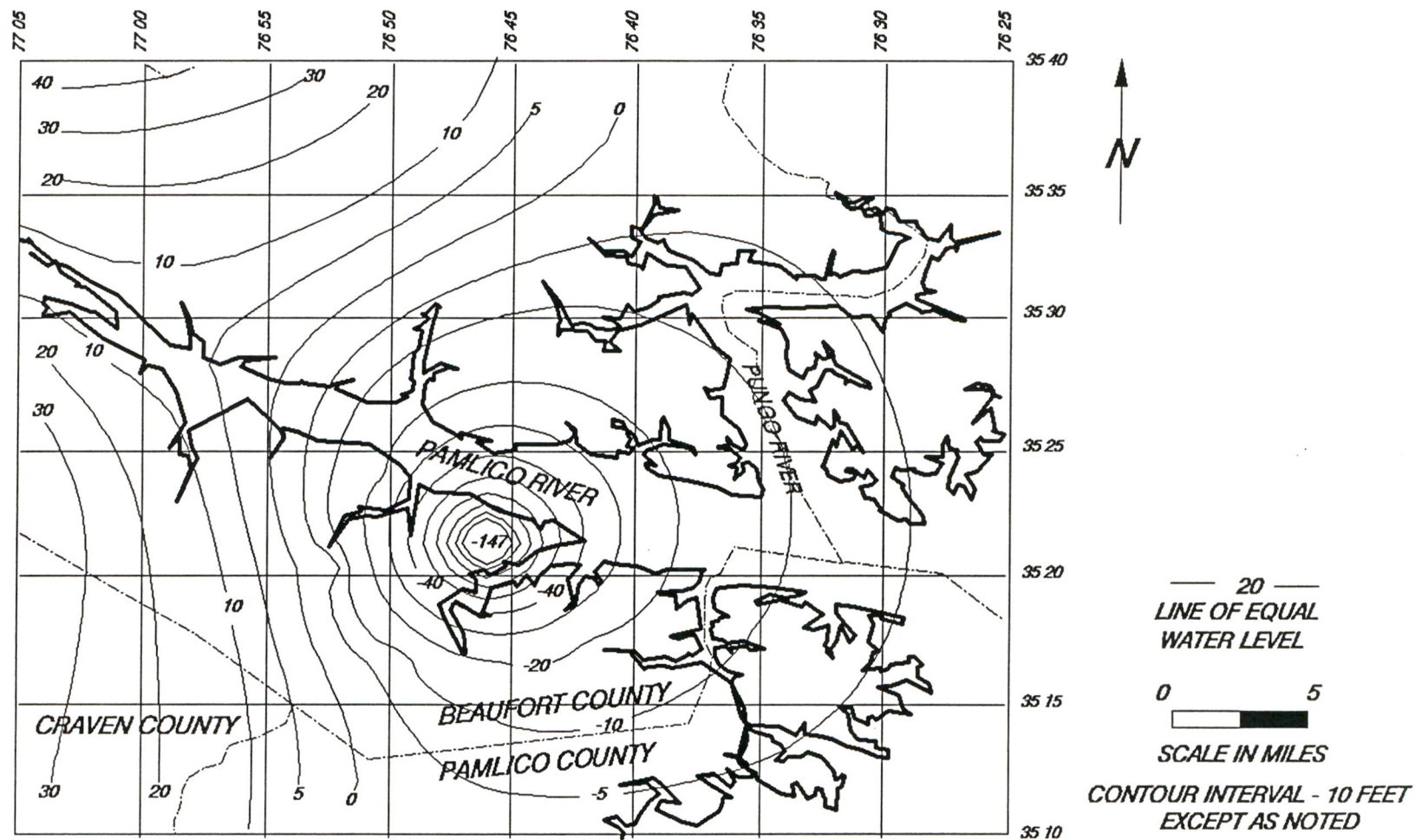


FIGURE 66 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 56.08 MGD, NORTHEAST MINE ADVANCE LOCATION 2 5 INJECTION WELLS AT 5 MILE RADIUS

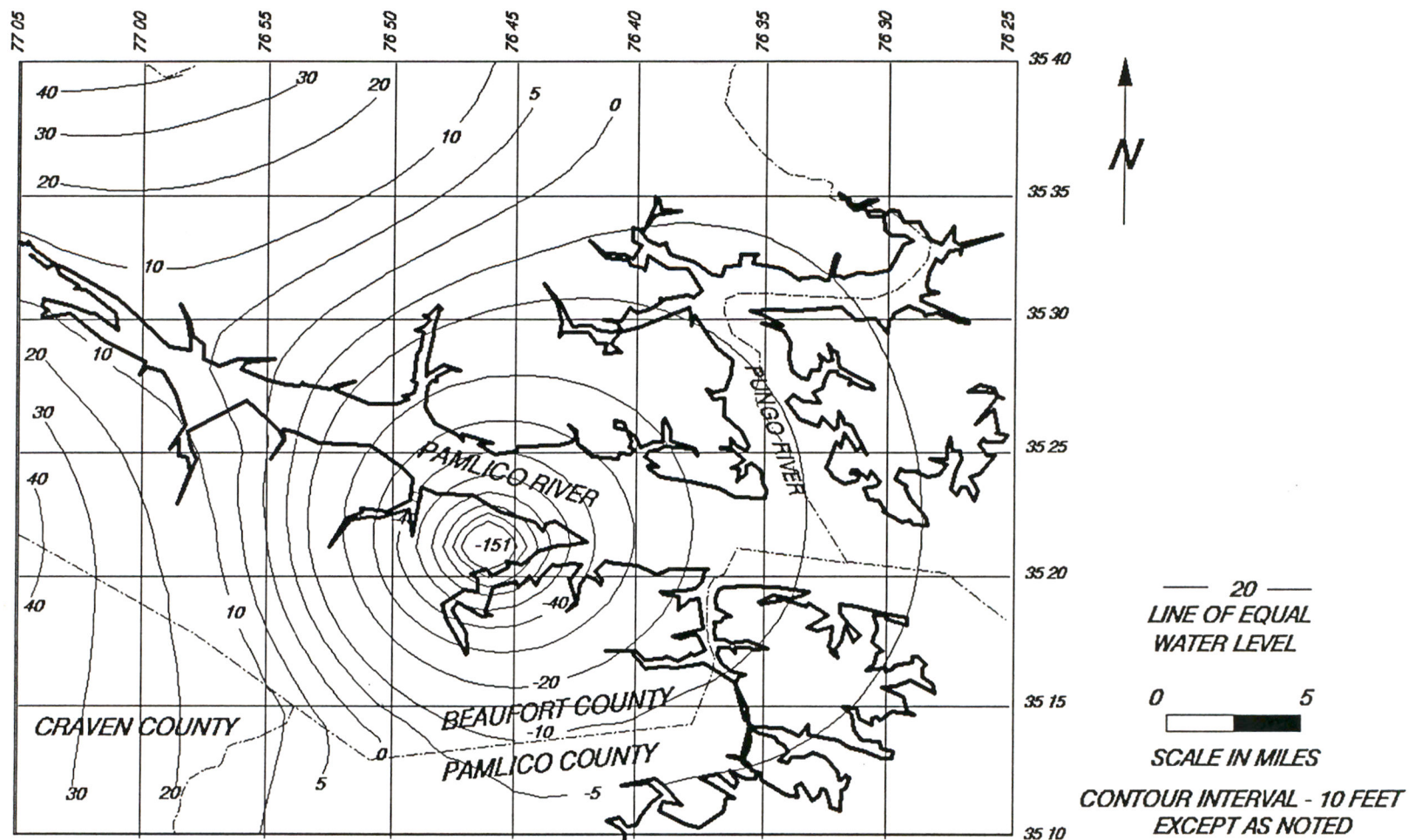
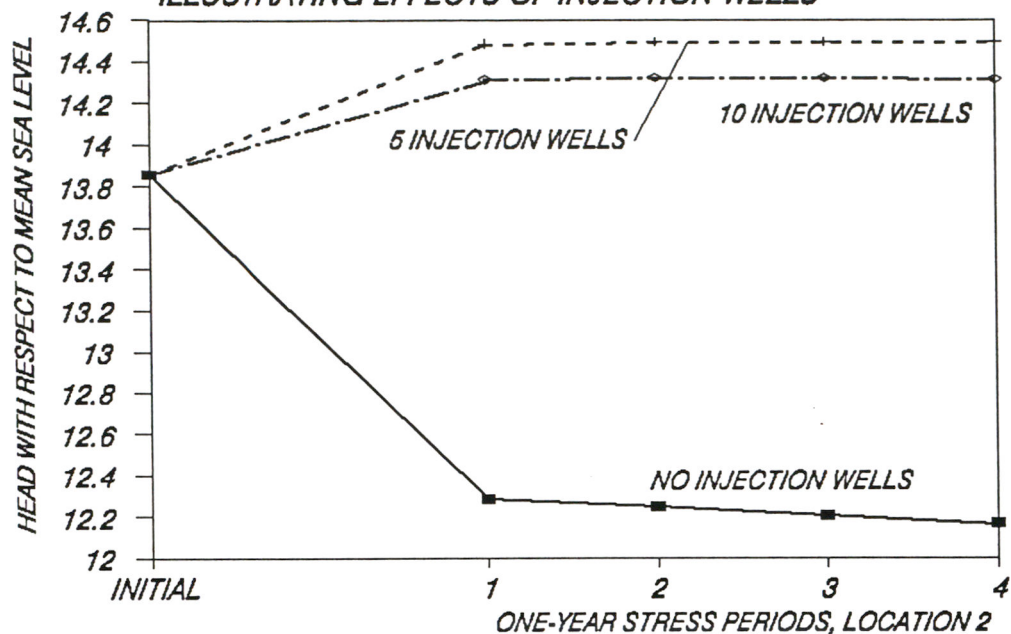


FIGURE 67 - SIMULATED POTENTIOMETRIC SURFACE MAP OF THE CASTLE HAYNE AQUIFER (LAYER 2), 56.08 MGD, NORTHEAST MINE ADVANCE LOCATION 2
10 INJECTION WELLS AT 10 MILE RADIUS

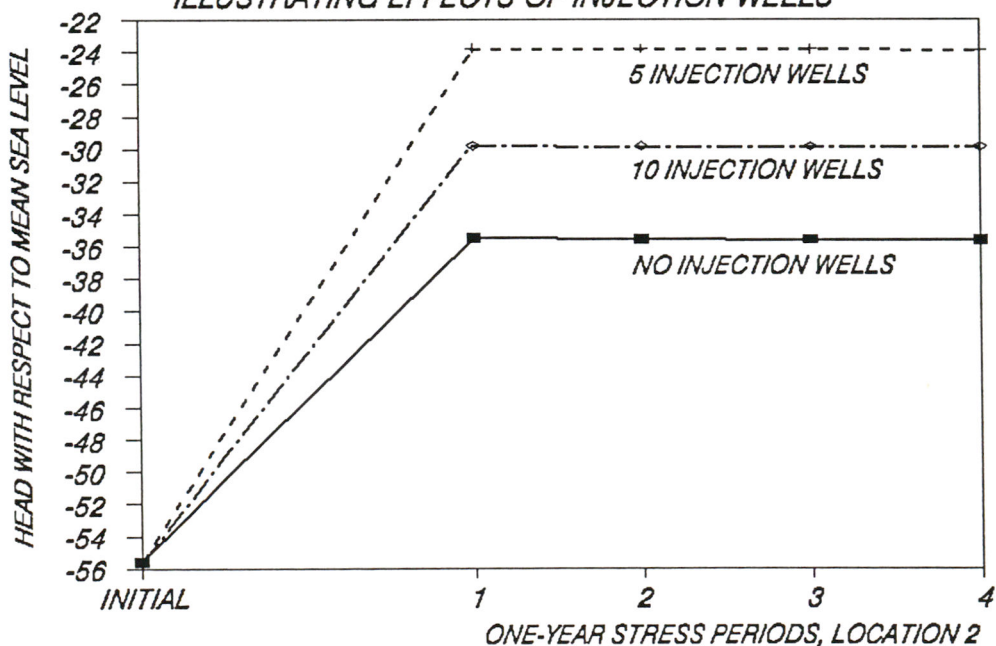
hydrographs for wells located at specific areas were compared before and after implementation of the injection wells. Comparisons of simulated head changes were performed for wells located near the east Washington (A), Aurora (B), Texasgulf mine plant (C), Yeatesville (D), Belhaven (E), and the east Bath (F) areas as shown on Figure 41. These comparisons are presented on Figures 68 to 73. It is evident in these figures that the array of five injection wells was generally more efficient in reducing the estimated head reductions at these locations, especially in areas proximal to the active mine location. The series of ten injection wells also diminished the anticipated head reductions at these locations, but to a lesser degree than the five nearer to the mine location.

The increased heads resulting from the previous injection well simulations is also evident at the active mine area. The heads at the mine location increased by nearly nine feet as a result of the five injection wells and about four feet due to the ten injection wells (Table 10). As a result, the pumping rate at active mine locations would have to be increased to maintain safe mining conditions. Using the specific capacity for the mine location used in the simulations, the pumping rate required to achieve the required heads would have to be increased by approximately 5.5 percent during operation of five injection wells and approximately 2.4 percent during operation of ten injection wells.

**FIGURE 68 - SIMULATED HYDROGRAPHS FOR WELL A, E. WASHINGTON AREA
ILLUSTRATING EFFECTS OF INJECTION WELLS**

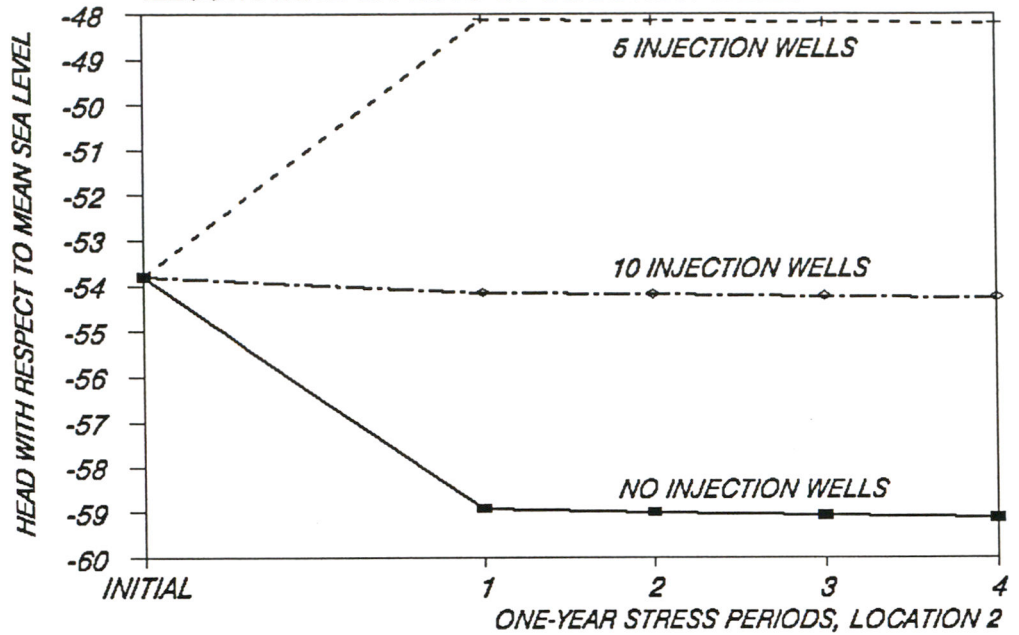


**FIGURE 69 - SIMULATED HYDROGRAPHS FOR WELL B, AURORA AREA
ILLUSTRATING EFFECTS OF INJECTION WELLS**

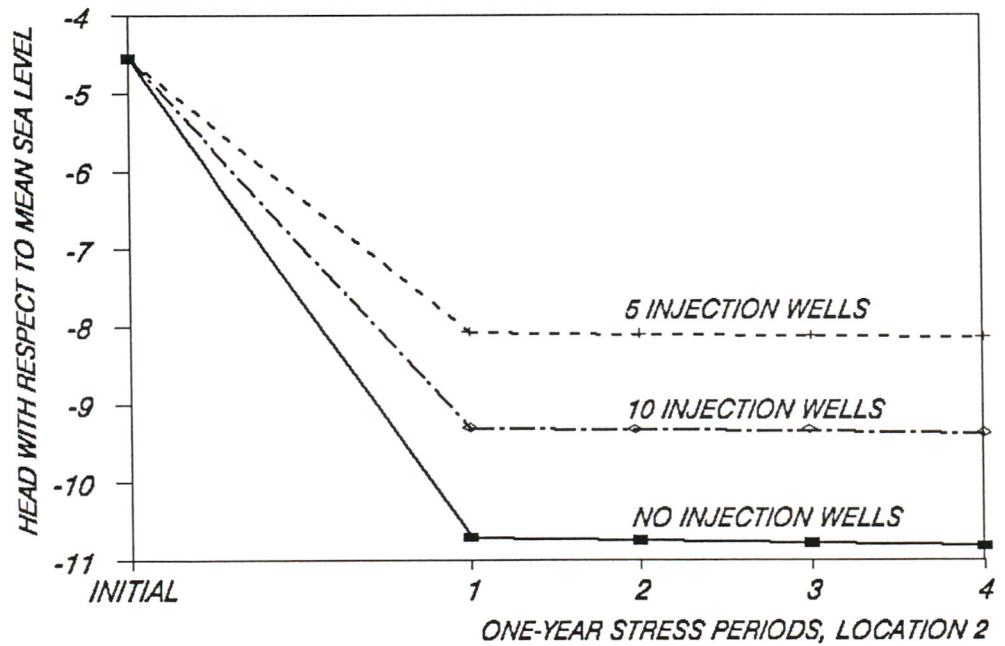


NOTE: WELL LOCATIONS PRESENTED ON FIGURE 41

**FIGURE 70 - SIMULATED HYDROGRAPHS FOR WELL C, MINE PLANT AREA
ILLUSTRATING EFFECTS OF INJECTION WELLS**

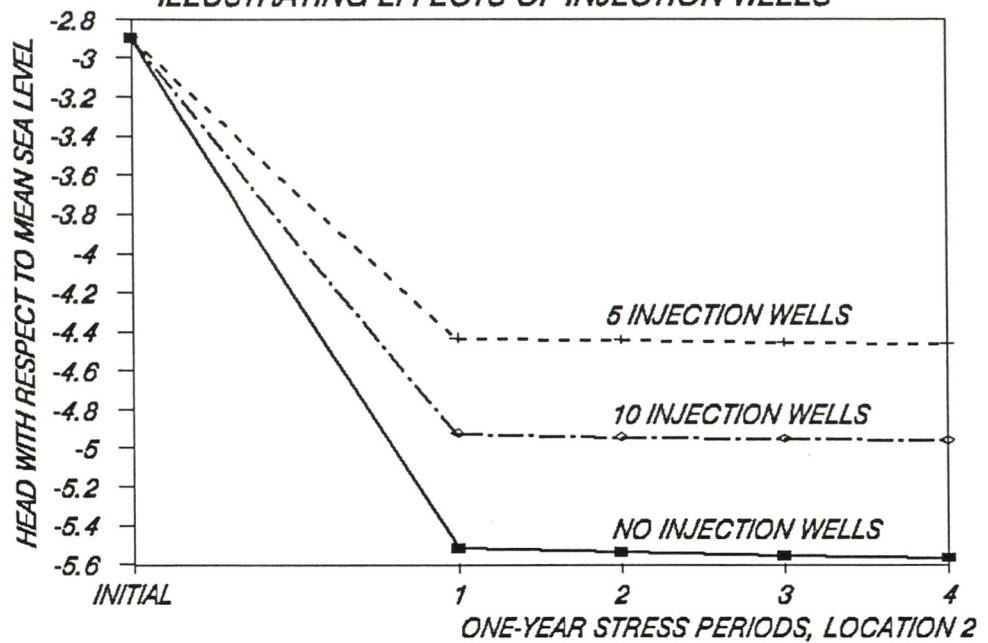


**FIGURE 71 - SIMULATED HYDROGRAPHS FOR WELL D, YEATESVILLE AREA
ILLUSTRATING EFFECTS OF INJECTION WELLS**

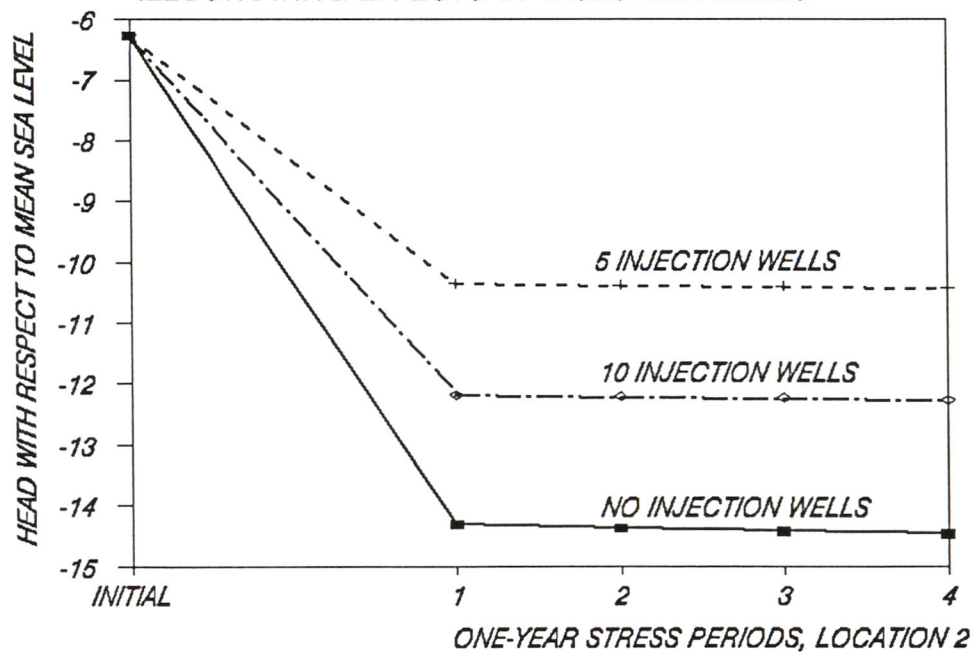


NOTE: WELL LOCATIONS PRESENTED ON FIGURE 41

**FIGURE 72 - SIMULATED HYDROGRAPHS FOR WELL E, BELHAVEN AREA
ILLUSTRATING EFFECTS OF INJECTION WELLS**



**FIGURE 73 - SIMULATED HYDROGRAPHS FOR WELL F, EAST BATH AREA
ILLUSTRATING EFFECTS OF INJECTION WELLS**



NOTE: WELL LOCATIONS PRESENTED ON FIGURE 41

Table 10 - Comparison of simulated heads at pumping center, mine location 2, with and without injection wells

ONE-YEAR TIME STEPS	SIMULATED HEADS AT MINE LOCATION 2, FEET MSL		
	NO INJECTION WELLS	5 INJECTION WELLS-5 MI.	10 INJECTION WELLS-10 MI.
1	-155.1	-146.4	-151.1
2	-155.1	-146.5	-151.2
3	-155.2	-146.5	-151.2
4	-155.3	-146.5	-151.2

NOTE: LOCATIONS OF INJECTION WELLS AND MINE LOCATION 2 PRESENTED ON FIGURE 65.

SUMMARY OF POTENTIAL MITIGATIVE STRATEGIES

The calibrated flow model was used to evaluate three potential strategies for reduction of the required depressurization pumping rate at the Texasgulf facility. These included 1) reductions due to the continued decrease in heads in the Cretaceous aquifer system, 2) reductions due to the operation of a municipal wellfield located approximately 17 miles northwest of the mine areas, and 3) simulations of artificial recharge through use of injection wells.

Simulations of aquifer depressurization with and without consideration of head decreases in underlying units indicated that the potentiometric surface of the Castle Hayne aquifer (layer 2) does decrease slightly when the potentiometric surface of the Cretaceous units decreases. Utilizing a

surface of the Cretaceous units decreases. Utilizing a Cretaceous head decrease of 2.5 ft/yr, it was estimated that required depressurization pumping rates could be decreased by approximately 0.7 percent at the mine locations. However, the mean annual decline values indicated that pumping could not be reduced each year.

Simulations indicated that groundwater pumping from the Castle Hayne aquifer for municipal supply at the Washington wellfield would slightly lower the head at the mine locations, reducing the required pumping at each location. Based on the simulations of the effects of the wellfield, it was estimated that pumping could be reduced an additional 0.4 percent.

Based on these simulations, it was determined that the previously estimated depressurization pumping rate for the northeast mine advance could be reduced a total of approximately 1.1 percent as a result of the combined effects of the declining Cretaceous heads and the Washington wellfield withdrawals. In order to evaluate the accuracy of these reduced pumping rates, additional simulations were performed implementing these rates concurrently with the trend of declining Cretaceous heads and the Washington wellfield withdrawals. **These simulations confirmed that the estimated required pumping rates for the northeast mine advance are approximately 49.53, 55.47, and 64.91 MGD at locations 1, 2, and 3, respectively; assuming the lean ore is in place. Estimated pumping rates of 52.86, 58.90, and 68.70 MGD will be**

required if the lean ore is not in place.

Simulations of series of injection wells positioned in a semicircular array south and west of a mine location resulted in noticeable increases in heads in areas surrounding the mine. It was determined that an array of five injection wells in a five-mile radius from the pumping center was markedly more effective in reducing impacts than an array of ten wells in a ten-mile radius. However, operation of injection wells resulted in increased heads at the mine center. It was determined that pumping would have to be increased by approximately 5.5 and 2.4 percent for as a result of the operation of the five and ten injection wells, respectively.

Injection wells would also inhibit the lateral encroachment and/or upconing of chloride-rich waters into the Castle Hayne aquifer in the depressurized area. Additional simulations using particle tracking and/or solute transport models would be necessary to evaluate this issue.

REFERENCES

- Anderson, M.A., and Woessner, W.W., 1992, Applied groundwater modeling: simulation of flow and advective transport: Academic Press Inc., San Diego, CA, 381 p.
- Bossler, J.D., 1984, Standards and Specifications for Geodetic Control Networks: Federal Geodetic Control Committee, 33p.
- Brown, P.M., Miller, J.A. and Swain, F.M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geological Survey Professional Paper 796, 79 p.
- Coble, R.W., Strickland, A.G., and Bailey, M.C., 1989, Water level data for North Carolina - 1987: U.S. Geological Survey Open-File Report 89-68, 152 p.
- Daniel, Charles C., III, 1980, Hydrology, geology, and soils of pocosins: A comparison of natural and altered systems, in Pocosins: An integrated analysis of Coastal Plain freshwater wetlands in North Carolina, edited by C.J. Richardson, S.A. Anderson, and W.A. Thompson: Dowden Huthinson and Ross, Inc., Stroudsburg, PA.
- Davis, G.H., 1987, Land subsidence and sea level rise on the Atlantic Coastal Plain of the United States: Environmental Geology and Water Science, Vol. 10, No. 2, p. 67-80
- DeWiest, R.J.M., Sayre, A.N., and Jacob, C.E., 1967, Evaluation of potential impact of phosphate mining on ground-water resources of Eastern North Carolina: North Carolina Department of Water Resources, 167 p.
- Driscoll, F.G., 1986, Groundwater and wells, 2nd ed.: Johnson Filtration Systems, Inc., St. Paul, MN, 1089 p.
- Eimers, J.L., Lyke, W.L., and Brockman, A.R., 1990, Simulation of ground-water flow in aquifers in cretaceous rocks in the central coastal plain, North Carolina: U.S. Geological Survey Water-Resources Investigations Report 89-4153, 101 p.
- Eimers, J.L., 1992, personal communication
- Floyd, E.O., 1969, Ground-water resources of Craven County, North Carolina: U.S. Geological Survey Hydrologic Investigations Atlas HA-343

- Franke, O.L., Reilly, T.E., and Bennett, G.D., 1984, Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems--an introduction: U.S. Geological Survey Open File Report 84-458, Book 3, Chapter B5, 15 p.
- Freeze, R.A. and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 p.
- Giese, G.L., Eimers, J.L., and Coble, R.W., 1991, Simulation of ground-water flow in the coastal plain aquifer system of North Carolina: U.S. Geological Survey Open-File Report 90-372, 178 p.
- Gilmore, I.K. "Tex", 1992, personal communication
- Hargis, D.R., 1982, Regional flow model of upper Castle Hayne aquifer: North Carolina, Hargis and Montgomery, Inc. Consultants Report, 33 p.
- Heath, R.C., 1975, Hydrology of the Albemarle-Pamlico Region, North Carolina: U.S. Geological Survey Water Resources Investigations 9-75, 98 p.
- _____, 1984, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.
- _____, 1992, written communication
- Leggette, Brashears and Graham, Inc., (LBG, Inc.) 1991, Technical Report in Support of Renewal and Modification of Water Use Permit No. 3: Consultants Report to Texasgulf, Inc., 103 p.
- Leggette, Brashears and Graham, Inc., 1992, 1991 Annual Summary of Ground-Water Levels and Chloride Concentration Trends in the Area of Aurora, North Carolina: Consultants Report to Texasgulf, Inc., 33 p.
- McDonald, M.G. and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey, Techniques of Water Resources Investigations, Book 6, Chapter A1, 528 p.
- North Carolina Board of Water and Air Resources, Texasgulf Sulfur, NC Phosphate Corp. (Joint Study), 1971, Hydrogeology and effects of pumping from Castle Hayne aquifer system: 146 p.
- North Carolina Department of Natural and Economic Resources (NCDNER), 1974, Groundwater Section, Status report on groundwater conditions in Capacity Use Area No. 1,

Central Coastal Plain: North Carolina groundwater bulletin No. 21: 146 p.

- _____, 1976, Interim report on groundwater conditions in Capacity Use Area No. 1, central coastal plain, North Carolina, 1974-1975: 55 p.
- Peek, H.M. and Nelson, P.F., 1975, Potential effects of withdrawals from the Castle Hayne aquifer for expanded phosphate mining in Beaufort County, North Carolina, Report of investigation No. 11: 33 p.
- Poland, J.F. and Davis, G.H., 1969, Land subsidence due to withdrawals of fluids in Reviews in engineering geology, Vol. II, edited by Varnes, D.J. and Kiersch, G., Geological Society of America, 350 p.
- Richards, H.G., 1950, Geology of the coastal plain of North Carolina: Transactions of the American Philosophical Society, vol. 40, Part 1, 83 p.
- Sherwani, J.K., 1973, Computer simulation of ground water aquifers of the coastal plain of North Carolina: University of North Carolina Water Resources Research Institute Report No. 75, 102 p.
- Thompson, G., 1992, personal communication
- Waltham, A.C., Ground subsidence: Chapman and Hall, Inc., New York, NY, 202 p.
- Whalen, C.T., 1978, Control leveling: National Geodetic Survey-NOAA Technical Report NOS 73 NGS 8, 20 p.
- Winner, M.D., Jr., and Coble, R.W., 1989, Hydrogeologic framework of the North Carolina Coastal Plain aquifer system: U.S. Geological Survey Open-File Report 87-690, 155 p.
- Winner, M.D., Jr., and Lyke, W.L., 1986, History of ground-water pumpage and water-level decline in the Black Creek and upper Cape Fear aquifers of the central coastal plain of North Carolina: U.S. Geological Survey Water-Resources Investigations Report 86-4168, 21 p.