Hydrogeologic Framework and Ground Water Conditions in the North Carolina East Central Coastal Plain

By: Jeff C. Lautier

North Carolina Department of Environment and Natural Resources
Division of Water Resources
August, 2009

TABLE OF CONTENTS

Page Number

FIGURES

Figure No.

TABLES

APPENDIX

ILLUSTRATIONS

Plate No.

Executive Summary

This report is part of a series published by the North Carolina Division of Water Resources, as part of an ongoing effort to provide current interpretations of the hydrogeologic framework and ground water resources of the North Carolina Coastal Plain. Previous investigations have covered the North Albemarle area, the Central and Southern Coastal Plains (Lautier 1998, 2001, 2006)

The East-Central Coastal Plain of North Carolina, as covered in this study, is made up of the tidewater region between the Albemarle Sound and Onslow Bay. It is referred to as a tidewater region because many of the rivers and streams are affected by oceanic tidal fluctuations. The study area includes Beaufort, Washington, Tyrrell, Dare, Hyde, Pamlico, Craven, and Carteret Counties (figure i).

This region has experienced ever-increasing reliance on ground water as a source of water supply resulting from population growth and tourism. In addition, open pit mining operations that require dewatering have also placed increased stress on the ground water system. For this reason it is important to understand in more detail, the three dimensional framework of aquifers and confining units, their hydraulic properties, and how they are being affected by pumping stresses. Moreover, it is essential to understand the distribution of salt water in the system, and how it is being affected by pumping.

The area covered in this study is situated within the tidewater region of the North Carolina Coastal Plain. The region has been described by Stephenson and others (1912) and Nelson (1964) as a broad, eastward dipping plain that encompasses one of a series of en echelon marine terraces which formed during the Pleistocene era, and were deposited in parallel orientation with the Atlantic Coastline. Stephenson and others (1912) named it the Pamlico terrace, as it is transected by the Pamlico River and Sound. As indicated on the geologic map of North Carolina (Brown and others, 1985) the western boundary of the terrace is an escarpment (Suffolk scarp) that runs north to south across the study area from the town of Plymouth in Washington County, to the town of Newport in Carteret County. The western-most section of the study area extends a few miles to the west of the Suffolk Scarp on an older marine terrace. Land surface elevations across the region vary from sea level to 55 feet with the highest elevations found in the western-most part, although the dunes on the Outer Banks can exceed 50 feet above sea level. The region is generally of low relief and swampy. A number of large, natural lakes are present, including Phelps, Mattamuskeet, Pungo, and New Lakes. The Pamlico, Neuse, Pungo, and Alligator Rivers dissect the land surface along their courses to the Albemarle and Pamlico Sounds.

The geology of the East Central Coastal Plain may be characterized as a gently southeastward dipping, and southeastward thickening wedge of sediments and sedimentary rock ranging in age from Recent through Cretaceous (possibly Triassic) which rests on an underlying basement complex of Paleozoic age rocks. The basement

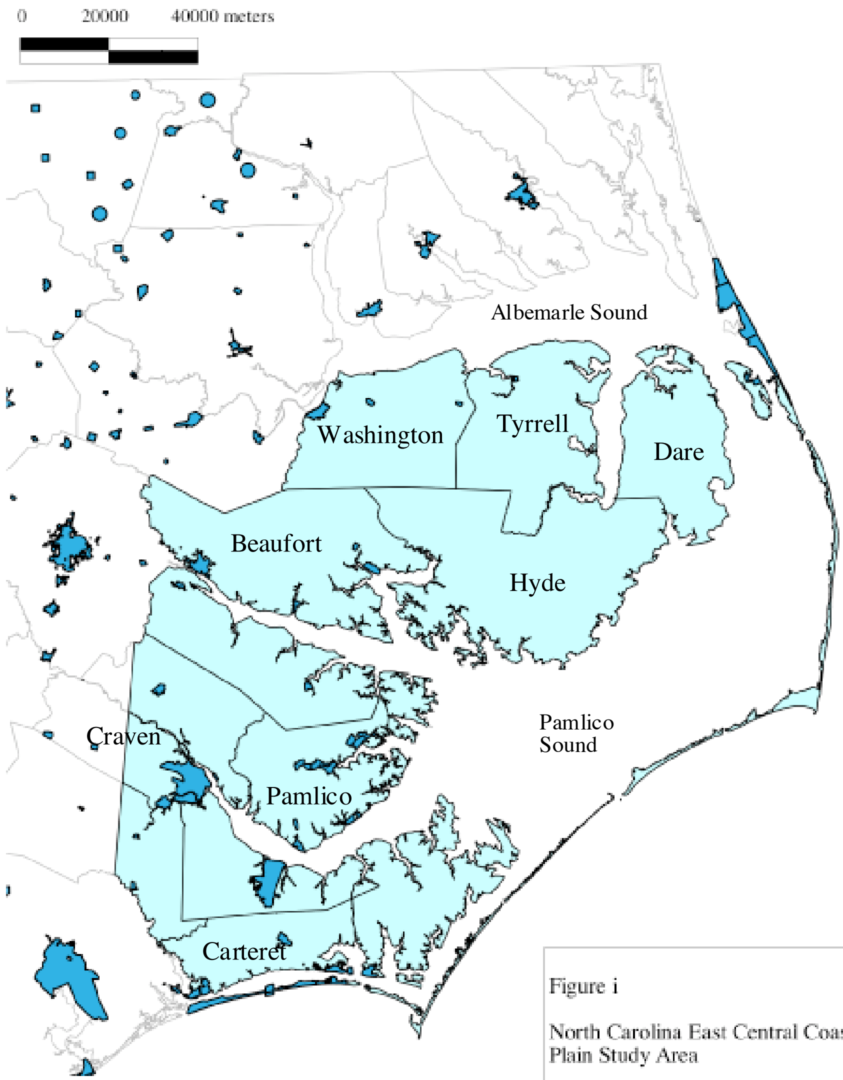


Figure i

North Carolina East Central Coastal Plain Study Area surface ranges in elevation between 1,300 and 10,000 feet below sea level within the area of study, and dips southeast at a rate of 40 feet per mile in the western part of the area to 125 feet per mile in the area of the Outer Banks. The sediment wedge is comprised of layers and lenses of sand, clay, silt, limestone, gravel, shell material and combinations thereof which range in total thickness from 1,400 to as much as 10,000 feet as measured at the Humble Oil Co. Cape Hatteras Lighthouse No. 1 well in Dare County. Beneath a veneer of Quaternary and Pliocene age sediments, the Eocene Castle Hayne Formation subcrops along the western fringe of the study area. Older formations subcrop or outcrop beyond the western limits of the area. Deposition of the sediment wedge occurred in cyclic fashion during alternating transgressions and regressions of the Atlantic Ocean, in marine to non-marine environments.

The sedimentary column of the East Central Coastal Plain is subdivided into geologic formations and formation members based upon position of layers in the sequence of sediments, lithology, and faunal composition. The subdivision of these deposits into aquifers and confining units is based on the delineation of non-permeable versus hydraulically connected permeable units, the boundaries of which sometimes, and sometimes do not, correspond to geologic formation boundaries. Aquifers and confining units are commonly made up of more than one formation, or may include only part of a formation or parts of several formations due to the discontinuous distribution of strata in the East Central Coastal Plain. The relationship of the geologic column to the system of hydrogeologic subdivisions as defined by this study is depicted in figure ii.

The hydrogeologic system in the study region, from basement to land surface, consists of eight regionally significant aquifers and the intervening confining units that separate them. They are mentioned from oldest to youngest as follows:

The Lower Cape Fear aquifer, which is comprised along with its confining unit, of the lower part of the Cape Fear Formation of Cretaceous age. The Lower Cape Fear aquifer is underlain by sediments of Lower Cretaceous and possibly Triassic age. Due to a lack of water level data it is impossible to determine where the lower boundary of the Lower Cape Fear aquifer and top of a possible Lower Cretaceous Aquifer occurs.

The Upper Cape Fear aquifer, which corresponds to the upper part of the Cape Fear Formation and sometimes the lower part of the Cretaceous Black Creek Formation. The confining unit is composed of clay or silt beds present in the lower part of the Black Creek or upper part of the Cape Fear Formation.

The Black Creek aquifer, which corresponds primarily to the Black Creek Formation. In some areas the aquifer includes the upper part of the Cape Fear Formation and the lower part of the Cretaceous Peedee Formation. The confining unit is made up of

Figure ii. Relationship of Geologic and Hydrogeologic Units in the North Carolina East Central Coastal Plain

North Carolina East Central Coastal Plain Geologic Units			North Carolina East Central Coastal Plain Hydrogeologic Units
System	Series	Formation	Aquifers and Confining Units
Quaternary	Holocene	Undifferentiated	Surficial Aquifer
	Pleistocene		
			Yorktown Confining Unit
Tertiary	Pliocene	Yorktown Formation	Yorktown Aquifer
	Miocene	Pungo River Formation	
			Castle Hayne Confining Unit
	Eocene	Castle Hayne Formation	Castle Hayne Aquifer
			Beaufort Confining Unit
	Paleocene	Beaufort Formation	Beaufort Aquifer
			Peedee Confining Unit
Upper Cretaceous		Peedee Fm.	Peedee Aquifer
			Black Creek Confining Unit
		Black Creek Formation	Black Creek Aquifer
			Upper Cape Fear Confining Unit
		Cape Fear Formation	Upper Cape Fear Aquifer
			Lower Cape Fear Confining Unit
			Lower Cape Fear Aquifer/Lower Cretaceous Aquifer Undifferentiated
Lower Cretaceous			

clay or silt beds in the upper part of the Black Creek or lower part of the Peedee Formations.

The Peedee aquifer, which is made up of the Peedee Formation. In the southeastern corner of the study area, the aquifer includes all, or part of, the Paleocene age Beaufort Formation. The confining unit is generally present in the Beaufort Formation or upper part of the Peedee Formation.

The Beaufort Aquifer, which is made up primarily of the Beaufort Formation. The confining unit is made up of the upper part of the Beaufort Formation and in some places the lower part of the Castle Hayne Formation. The aquifer may also include sands in the Peedee Formation in some areas.

The Castle Hayne aquifer is comprised primarily of the Eocene age Castle Hayne Formation. The confining unit occurs in the Quaternary age units that overly the aquifer.

The Yorktown Aquifer is made up primarily of the Pliocene age Yorktown Formation and the Miocene age Pungo River Formation. The upper part of the Yorktown aquifer may also include in some areas, sediments of Quaternary age.

The surficial, or water table aquifer, which is made up primarily of Quaternary age sediments. It also includes parts of older formations depending on the varying age of underlying sediments and the varying stratigraphic position of the uppermost confining layer.

A typical hydrogeologic cross section through the East Central Coastal Plain is shown in figure iii, exhibiting the complexity of ground water flow patterns and salt water interfaces in relation to hydrogeologic units. Ground water flows in a rather complex three dimensional pattern through the subsurface in a multilayered Coastal Plain environment. Flow occurs laterally through aquifers from recharge to discharge areas along flowlines which parallel directions of steepest hydraulic gradient. Flow also occurs vertically upward to discharge areas or downward in recharge areas in response to differences in hydraulic head between aquifers.

The system of eight regional aquifers and intervening confining units found in the Quaternary through Cretaceous age sedimentary wedge in the East Central Coastal Plain were delineated in terms of their lateral distribution, thickness, hydraulic properties, and relationship to stratigraphic units. Moreover, aquifers were described in regard to ground water flow interactions, distribution of salt water and chloride concentrations, and natural or pump induced ground water movement.

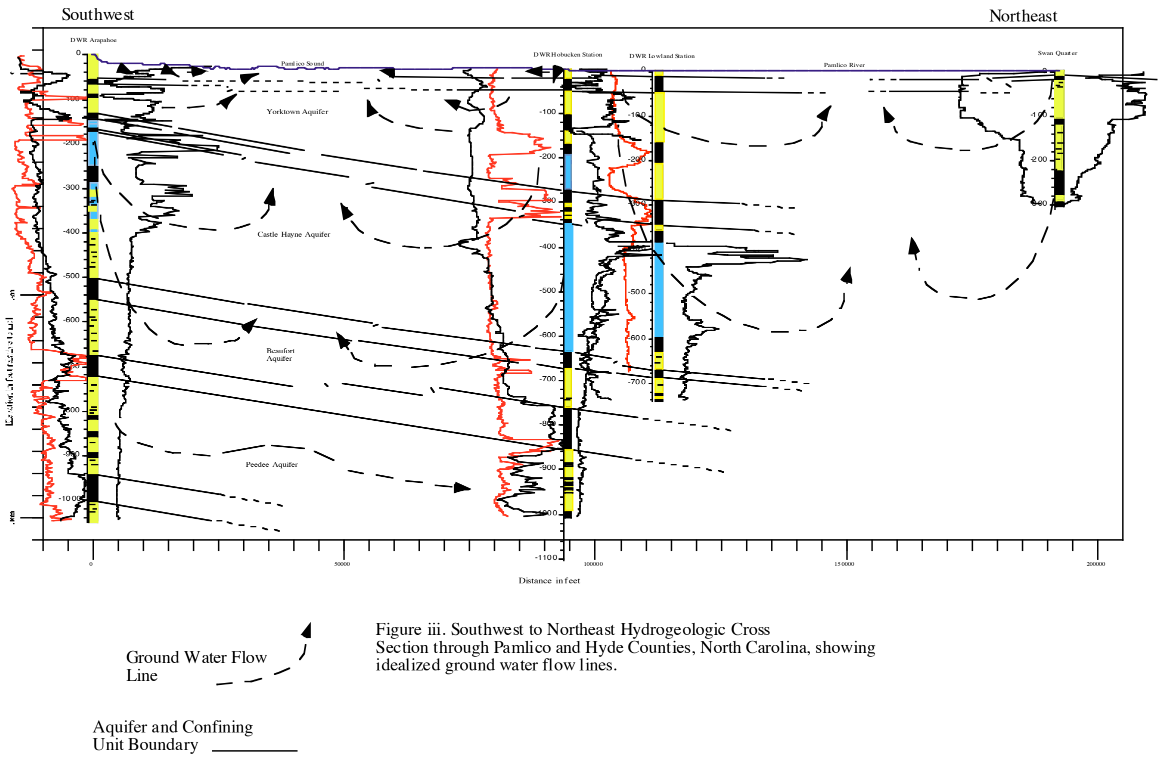


Figure iii. Southwest to Northeast Hydrogeologic Cross Section through Pamlico and Hyde Counties, North Carolina, showing idealized ground water flow lines.

Introduction

This report is part of a series published by the North Carolina Division of Water Resources, as part of an ongoing effort to provide current interpretations of the hydrogeologic framework and ground water resources of the North Carolina Coastal Plain. Previous investigations have covered the North Albemarle area, the Central and Southern Coastal Plains (Lautier 1998, 2001, 2006)

The East Central Coastal Plain of North Carolina, as covered in this study, is made up of the tidewater region between the Albemarle Sound and Onslow Bay. It is referred to as a tidewater region because many of the rivers and streams are affected by oceanic tidal fluctuations. The study area includes Beaufort, Washington, Tyrrell, Dare, Hyde, Pamlico, Craven, and Carteret Counties (figure 1).

This region has experienced ever-increasing reliance on ground water as a source of water supply resulting from population growth and tourism. In addition, open pit mining operations that require dewatering have also placed increased stress on the ground water system. For this reason it is important to understand in more detail, the three dimensional framework of aquifers and confining units, their hydraulic properties, and how they are being affected by pumping stresses. Moreover, it is essential to understand the distribution of salt water in the system, and how it is being affected by pumping.

Previous Studies

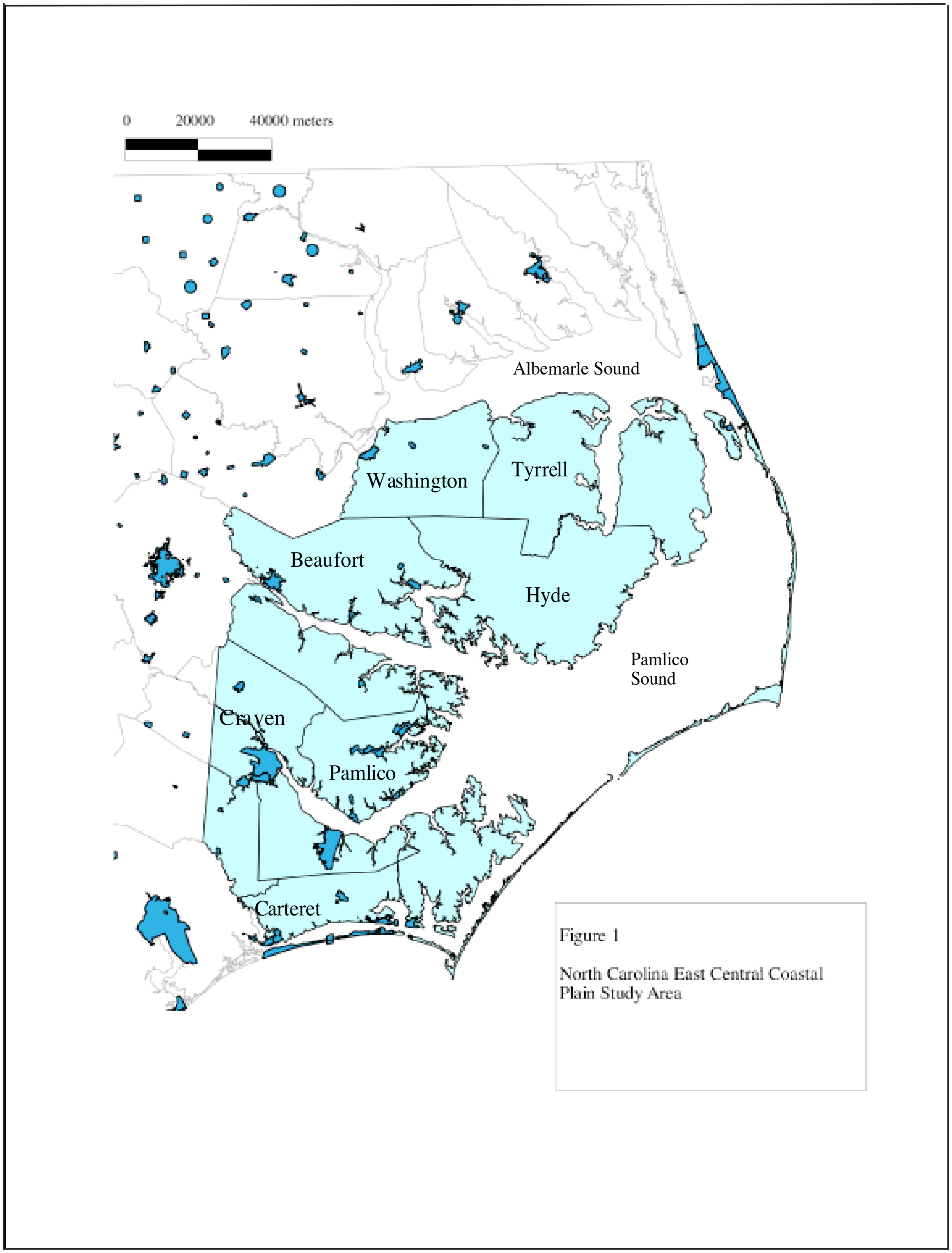
Many local and regional geologic and hydrogeologic studies have been conducted in the area covered by this report. The publications that most relate to the current study are mentioned as follows, starting with the most recent:

Winner and Coble, 1989, conducted a hydrogeologic framework study of the entire North Carolina Coastal Plain. They defined and described the major regional aquifers and confining beds, and mapped the positions of salt water interfaces using available data accumulated up to the year 1989.

Brown, Miller and Swain, 1972, conducted a regional structural and stratigraphic study of the U.S. Atlantic Coastal Plain from North Carolina to New York. They defined 17 chronostratigraphic units, ranging in age from Jurassic to post-Miocene.

DeWeist, Sayre, and Jacobs, 1967, presented a report on the potential or predicted impact of phosphate mining on ground water levels in Beaufort and surrounding counties.

Nelson, 1964, published a report dealing with the geology and ground water resources of the Swanquarter area of the North Carolina Coastal Plain, covering Dare, Hyde, Pamlico, Tyrrell and Washington Counties. The report concentrated on describing the fresh water


0 20000 40000 meters
Albemarle Sound
Washington
Tyrrell
Beaufort
Hyde
Pamlico
Sound
Craven
Pamlico
Carteret
Figure 1
North Carolina East Central Coastal
Plain Study Area

aquifers in terms of distribution and thickness, hydraulic properties, and ground water levels.

Acknowledgements

The author would like to thank colleagues in the North Carolina Division of Water Resources Ground Water Management Section for collecting field data for this report, including TDEM surveys, water level and chloride concentration measurements. Thanks are extended to Michael Bauer, John Barr, Barbara Peck, Susan Laughinghouse, and Paul Williams. Also, thanks go to Nat Wilson for making the data so easily accessible via the DWR website, and for his technical input on TDEM field data collection and processing. Also, much appreciation is extended to Nat Wilson for the review of this report, which helped to improve it greatly.

Hydrogeologic Setting

The area covered in this study is situated within the tidewater region of the North Carolina Coastal Plain. The region has been described by Stephenson and others (1912) and Nelson (1964) as a broad, eastward dipping plain that encompasses one of a series of en echelon marine terraces which formed during the Pleistocene era, and were deposited in parallel orientation with the Atlantic Coastline. Stephenson and others (1912) named it the Pamlico terrace, as it is transected by the Pamlico River and Sound. As indicated on the geologic map of North Carolina (Brown and others, 1985) the western boundary of the terrace is an escarpment (Suffolk scarp) that runs north to south across the study area from the town of Plymouth in Washington County, to the town of Newport in Carteret County. The western-most section of the study area extends a few miles to the west of the Suffolk Scarp on an older marine terrace. Land surface elevations across the region vary from sea level to 55 feet with the highest elevations found in the western-most part, although the dunes on the Outer Banks can exceed 50 feet above sea level. The region is generally of low relief and swampy. A number of large, natural lakes are present, including Phelps, Mattamuskeet, Pungo, and New Lakes. The Pamlico, Neuse, Pungo, and Alligator Rivers dissect the land surface along their courses to the Albemarle and Pamlico Sounds.

The geology of the East Central Coastal Plain may be characterized as a gently southeastward dipping, and southeastward thickening wedge of sediments and sedimentary rock ranging in age from Recent through Cretaceous (possibly Triassic) which rests on an underlying basement complex of Paleozoic age rocks. The basement surface ranges in elevation between 1,871 and 9,854 feet below sea level within the area of study, and dips east-southeast at an average rate of 282 feet per mile. The sediment wedge is comprised of layers and lenses of sand, clay, silt, limestone, gravel, shell material and combinations thereof which range in total thickness from 1,400 to as much as 10,000 feet as measured at the Humble Oil Co. Cape Hatteras Lighthouse No. 1 well in Dare County. Beneath a veneer of Quaternary and Pliocene age sediments, the Eocene Castle Hayne Formation subcrops along the western fringe of the study area. Older formations subcrop or outcrop beyond the western limits of the area. Deposition of the sediment wedge occurred in cyclic fashion during alternating transgressions and regressions of the Atlantic Ocean, in marine to non-marine environments.

The sedimentary column of the East Central Coastal Plain is subdivided into geologic formations and formation members based upon position of layers in the sequence of sediments, lithology, and faunal composition. The subdivision of these deposits into aquifers and confining units is based on the delineation of non-permeable versus hydraulically connected permeable units, the boundaries of which sometimes, and sometimes do not, correspond to geologic formation boundaries. Aquifers and confining units are commonly made up of more than one formation, or may include only part of a formation or parts of several formations due to the discontinuous distribution of strata in the East Central Coastal Plain. The relationship of the geologic column to the system of hydrogeologic subdivisions as defined by this study is depicted in figure 2.

The hydrogeologic system in the study region, from basement to land surface, consists of eight regionally significant aquifers and the intervening confining units that separate them. They are mentioned from oldest to youngest as follows:

The Lower Cape Fear aquifer, which is comprised along with its confining unit, of the lower part of the Cape Fear Formation of Cretaceous age. The Lower Cape Fear aquifer is underlain by sediments of Lower Cretaceous and possibly Triassic age. Due to a lack of water level data it is impossible to determine where the lower boundary of the Lower Cape Fear aquifer and top of a possible Lower Cretaceous Aquifer occurs.

The Upper Cape Fear aquifer, which corresponds to the upper part of the Cape Fear Formation and sometimes the lower part of the Cretaceous Black Creek Formation. The confining unit is composed of clay or silt beds present in the lower part of the Black Creek or upper part of the Cape Fear Formation.

The Black Creek aquifer, which corresponds primarily to the Black Creek Formation. In some areas the aquifer includes the upper part of the Cape Fear Formation and the lower part of the Cretaceous Peedee Formation. The confining unit is made up of clay or silt beds in the upper part of the Black Creek or lower part of the Peedee Formations.

The Peedee aquifer, which is made up of the Peedee Formation. In the southeastern corner of the study area, the aquifer includes all, or part of, the Paleocene age Beaufort Formation. The confining unit is generally present in the Beaufort Formation or upper part of the Peedee Formation.

Figure 2. Relationship of Geologic and Hydrogeologic Units in the North Carolina East Central Coastal Plain

North Carolina East Central Coastal Plain Geologic Units			**North Carolina East Central Coastal Plain Hydrogeologic Units**
System	Series	Formation	Aquifers and Confining Units
Quaternary	Holocene	Undifferentiated	Surficial Aquifer
	Pleistocene		
			Yorktown Confining Unit
Tertiary	Pliocene	Yorktown Formation	Yorktown Aquifer
	Miocene	Pungo River Formation	
			Castle Hayne Confining Unit
	Eocene	Castle Hayne Formation	Castle Hayne Aquifer
			Beaufort Confining Unit
	Paleocene	Beaufort Formation	Beaufort Aquifer
			Peedee Confining Unit
Upper Cretaceous		Peedee Fm.	Peedee Aquifer
			Black Creek Confining Unit
		Black Creek Formation	Black Creek Aquifer
			Upper Cape Fear Confining Unit
		Cape Fear Formation	Upper Cape Fear Aquifer
			Lower Cape Fear Confining Unit
			Lower Cape Fear Aquifer/Lower Cretaceous Aquifer Undifferentiated
Lower Cretaceous			

The Beaufort Aquifer, which is made up primarily of the Beaufort Formation. The confining unit is made up of the upper part of the Beaufort Formation and in some places the lower part of the Castle Hayne Formation. The aquifer may also include sands in the Peedee Formation in some areas.

The Castle Hayne aquifer is comprised primarily of the Eocene age Castle Hayne Formation. The confining unit occurs in the Quaternary age units that overly the aquifer.

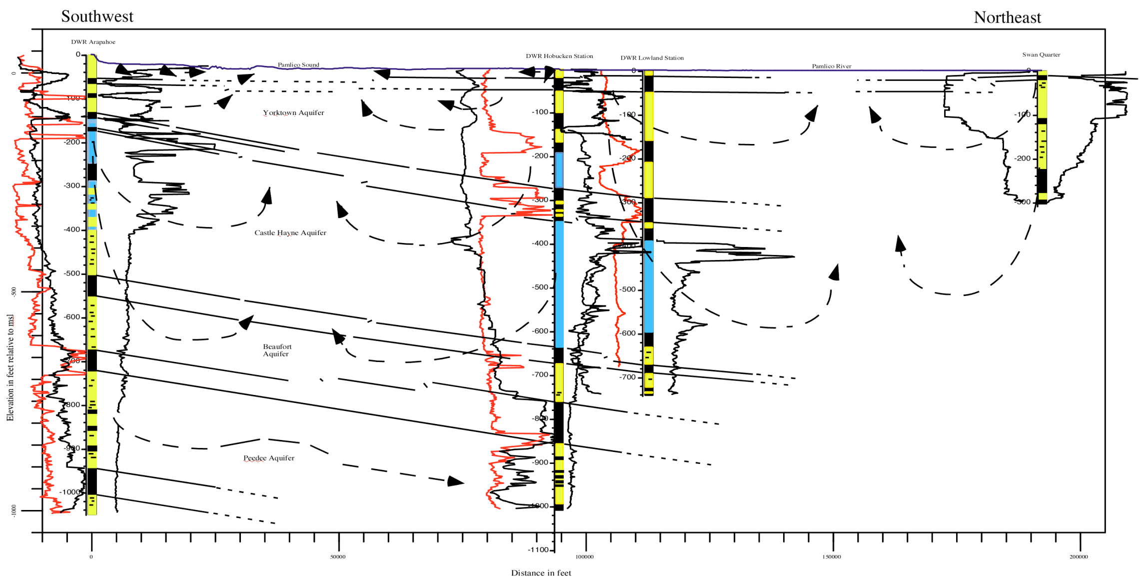
The Yorktown Aquifer is made up primarily of the Pliocene age Yorktown Formation and the Miocene age Pungo River Formation. The upper part of the Yorktown aquifer may also include in some areas, sediments of Quaternary age.

The surficial, or water table aquifer, which is made up primarily of Quaternary age sediments. It also includes parts of older formations depending on the varying age of underlying sediments and the varying stratigraphic position of the uppermost confining layer.

General Description of the Ground Water System

A typical hydrogeologic cross section through the East Central Coastal Plain is shown in figure 3, exhibiting the complexity of ground water flow patterns and salt water interfaces in relation to hydrogeologic units. Ground water flows in a rather complex three dimensional pattern through the subsurface in a multilayered Coastal Plain environment. Flow occurs laterally through aquifers from recharge to discharge areas along flowlines which parallel directions of steepest hydraulic gradient. Flow also occurs vertically upward to discharge areas or downward in recharge areas in response to differences in hydraulic head between aquifers.

All of the aquifers contain salt water over regions of varying extent, due to fluctuations of sea level that occurred during deposition of coastal plain sediments. The surficial aquifer contains salt water on the barrier islands offshore in Dare, Hyde and Carteret Counties, as well as along the fringes of the coastline, and along the fringes of rivers and streams where tidal affects can cause salt water intrusion. As recognized by Winner and Coble (1989), the position of fresh water-salt water interfaces within North Carolina Coastal Plain aquifers has a very complex pattern. Sediments were deposited during cyclic fluctuations of sea level over geologic time. The seaward limit of fresh water is unique for each aquifer as governed by variations in hydraulic properties, position and rates of recharge, thickness and hydraulic conductivity of overlying confining beds, and hydraulic gradients. Salt water interfaces are not sharply defined, but occur as transition zones of variable width due to diffusion between salty and fresh water. The movement of fresh ground water through deeper confined aquifers in the coastal plain causes interfaces to retreat slowly seaward over geologic time. However, in areas



Ground Water Flow
Line

Aquifer and Confining
Unit Boundary

Figure 3. Southwest to Northeast Hydrogeologic Cross
Section through Pamlico and Hyde Counties, North Carolina, showing
idealized ground water flow lines.

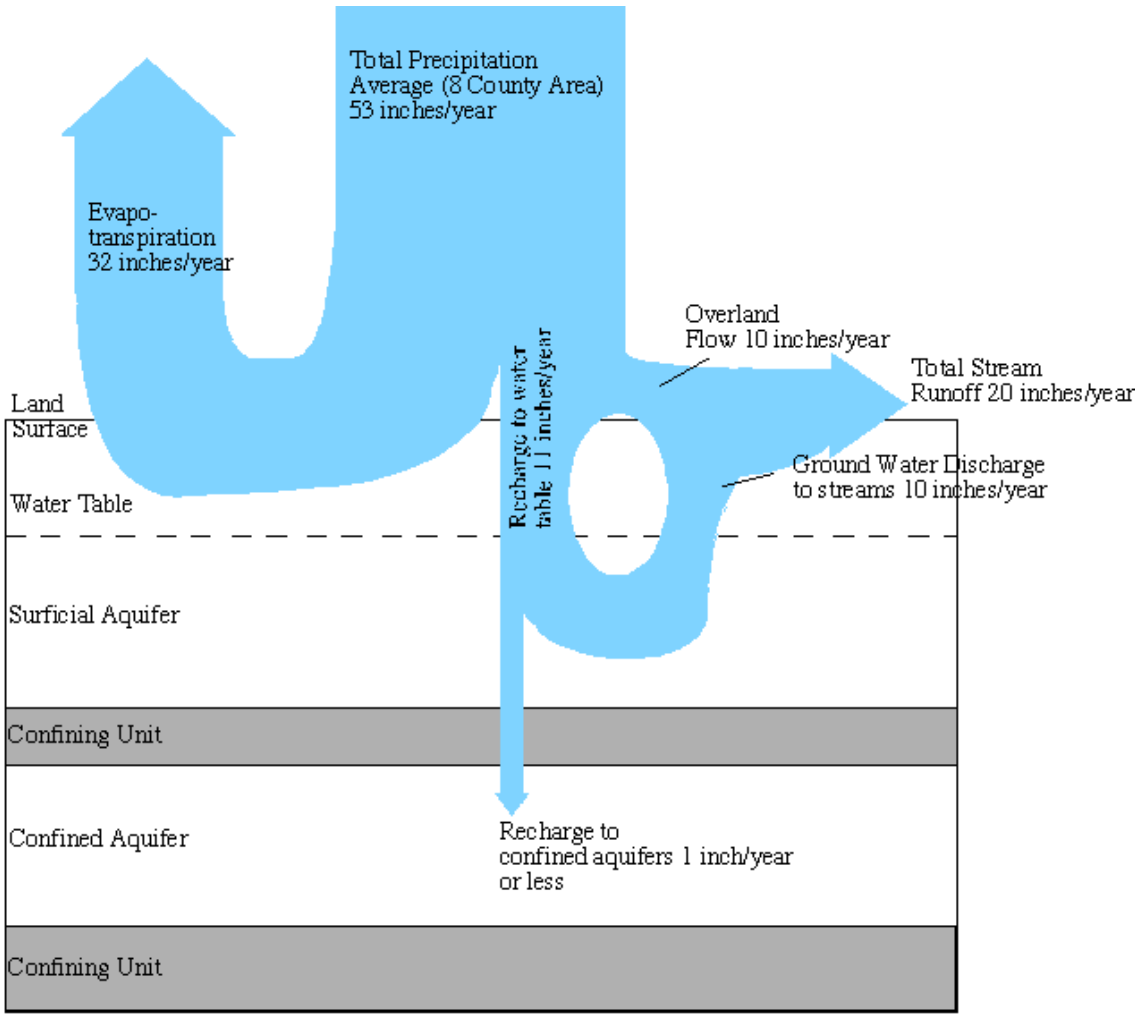


Figure 4. Generalized average water budget model for the North Carolina East Central Coastal Plain ground water system (adapted from Hardin, Fine, and Spruill, 2003, Wilder and others, 1978, Winner and Simmons, 1977, U.S. Geological Survey)

of heavy ground water pumping and resultant water level declines, saline ground water can move toward pumping centers due to a reversal of hydraulic gradient.

As illustrated by a generalized annual water budget model for the East Central Coastal Plain (figure 4), recharge occurs predominantly through rainfall, which enters the surficial (or water table) aquifer. The eight county area receives an average of 53 inches of total precipitation per year based on historical records covering the years between 1933 to 2007 (Southeast Regional Climate Center, table 1). Using precipitation data averaged for the whole eight county area, it was determined that about 20 inches of the 53 inches of total annual precipitation is lost to overland flow and ground water discharge to nearby surface water bodies, or 37 per cent. Another 32 inches (60 per cent) are taken up annually through evapotranspiration, based on Winner and Simmons (1977) estimates for the Creeping Swamp watershed in Pitt, Beaufort and Craven Counties. Of the 11 inches of water that enters the water table as recharge, 10 inches per year flows from recharge to discharge areas such as the Pamlico, Neuse, Alligator and Pungo Rivers and Lakes Matamuskeet, Pungo, Phelps, and New, and area creeks, drainage canals, swamps, estuaries and sounds. One inch or less of ground water per year enters the deeper confined aquifers as recharge. This water budget model assumes steady state conditions in which no pumping from the ground water system is occurring.

COUNTY	ANNUAL PRECIPITATION IN INCHES
Beaufort	50.18
Washington	52.00
Tyrrell	50.43
Hyde	52.09
Dare	55.52
Pamlico	54.83
Carteret	55.56
Craven	55.38
10 county average:	53.24

source: Southeast Regional Climate Center

Table 1: Average of Total Annual Precipitation (in inches) from 1933 to 2007 for the North Carolina East Central Coastal Plain (period of record varies within time frame depending on measurement station)

Of particular significance to the ground water system in the study region is a major withdrawal (approximately 57 million gallons per day) from the Castle Hayne and shallower aquifers, near Aurora in Beaufort County. The purpose is to dewater a large open pit via a system of pumping wells in order to mine phosphate ore from the Pungo River Formation of Miocene age. The impact to the ground water system is discussed in a later section of this report.

Methods Used for Investigation of the Subsurface

The following tools and techniques were used to separate the Quaternary through Cretaceous sedimentary section into component hydrogeologic units and to map and describe them across the study area.

1. Observation of significant differences in water levels across confining units, indicating hydraulic separation between aquifers, or the lateral persistence of water levels indicating the continuity of an aquifer.

2. Interpretation and correlation of borehole geophysical logs, including spontaneous potential, gamma ray, single point resistance, and resistivity logs. The spontaneous potential (SP) log is a recording versus depth of the difference between the potential of a movable electrode in the borehole and the fixed potential of a surface electrode. The SP is the resulting effect of several electromotive forces, including clay potential, liquid junction potential, and electrokinetic potential. The right-hand boundary of the curve generally indicates impermeable formations such as clay. The left-hand boundary generally indicates formations of higher permeability such as those made up of sand or porous limestone. The SP log was used in this study to determine permeable bed boundaries, and to estimate thickness and percentage of permeable materials. In addition, it permitted correlation of beds from well to well, in conjunction with gamma ray, resistivity and lithologic logs.

The gamma ray curve is a measurement of natural gamma radiation emitted by a geologic formation. Higher curve values are reflective of higher amounts of clay and phosphate minerals in the area of study, whereas lower curve values were indicative of the presence of limestone and sand in the geologic section. Gamma ray curves in many cases were valuable for correlation, by virtue of having produced distinctive signatures across zones of phosphate mineralization.

The single point resistance log is a measurement of electrical resistance, measured in ohms, between an electrode in a well and an electrode at the land surface, or between two electrodes in a well. The measurement does not take into account the length or cross-sectional area of the current travel path, and thus cannot be used for quantitative interpretation (Keyes, 1990). However, the single point resistance curve was useful for interpreting lithology and for thin bed detection.

Normal resistivity logs measure formation resistivity in ohm-meters, which takes into account the length and cross sectional area of the current travel path. Thus, short and long normal measurements take into account the intrinsic properties of the material and can be used for quantitative interpretation of formation fluids. The long normal curve provides a reading beyond the flushed zone of the borehole where formation fluids are generally undisturbed by drilling fluid.

Resistivity curves in combination with SP and gamma ray curves helped to distinguish between fresh water and salt water bearing strata, and between permeable and non-permeable strata. The combination of log types were used to identify and correlate aquifer and confining unit tops and bases, and to calculate the percentage of permeable material, and the net thickness, in feet, of permeable material in each aquifer.

3. Interpretation and correlation of lithologic logs from both core and cutting samples. Lithologic logs were used in combination with borehole geophysical logs to define vertical and lateral stratigraphic variations in the subsurface. Formation tops from North Carolina Geologic Survey litho-stratigraphic logs were used in accordance with well log correlations to determine the relationship between stratigraphic and hydrogeologic units. Formation tops were plotted on a network of hydrogeologic cross sections (plates 2-14) prepared for this report.

4. Observation of differences in chloride concentrations across confining units, and chloride concentration similarities within the same aquifer.

5. Observation of drawdown effects observed from pump test data.

6. Observation of the lateral transmission of drawdown effects from pumping, indicating the lateral continuity of an aquifer. Pump test data was used to determine transmissivity, specific capacity, hydraulic conductivity, and storativity of aquifers, and vertical hydraulic conductivity of confining beds.

7. Interpretation of apparent resistivity measurements from Time Domain Electromagnetic Soundings (TDEM). This is a surface geophysical technique by which an electromagnetic field is induced at land surface. As soon as the transmitter current is stopped, eddy currents are propagated into the subsurface from a transmitter loop. A secondary magnetic field is generated that changes with time as the eddy currents propagate downward through the subsurface. A central receiver coil measures changes in the magnetic field, which are recorded by the TDEM system over the course of the sounding time. The velocity and decay rate of the eddy currents are directly related to the electrical resistivity of the subsurface, and are converted by TEMIX XL software into apparent resistivity values. The resistivity of a geologic formation is affected by the fluid contained within the formation, its effective porosity, and the percentage of clay (Keyes, 1990). Increases in fluid salinity, effective porosity, and clay content all have the effect of causing decreased resistivity values. Decreases in the same produce increased

resistivity values. Therefore, it is important to understand how changes in these variables are affecting TDEM response. Employed in conjunction with borehole geophysical logs and chloride sample data, TDEM profiles provided information which allowed for interpretation of chloride distribution patterns between areas of well control. A limitation of TDEM is that TEMIX XL smooth modeling allows for a maximum of 19 layers. TEMIX uses statistical analysis to arrive at the average resistivity value of each layer, which limits the resolution for the purposes of stratigraphic definition. For this reason, TDEM is not always useful for mapping of hydrogeologic units.

A regional network of cross sections was constructed across the study area in order to trace the lateral distribution and thickness of hydrogeologic units. Lines representing the elevation of land surface were superimposed on each cross section in order to show recharge-discharge relationships. Land surface elevation data was used from a USGS digital elevation model by plotting the lines of section on the model surface. Maps of the elevation of the tops of units were constructed, along with maps of the thickness of aquifers and confining beds. Potentiometric surface maps were prepared for the Yorktown, Castle Hayne, Beaufort, Peedee and Black Creek Aquifers using water level data collected by the North Carolina Division of Water Resources in February through March, 2009.

Hydrogeologic Framework of the Study Area

The system of eight regional aquifers and intervening confining units found in the Quaternary through Cretaceous age sedimentary wedge in the East Central Coastal Plain were delineated in terms of their lateral distribution, thickness, hydraulic properties, and relationship to stratigraphic units. Moreover, aquifers were described in regard to ground water flow interactions, distribution of salt water and chloride concentrations, and natural or pump induced ground water movement.

Aquifers and confining layers are described as follows:

Surficial Aquifer

The surficial, or water table aquifer is the shallowest aquifer in the hydrogeologic system underlying the coastal plain. It is the first to receive recharge through infiltration of rainwater, which moves downward from the land surface to the water table. Thus, the water table fluctuates in elevation within the aquifer along with changes in ground water recharge and storage. Ground water moves laterally within the surficial aquifer from recharge to discharge areas such as rivers, lakes, swamps, and other surface water bodies. It also moves down gradient in recharge areas into deeper confined aquifers. A significant portion of the study area consists of ground water discharge areas due to the high percentage of land surface being occupied by lowland swamps, lakes and drainages.

In ground water recharge areas, where by definition, an unsaturated zone exists above the water table, the depth to the water table varies between a few inches to 13 feet below land surface depending on location, and seasonal variations in rainfall and evapo-transpiration. Depth to the water table is deepest in higher elevation areas in western Beaufort, Craven and Carteret Counties. In slightly higher elevation areas of the swamps, intermittent recharge can occur where the top of the saturated zone alternates in position between land surface and below land surface (Heath, 1994). Perennial recharge occurs in interstream, non-wetland areas where the top of the saturated zone is always below land surface.

The surficial aquifer is present throughout the region, and is principally composed of Quaternary age sand, shell and clay beds of marginal marine, lacustrine and fluvial origin. It also is made up of older Pliocene Yorktown deposits in some areas where the confining unit occurs at a lower position in the stratigraphic section. Peat deposits are common at the surface in this area, averaging near five feet in thickness, but can be as much as fifteen feet thick (Ingram, 1987). The top of the aquifer corresponds to the land surface, with a variation in thickness between 4 and 140 feet. Maximum thickness was observed in a Texas Gulf well at Wades Point in Beaufort County where no significant clay layer is present down to 140 feet below land surface.

Due to variations of soil types and infiltration capacities, vegetation, and slight differences in climate, recharge rates to the surficial aquifer vary considerably within the area covered in this report. Recharge rates can be estimated using the General Soil Map of North Carolina (Tant and others, 1974). The General Soil Map indicates that the study region is primarily covered by soils exhibiting poor infiltration capacity. Heath (1980) estimated that poorly drained peat, clay, clay loam, and sandy clay loam may have recharge rates as low as 5 inches per year. The water budget model would be different for the coastline of Dare and Hyde Counties, the Outer Banks, and part of western Beaufort County where soils are indicated by Tant and others, 1974 to have moderate infiltration capacity. Thus recharge rates in those soils would be somewhat greater than 5 inches per year, although they make up a low percentage of the land area covered by this report. Winner (1975) estimated that ground water recharge to the surficial aquifer in the Cape Hatteras area is about 340 million gallons per year per square mile, or about 19.6 inches per year.

The presence of salt water in the surficial aquifer is limited to the shorelines of the coastal counties, and the banks of rivers where tidal effects allow inland movement of salt water. On the barrier islands which make up the Outer Banks of Dare, Hyde and Carteret Counties, fresh water occurs in small, isolated, lens shaped bodies above denser salt water in the surficial aquifer (Winner, 1975, 1978).

The surficial aquifer is used to a limited degree as a domestic source of water with yields that range between 2 and 10 gallons per minute (Nelson, 1964). The quality is poor however due to high iron content.

Yorktown Confining Unit

The clay and silt beds of the lower Quaternary and upper part of the Yorktown Formation form the upper-most regional confining unit in the study area, named the Yorktown confining unit. It is most aptly described as a series of discontinuous clay and silt beds that vary in stratigraphic position across the region. In some wells its appears on electric logs as a massive section of clay with as much as 98 feet of thickness (Texas Gulf test well no. 8). A contour map of the thickness of the unit (plate 22) indicates a range of 6 to 98 feet, with areas of maximum thickness in eastern Beaufort, Carteret, and northwestern Tyrrell Counties. The unit is absent in some wells in the area, allowing direct hydraulic communication between permeable surficial and Yorktown age sediments.

Yorktown Aquifer

The Yorktown Aquifer is made up of sands within the Pliocene Yorktown and Miocene Pungo River Formations, and in some areas may include Quaternary age sediments. There is no evidence at this time to suggest that the Pungo River Formation makes up a separate aquifer. The Yorktown Formation is principally composed of fine to medium grained shelly, clayey sand, bluish-gray in color, alternating with beds of bluish gray clay. The basal part of the Yorktown Formation often contains medium to coarse sand, including reworked phosphatic sediments from the underlying Pungo River Formation. The Pungo River Formation is generally described as brown phosphatic sand, with gray to green calcareous and diatomaceous clays, dolomitic limestone, and minor gray shell limestone, white chalk and dolomite (Miller, 1982). Where the aquifer includes sediments of Quaternary age the lithology is made up of fine to coarse grained, gray to tan colored sands and thin clay interbeds.

As displayed in cross-sections A-A' through F-F' (plates 2-7), the aquifer is prominently wedge-shaped in profile from west to east, and ranges in total thickness from 0 where the unit pinches out, to 992 feet in the Rapp Oil Co. Twiford No. 1 well in Dare County. Sand bodies in the Yorktown Aquifer appear in cross-sectional profile to be discontinuous and somewhat lenticular in nature. It is possible that individual sand bodies or groups of sands may be acting as separate aquifers within the Yorktown due to its discontinuous nature of deposition. Data from DWR monitoring stations such as Arapahoe and Phelps Lake in Pamlico and Washington Counties indicates that there are only minor head differences of 1 to 2 feet between individual sands. However, at New Lake monitoring station in Hyde County there is an approximate 5 foot head difference between two sand zones in the Yorktown (cross section G-G', plate 8), which could be significant for more localized characterization and subdivision of the aquifer.

The top of the aquifer dips from west to east, ranging in elevation from 10 feet above sea level in Beaufort County to 177 feet below sea level in Dare County (plate 23).

The variability of the confining unit in terms of thickness and position in the stratigraphic section produces uneven, undulating contour patterns on the elevation map.

The Yorktown Aquifer is the primary source of municipal water supply in Dare County, and is used along with the Castle Hayne Aquifer in Hyde and Tyrrell Counties. The Town of Columbia well field in Tyrrell County, yields as much as 270 gallons per minute from Yorktown screen zones between 65 and 128 feet below land surface (in 8 to 10 inch diameter wells). The Tyrrell County well field yields a maximum of 127 gallons per minute from an 8 inch diameter well screened from 123-143 feet. The Dare County Skyco water system pumps and treats salt water through reverse osmosis from ten 8 inch diameter wells screened from 300 to 425 feet. Sands open to these screen zones yield an average of 900 gallons per minute. In the vicinity of Manteo, in Dare County another ten 8 inch diameter wells are screened from 120 to 220 feet and yield a maximum average of over 1,000 gallons per minute. In Hyde County, in the vicinity of the town of Fairfield, two 8 inch wells in the County water system yield as much as 358 gallons per minute from the Yorktown. In the nearby town of Ponzer, two additional 10 inch wells yield a maximum of 679 gallons per minute from 280 to 295 feet. In Carteret County, the Yorktown Aquifer is used by the Town of Newport, which withdraws a maximum of 1,247,400 gallons per day from three 8 to 10 inch wells, or 866 gallons per minute.

A pump test by Harshburger (1963) was conducted on the Yorktown Aquifer in the vicinity of Aurora in Beaufort County. The test duration was 50 hours, during which a 10 inch well was pumped at a rate of 55 gallons per minute. Transmissivity was calculated to be 30,000 gpd/ft or 4,010 ft^2/day. Hydraulic conductivity was 250 gpd/ft^2 or 33.5 ft/day, and the storativity was reported as .0003.

It is evident from yield data and limited aquifer test data that transmissivity and hydraulic conductivity are generally very high in the Yorktown aquifer within the report area.

The Yorktown is the first confined aquifer below the surficial aquifer, and thus is recharged at a higher rate than deeper confined aquifers. This is evident by comparison of water level records between the surficial and Yorktown at several DWR monitoring stations (plates 2-14). Water levels in the Yorktown generally mimic the seasonal fluctuations of the water table, indicating rather quick recharge across the first confining layer. However, the Yorktown can only receive recharge in areas where the head in the surficial aquifer is higher than in the Yorktown, and much of the region is in a discharge setting where heads in the Yorktown are higher than in the surficial. In those areas, ground water moves upward to surface water bodies. Implicit on Yorktown hydrographs are the effects of the PCS Phosphate Quarry and dewatering operation. Variations in pumping rates as well as shifting of the centers of pumping due to pit location changes has occurred from July, 1965 to present.

The potentiometric surface of the Yorktown Aquifer (plate 49) ranges in elevation from 20 feet above sea level in the westernmost part of the study area to approximately 20 feet below sea level where pumping is occurring on the Dare County Outer Banks. Evident on the potentiometric surface map is a prominent trough or depression formed by water level contours in the area of the Pamlico River, indicating the discharge of ground water from the Yorktown Aquifer to the Pamlico River and Sound. The depression in water level contours is somewhat accentuated by the effects of pumping at PCS Phosphate, near Aurora, in Beaufort County.

The presence of salt water in the Yorktown Aquifer is limited to the eastern part of the study area in Tyrrell, Dare, Hyde, and northeastern tip of Washington County. For the purposes of this study, the salt water/fresh water interface was defined by use of chloride measurements made from water samples and by interpretation of TDEM resistivity measurements. A plot of chloride concentration in ppm versus TDEM derived resistivity (figure 5) indicates that the boundary between fresh versus salty ground water in this aquifer occurs at a range of 10 to 15 ohm-meters. Resistivity values of more than 15 ohm-meters generally correspond to fresh water, and below 15 ohm-meters to salt water, although clay interbeds or intersticial clays within the aquifer will suppress resistivity values. The presence of clay thus has a masking effect on resistivity values, and must be accounted for when attempting to use resistivity to interpret chloride concentration. Variations in the effective porosity of a formation will also have an effect on the value of resistivity. This is the reason that the plot of resistivity versus chloride concentration (figure 5) does not plot perfectly along a straight line.

The intersection of the 250 ppm chloride interface with the base of the aquifer is indicated on plate 23. From this line to the coastline of the mainland the upper part of the aquifer is fresh and the lower part is salty. The upper part of the aquifer is also fresh on Roanoke Island, and where documented in wells on the Outer Banks within the study area. This is illustrated on cross section A-A' (plate 2). TDEM cross section a-a' (plate 16) provides a clear indication of the Yorktown fresh water-salt water interface at the 10 ohm-meter boundary near sounding M11T in Tyrrell County. The large width of the interface is an indication of the high transmissivity of the aquifer and the ease with which salt water has been flushed eastward over geologic time. The Yorktown is also the first confined aquifer in the system and is recharged at a higher rate than the underlying Castle Hayne and deeper aquifers.

Castle Hayne Confining Unit

The Castle Hayne confining unit is made up of clay and silt beds with lesser amounts of sand that occur within the lower part of the Pungo River Formation of Miocene age. The top and base of this unit correspond respectively to the base of the Yorktown Aquifer, and the top of the Castle Hayne Aquifer. The unit thickens generally from west to east from a minimum of 6 feet, to a maximum of 165 feet near Kill Devil Hills in Dare County.

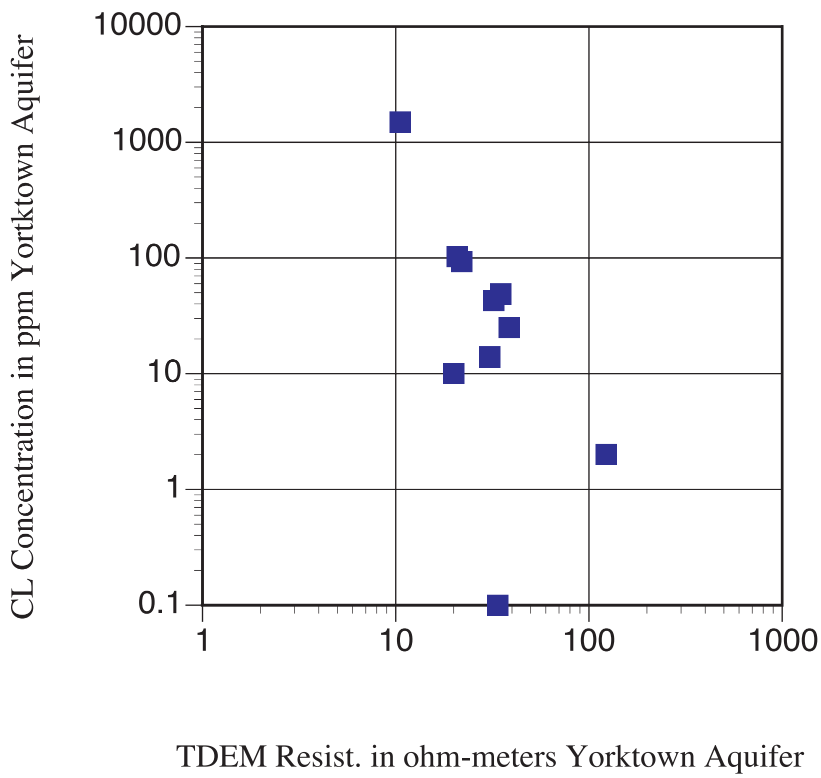
Castle Hayne Aquifer

The Castle Hayne aquifer within the area of this study, is the most prolific and high yielding aquifer in the North Carolina Coastal Plain. It is principally composed of the Eocene age Castle Hayne Formation, which consists of very permeable, gray to white molluscan moldic limestones and dolomites. It is interbedded and underlain by fine to medium grained calcareous sands and clays. The lower part of the Castle Hayne Aquifer may include over some parts of the study area, highly glauconitic sands of the uppermost Beaufort Formation of Paleocene age.

The aquifer is present throughout the study area, thickening prominently from west to east from 30 feet or less in western Beaufort County, to greater than 520 feet in Dare County (plate 28). Within the area of this study the top of the aquifer is picked at the top of the Castle Hayne Limestone, as there are no apparent lower sand zones in the overlying Pungo River Formation that are hydraulically connected. According to a contour map of its elevation (plate 27), the top of the aquifer dips gently eastward at a rate of about 7 to 25 feet per mile, ranging in elevation from slightly above sea level in western Beaufort County, to greater than a thousand feet below sea level in Dare County. The base of the aquifer occurs at the top of the Beaufort confining unit.

The most extensive pump tests of the Castle Hayne Aquifer were conducted in December, 1962, and published in a report by Harshberger (1963). They are also discussed in DeWeist, Sayre and Jacobs (1967). One test was conducted near Aurora in Beaufort County, in the vicinity of what later became the PCS Phosphate Quarry. A 10 inch diameter well, 225 feet deep, was pumped for 28 hours at a rate of 1,070 gallons per minute. The drawdown and recovery were measured in the pumping well and in nine shallow and eight deep observation wells. An analysis of the test using the Theis method resulted in a calculated transmissivity value of 245,000 gpd/ft, or 32,754 ft^2/day, a storativity of .0008, and a hydraulic conductivity of about 2,500 gpd/ft^2, or 335 ft/day. Another test was conducted near Lee Creek in Beaufort County. A 20 inch diameter test well of 200 feet depth was pumped at a rate of 3,500 gallons per minute for 35 days. The transmissivity was calculated to be 390,000 gpd/ft or 52,139 ft^2/day, a storativity value of .00019, and a hydraulic conductivity of 174 ft/day. Both tests were interpreted by DeWeist and others (1967) as indicating downward leakance across the Castle Hayne confining unit from the Yorktown aquifer, and upward leakance from the Beaufort Aquifer. Another analysis was presented in the 1967 report which was conducted after the mining/dewatering operation began. Plots of head data from 8 monitoring wells at various distances up to 24 miles from the mine pit were analyzed using the Theis method. The transmissivity was calculated to be 300,000 gpd/ft, or 40,106 ft^2/day.

Figure 5: Plot of Chloride Concentration in parts per million vs. TDEM derived resistivity in ohm-meters in the North Carolina East Central Coastal Plain

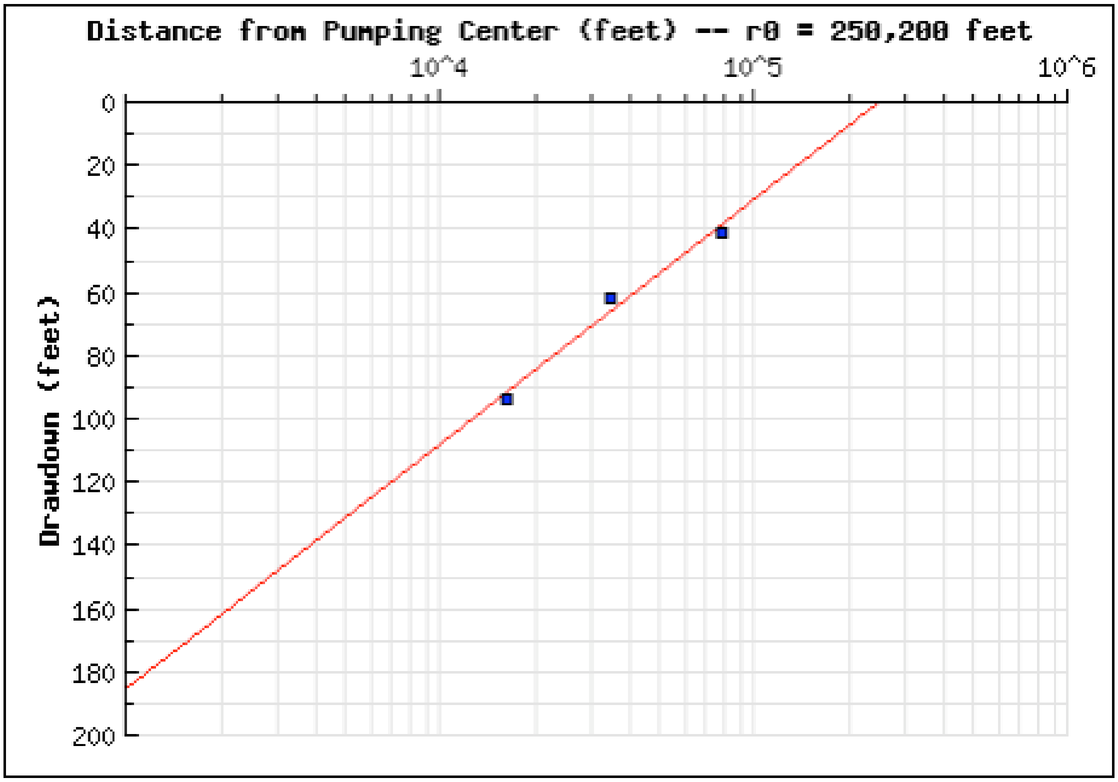


For the purposes of this study, a Jacobs distance drawdown analysis was conducted using NCDWR Castle Hayne monitoring wells at Lee Creek, Arapahoe, and Bonnerton Stations in Beaufort County. Assuming an average pumping rate of 37,816 gallons per minute, May, 2002 water levels after 37 years of pumping from the quarry site were plotted on a semi-log graph (figure 6). Using a straight line drawn through the three points, a transmissivity value of 34,489 ft^2/day, storativity of .016066, and average hydraulic conductivity of 125 ft/day was calculated. The value of storativity is higher than calculated in the earlier tests, but may be due to the fact that over a longer duration of pumping (37 years) more leakage was induced through the confining unit from the overlying Yorktown Aquifer. Since the location of the quarry, and center of pumping has shifted many times since 1965, an aquifer test analysis of this nature should be considered "back of the envelope."

Two other aquifer tests were analyzed in Pamlico County at the DWR Arapahoe and Whortonsville monitoring stations. At Arapahoe, the transmissivity was determined to be 34,000 ft^2/day, hydraulic conductivity of 107 ft/day, and storativity of .000116. At Whortonsville, transmissivity was calculated to be a much lower 6,662 ft^2/day, storativity of .000013, and hydraulic conductivity of 17 ft/day. Lower values at Whortonsville are likely attributable to increased clay content in the Castle Hayne Aquifer as indicated by the drillers log.

Yields from the Castle Hayne Aquifer in this region generally range between 50 and 500 gallons per minute, but in Pamlico, Beaufort and Washington Counties over 1,000 gallons per minute can be obtained. Many of the wells only partially penetrate the aquifer, since that is generally sufficient for adequate water supply. To the east of the intersection of the 250 ppm chloride isochlor with the top of the aquifer, the Castle Hayne contains salt water in excess of the taste threshold and is not potable without treatment. For the purposes of this study, the 250 ppm isochlor was defined by use of chloride measurements made from water samples and by interpretation of TDEM resistivity measurements. A plot of chloride concentration in ppm versus TDEM derived resistivity (figure 7) indicates that the boundary between fresh versus salty ground water in this aquifer occurs at a resistivity value of approximately 25 ohm-meters. Resistivity values of greater than 25 ohm-meters generally correspond to fresh water, and below 25 ohm-meters to salt water, although clay interbeds within the aquifer will suppress the resistivity value as well. The eastern 250 ppm isochlor extends from eastern Washington County, southward through western Hyde, eastern Pamlico and eastern Carteret Counties as shown in plate 27. The intersection of the 250 ppm chloride isochlor with the base of the aquifer occurs along a line from Plymouth in Washington County to near Belhaven in Beaufort County and then follows a sinuous path through eastern Beaufort, western Pamlico and southern Craven Counties (plate 27). The transition zone between the 250 ppm chloride ischlor intersections with the top and base of the aquifer is where the upper part of the Castle Hayne Aquifer is fresh and the lower part is salty. The salt water

Figure 6: Jacobs Distance Drawdown Analysis of the Castle Hayne Aquifer using NCDWR monitoring wells at Lee Creek, Arapahoe and Bonnerton Stations in Beaufort and Pamlico Counties, NC. and the PCS Phosphate Mine pumping center



Pumping Rate: 37,816.66 gallons per minute
May, 2002 water levels
Test Duration: 18,662,400 minutes

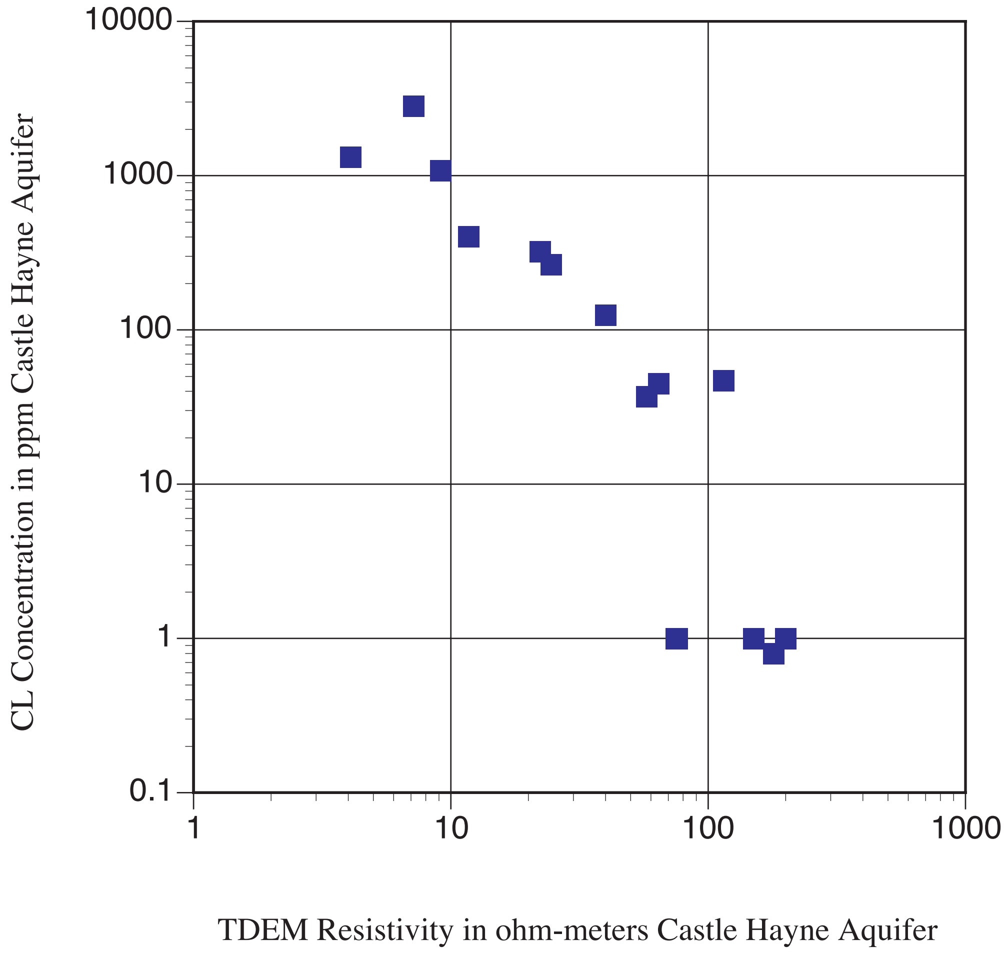
Transmissivity: 34,489 ft^2/day
Storativity: .016066
Hydraulic Conductivity Average: 125 ft/day

section is wedge shaped in cross sectional profile (plates 2-14) and thus slopes westward within the transition zone. The great width of the interface is a testament to the ease of circulation of ground water and high transmissivity of the aquifer in this area. To the north of the study area and on the northern side of the Albemarle Sound, the Castle Hayne Aquifer is much thinner and less transmissive. It exhibits a much more narrow transition zone due to the sluggish circulation of ground water. The narrowing of the transition zone over the area of the Pungo and Pamlico rivers and the East Dismal Swamp is more than likely due to the fact that it crosses a large area of ground water discharge where little recharge takes place. Thus the fresh water salt water interface position through this area has been slower to change.

The potentiometric surface of the Castle Hayne Aquifer (plate 50) within the area of study is dominated by a large cone of depression that has been present since mine dewatering operations began at Texas Gulf Corporation (now PCS Phosphate Corporation) in July, 1965. According to DeWeist and others, 1967, at the end of November, 1965, the virtual radius of the cone was about 19 miles, by February, 1966, 23.4 miles, and by May, 1966, it had grown to almost 28 miles. Withdrawals began at 31.3 mgd (million gallons per day) and by February, 1966 had increased to 65 mgd. Since 1965, the position of the mine excavation and pumping has shifted several times between Lee Creek and the present location in the vicinity of Aurora, Beaufort County. The mine presently pumps an average of 57 mgd, and the present day cone of depression has a maximum radius of approximately 28 miles, about the same as in May. 1966 At the center of the cone of depression the water level is maintained at approximately 150 feet below sea level in order to eliminate ground water discharge into the excavation.

A comparison of three potentiometric surface maps of the the Castle Hayne in Beaufort and northern Craven Counties from a pre-pumping time (June, 1965) (figure 8), a year after pumping began (September, 1966) (figure 9) and the present time (February, 2009) (figure 10) provides some interesting observations. Prior to when pumping began at Texas Gulf in June, 1965, potentiometric contours indicated flow and discharge of ground water from the Castle Hayne Aquifer to the Pamlico River (figure 9). A year after pumping began, a September, 1966 potentiometric map indicated that the gradient remained similar from the vicinity of Washington, North Carolina to about 15 miles down the Pamlico River, but the hydraulic gradient was reversed along the remaining stretch of the river and sound. Hydraulic head in the aquifer had been reduced to below the level of the base of the river. However, in the easternmost part of Beaufort County water levels have remained approximately the same from pre-pumping to present time and the hydraulic gradient is the steepest between this area and the pumping center. The elevation of the top of the aquifer is at or above sea level in easternmost Beaufort County. This apparently corresponds to an area of high recharge which has allowed the average potentiometric surface to remain unchanged since 1965. The hydrograph for the Castle Hayne Aquifer at the DWR Chocowinity monitoring station in eastern Beaufort County (figure 12) indicates prominent seasonal fluctuations in water levels and a thin cover of surficial sediments overlying the aquifer. This is indicative of a rapid rate of recharge to the aquifer.

Figure 7: Plot of Chloride Concentation in ppm (parts per million) vs. TDEM derived resistivity in ohm-meters for the Castle Hayne Aquifer in the North Carolina East Central Coastal Plain



According to a 1971 joint study report by the North Carolina Ground Water Division and others, during the 5 year period between 1965 and 1970, the chloride content of the Castle Hayne remained the same or decreased slightly in about 75 per cent of Beaufort County. Within the area affected by chloride increases, which occurred to the northeast of Lee Creek, the maximum increase was 110 ppm, with an average of 20 ppm according to the report. At the Lee Creek monitoring station (the site of the present DWR Lee Creek monitoring station) chloride concentrations increased from 200 ppm to nearly 500 ppm at the end of 1967 in screen zone 165-323' (well P17i6). Chloride levels remained above 250 ppm in this well up to the end of 1969 and then rapidly dropped to just over 100 ppm (figure 18). This drop did not correspond to a drop in pumping rates, but is probably attributable to a southward shift of the mine and center of pumping. The Yorktown well at Lee Creek (P17i7) did not show a corresponding increase in chloride concentration over the same measurement period, although it is possible that downward leakage occurred underneath the bed of the nearby Pamlico River and migrated to the Castle Hayne well. The natural hydraulic gradient under steady state/pre-pumping conditions in the area of the mine was in an upward direction with heads at a higher level in the deeper aquifers. This is due to the fact that the first mine site was in an area of natural discharge to the Pamlico River. Lowering of head in the Castle Hayne Aquifer due to pumping at the mine increased the upward vertical gradient relative to deeper salty aquifers, making it easier for ground water to move upwards in response to pumping. For example, in 1966 at the Lee Creek station site (figure 14), water levels in the Black Creek Aquifer were a few feet above sea level, while water levels in the Castle Hayne Aquifer were between 94 and 106 feet below sea level. This was a near maximum negative head differential due to the proximity of the wells at Lee Creek to the mine excavation (the Castle Hayne head at the excavation site had been drawn down to 120 feet below sea level). Current water levels at Lee Creek indicate that the Black Creek is 42 feet higher than the Castle Hayne (figure 14). At the new DWR Aurora II monitoring station, near the present site of the mine, the Black Creek Aquifer water level is 42 feet higher than the Castle Hayne and Beaufort water levels (figure 13).

Mine dewatering operations also created a downward vertical gradient from the Yorktown and surficial aquifers to the Castle Hayne which did not exist before. At Lee Creek, the surficial and Yorktown Aquifer water levels are both approximately 72 feet higher than the Castle Hayne.

Due to the steady decline of water levels in the Black Creek aquifer in the area of the mine. it can be deduced that water is moving from the Black Creek Aquifer, which is quite clay rich and less transmissive, into the shallower more transmissive aquifers under the prevailing negative head gradient near the center of cone of depression created by the mine. The Black Creek Aquifer is well confined and recharged at a much slower rate than the Castle Hayne Aquifer. This characteristic, combined with the fact that the transmissivity is much lower, has allowed for a long term, continuous decline of water levels in the Black Creek Aquifer due to the upward migration of salt water. At the DWR Bonnerton station, which is less than four miles from the present excavation site, Black

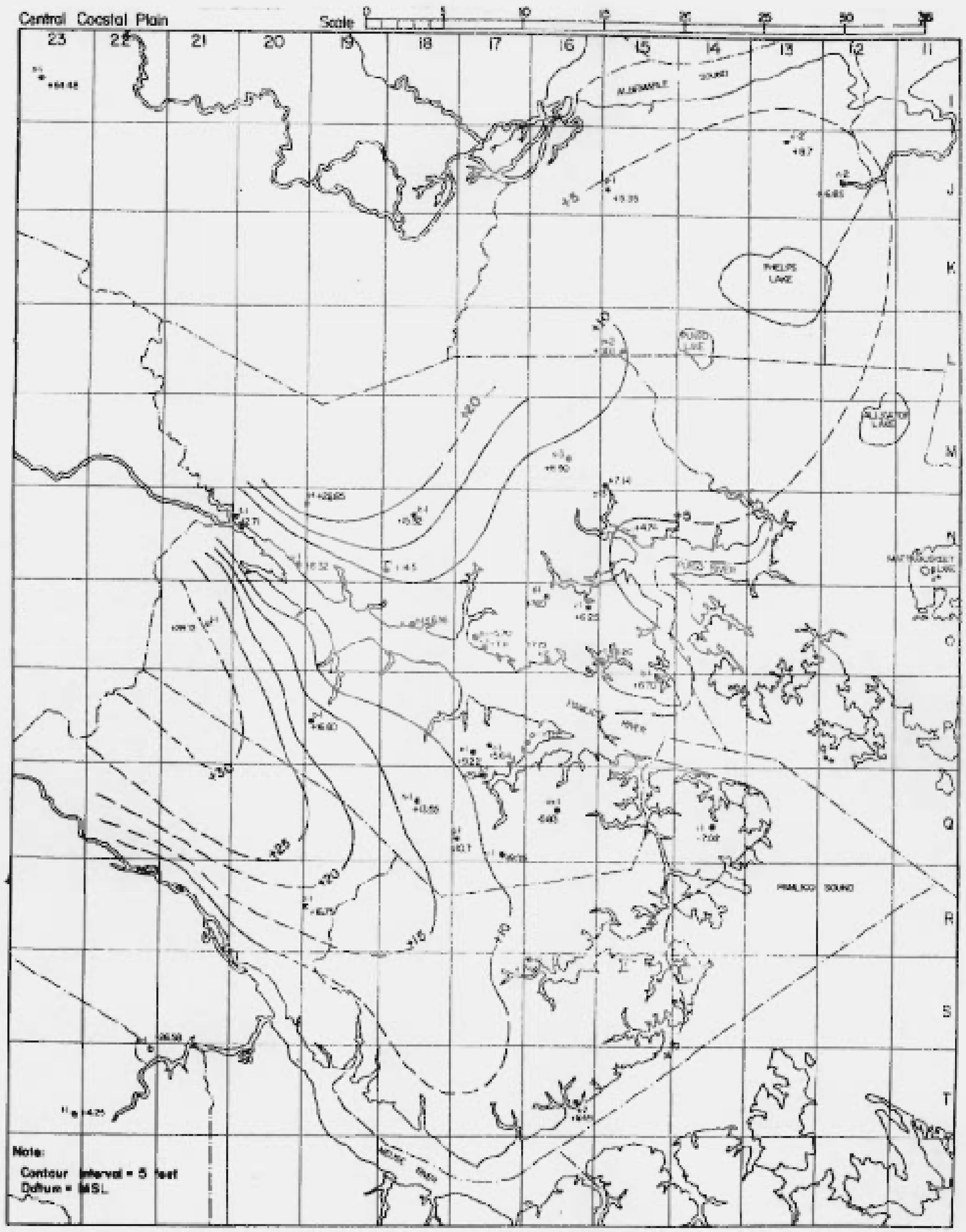
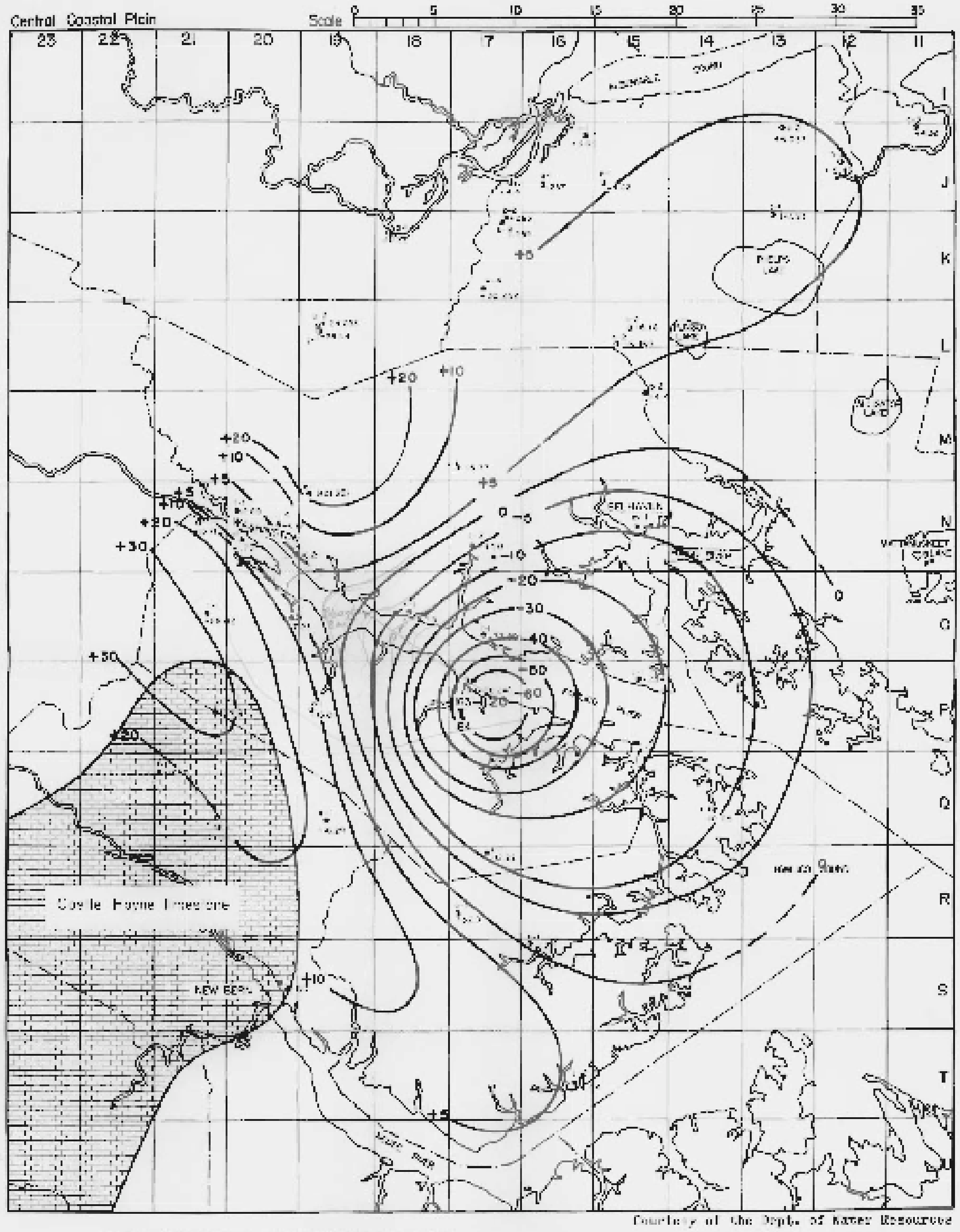


FIGURE 27. - PIEZOMETRIC SURFACE OF CASTLE HAYNE AQUIFER - JUNE 1965

Figure 8

From:

NC Groundwater Section, 1974, Status Report on Groundwater Conditions in Capacity Use Area No. 1 Central Coastal Plain, North Carolina, North Carolina Department of Natural and Economic Resources, 146 p.

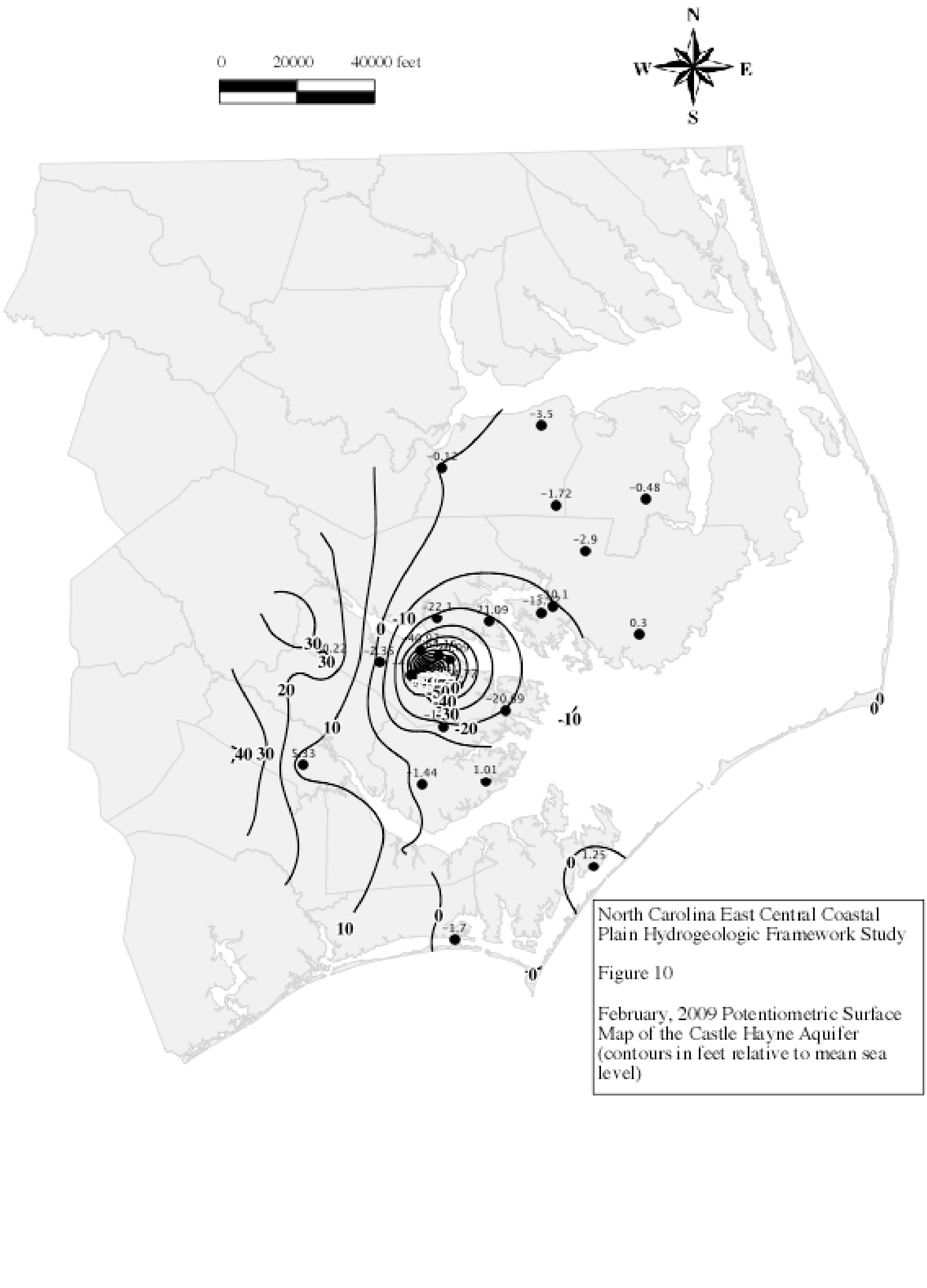


MAP SHOWING PIEZOMETRIC SURFACE OF THE CASTLE HAYNE AQUIFER
SEPTEMBER, 1966

FIG 17

Figure 9

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.



North Carolina East Central Coastal Plain Hydrogeologic Framework Study

Figure 10

February, 2009 Potentiometric Surface Map of the Castle Hayne Aquifer (contours in feet relative to mean sea level)

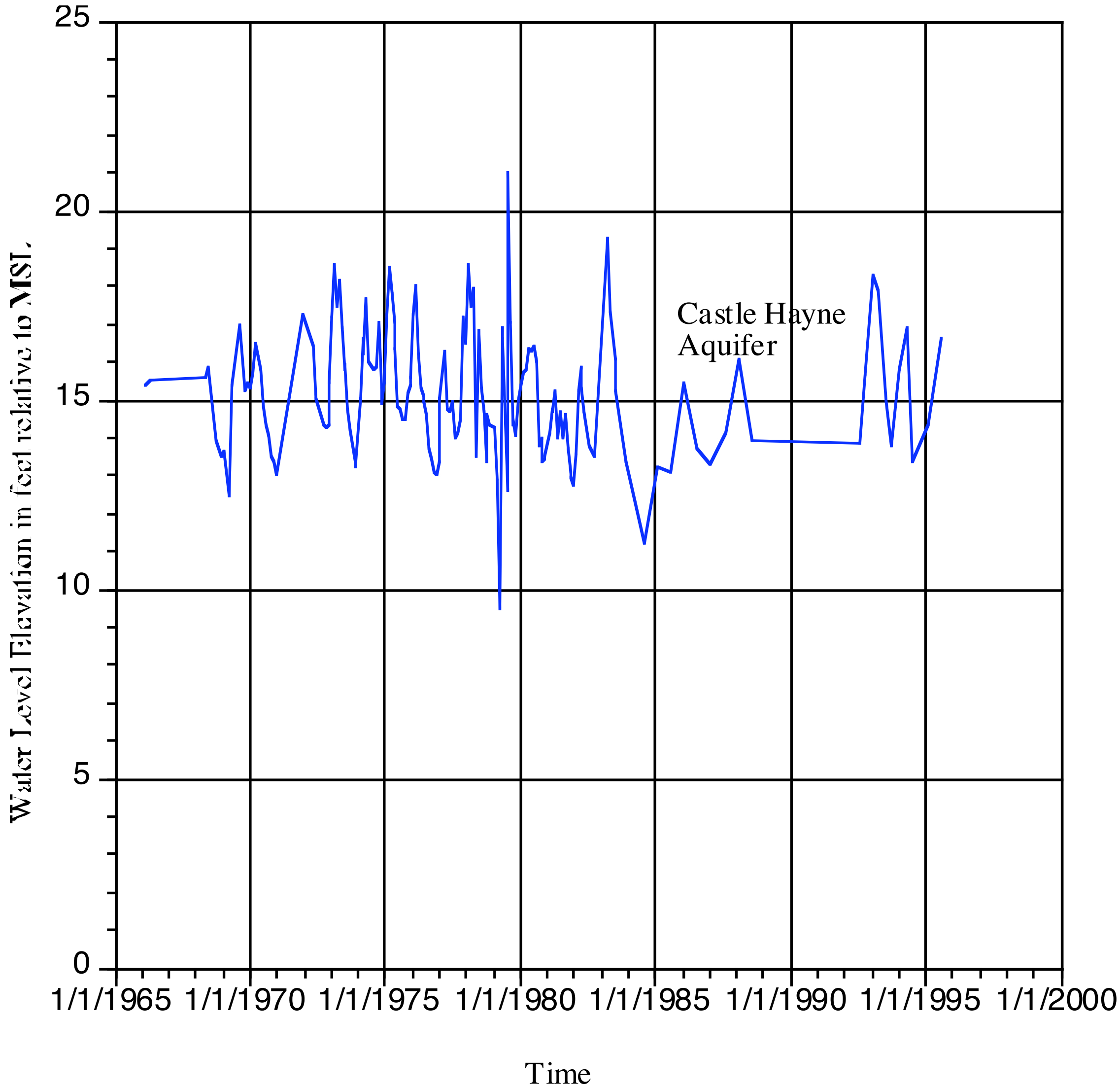


Figure 11: Hydrograph of NC Division of Water Resources
Chocowinity Monitoring Station in Beaufort County, NC

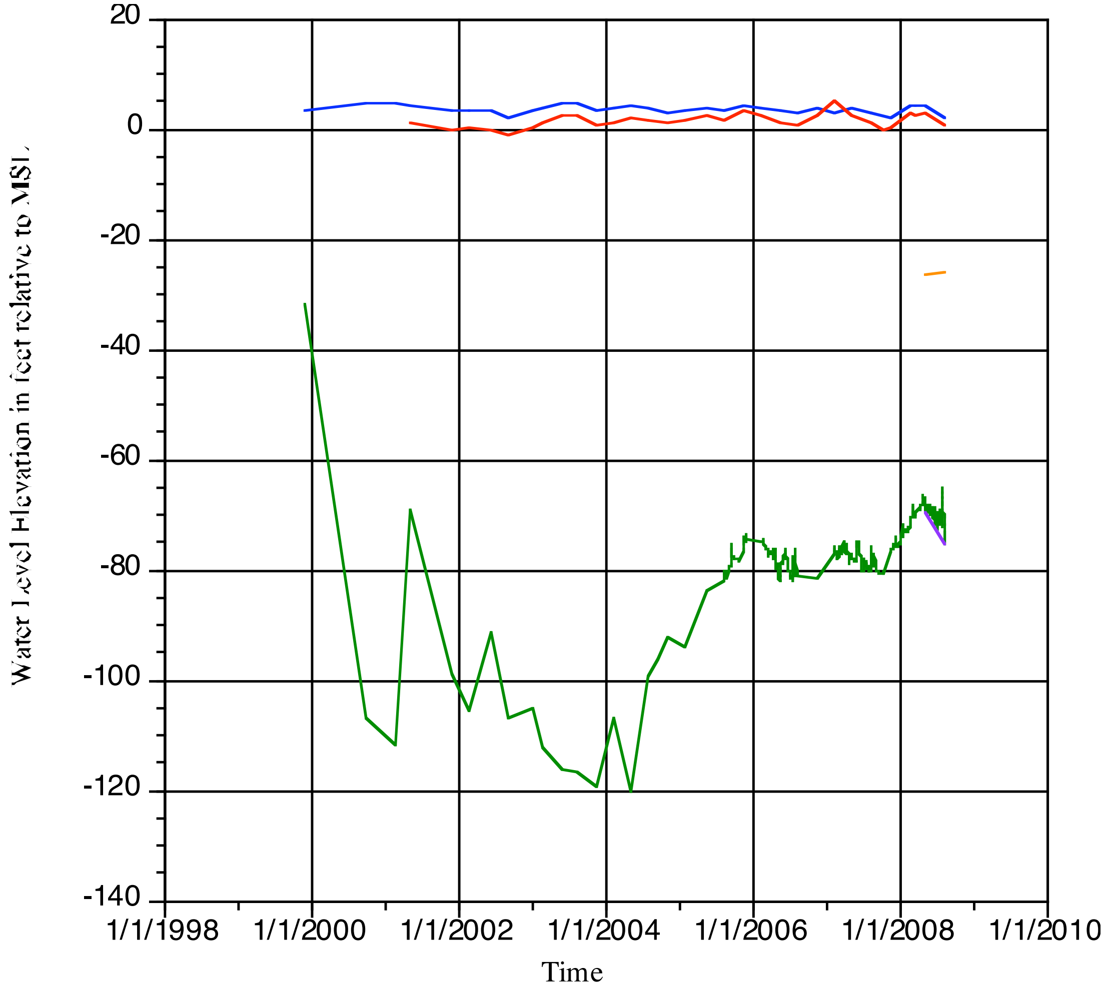


Figure 12: Hydrograph of NC Division of Water Resources Aurora II Monitoring Station in Beaufort County, NC

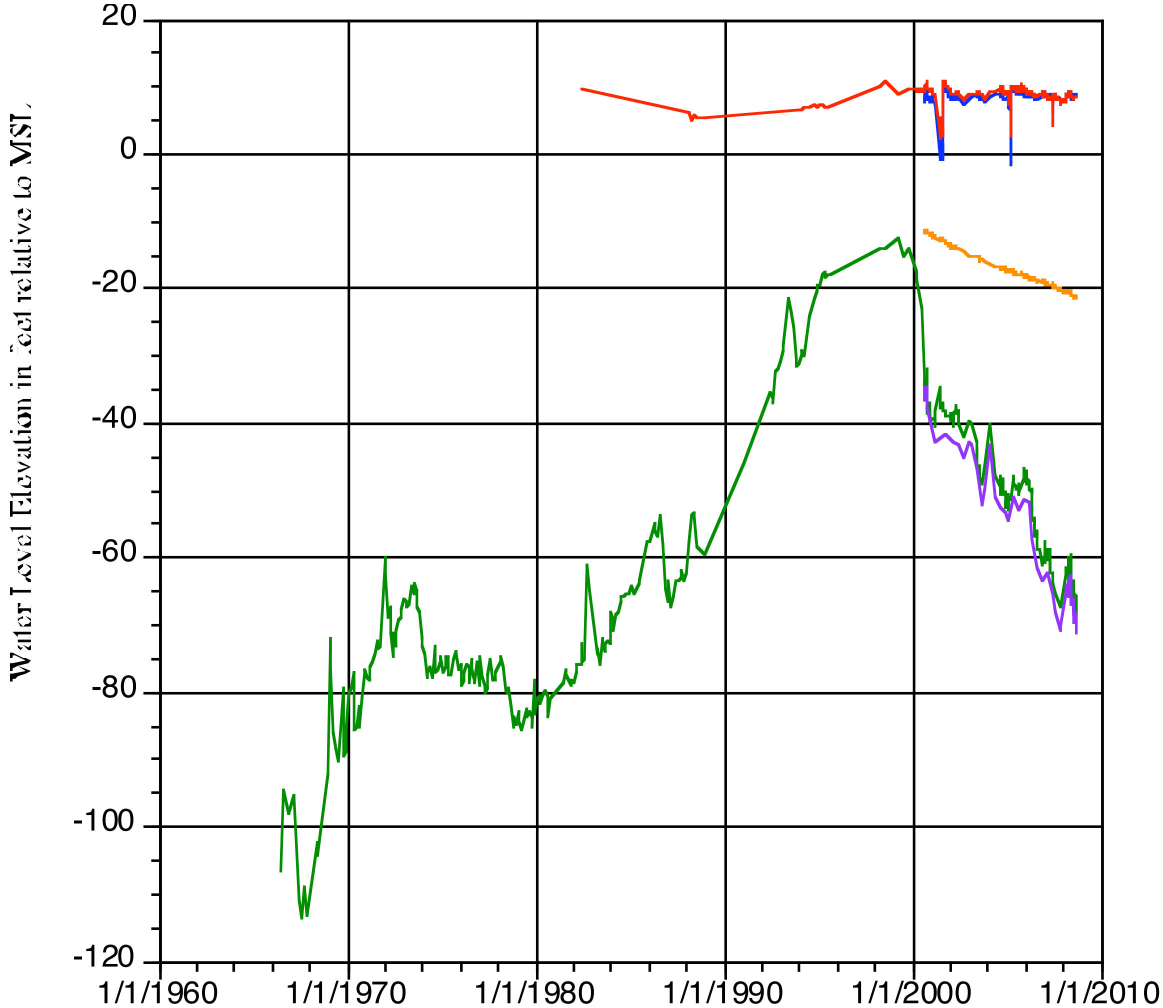
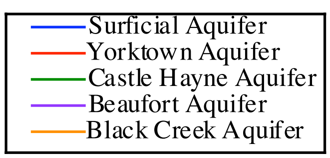


Figure 13: Hydrograph of NC Division of Water Resources
Lee Creek Monitoring Station in Beaufort County, NC



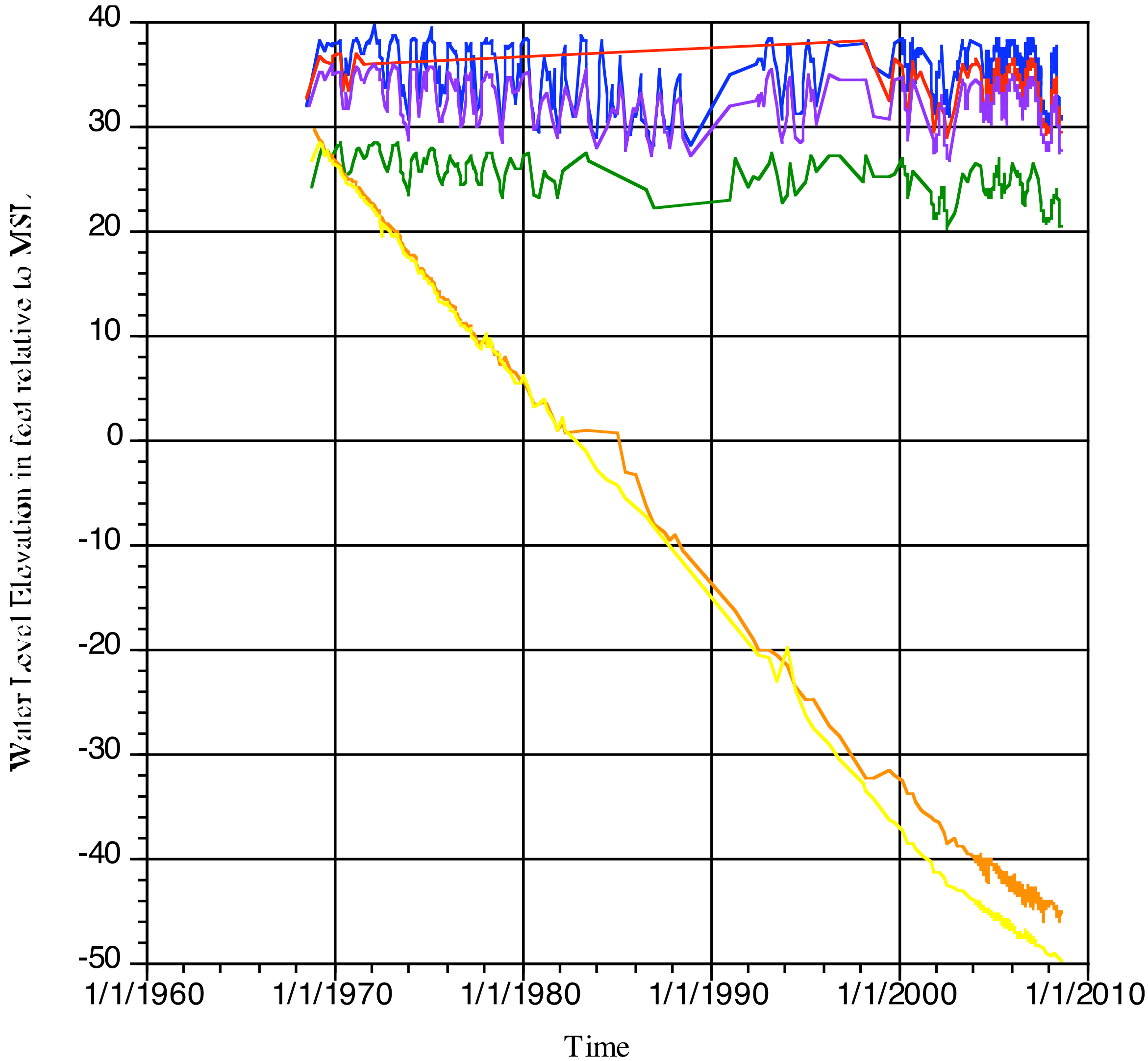
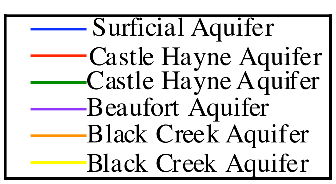


Figure 14: Hydrograph of NC Division of Water Resources
Wilmar Monitoring Station in Beaufort County, NC



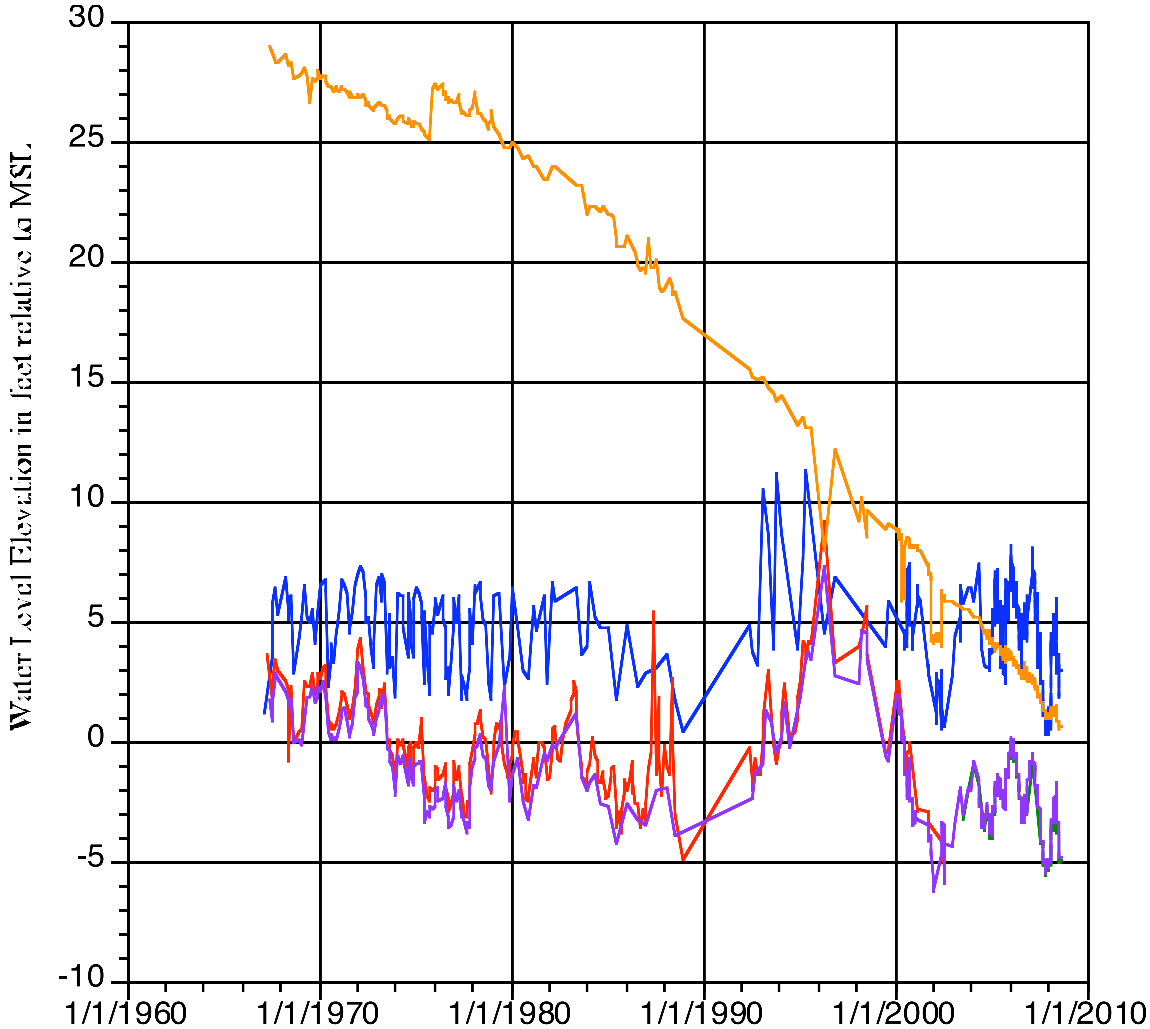
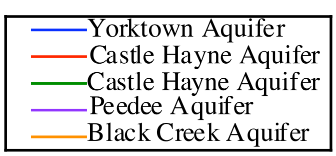


Figure 15: Hydrograph of NC Division of Water Resources
Cox Crossroads Monitoring Station in Beaufort County, NC



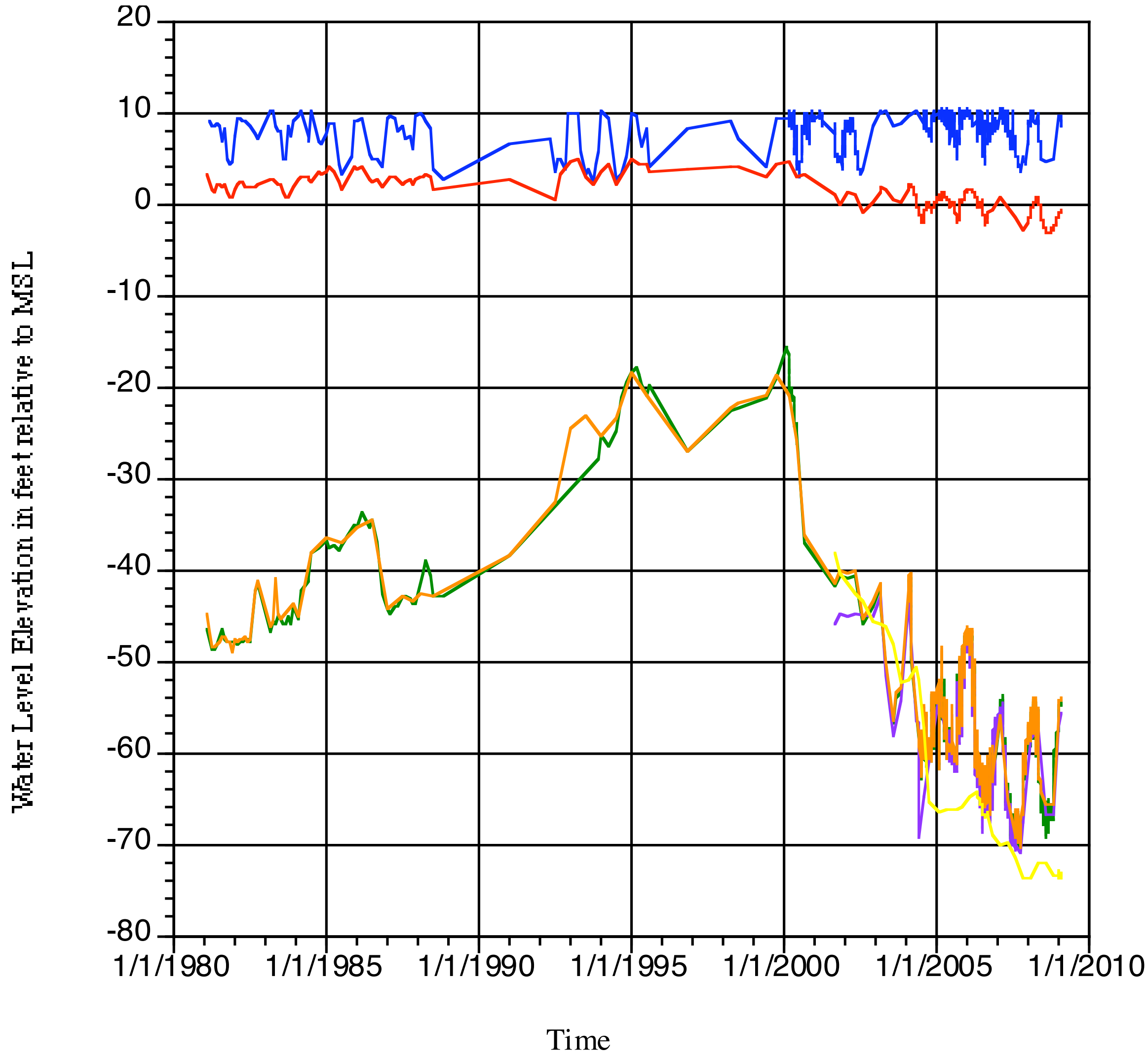
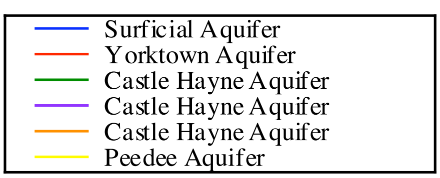


Figure 16: Hydrograph of NC Division of Water Resources Godley Farms Monitoring Station in Beaufort County, NC



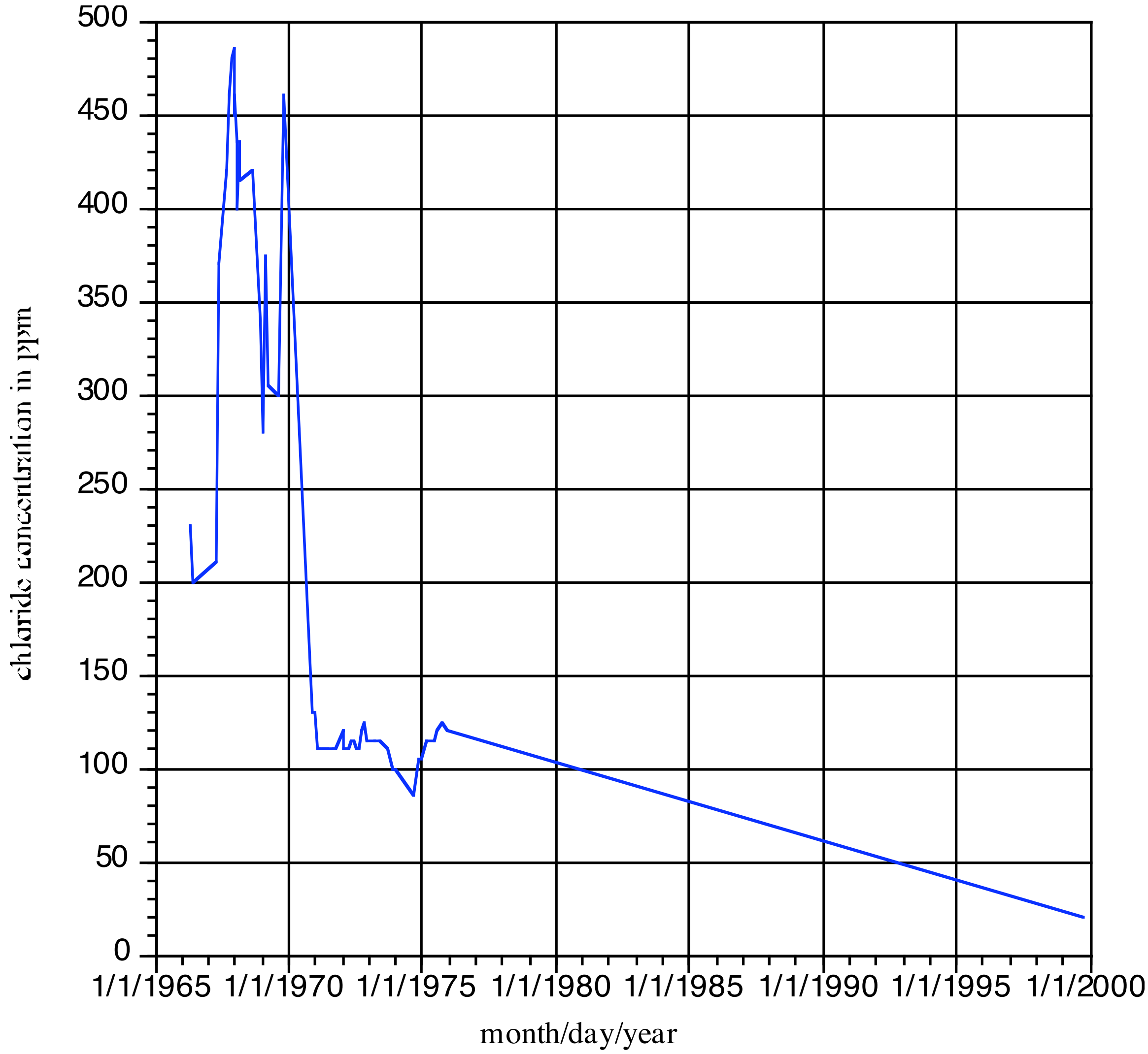


Figure 17: Plot of Chloride Concentration in parts per million from the Castle Hayne Aquifer well P17I-7 at the DWR Lee Creek Ground Water Monitoring Station in Beaufort County (May, 1966 to October, 1999)

Creek water levels appear to have have equilibrated with those of the Castle Hayne based on a relatively short period of record. Under this condition the water level in the Black Creek has ceased to decline and upward migration of salt water has effectively stopped. However, at the Aurora II monitoring station, the Black Creek water level is still 42 feet above the Castle Hayne due to the closer proximity of the station to the pumping center.

Pumping from the present day site of the mine has caused a westward shift in the position of the fresh water/salt water interface in the Castle Hayne Aquifer as evidenced by an increase in chloride levels in the DWR Godley monitoring station (plate 5). A zone in the lower part of the aquifer from 406 to 500 feet below land surface has seen an increase from 137 ppm to 564 ppm chloride between September, 2004 and October, 2007.

Beaufort Confining Unit

The Beaufort confining unit is made up of glauconitic clay and silt beds that occur in the upper part of the Beaufort Formation, and sometimes in the lower part of the Castle Hayne Formation. The top of the unit corresponds to the base of the Castle Hayne Aquifer, and the base of the unit to the top of the Beaufort Aquifer. The thickness of the unit varies between zero, where it is absent in a few wells across the study area to 140 feet in eastern Dare County (plate 30). The elevation of the top varies between slightly above sea level in westernmost Beaufort County, to greater than 1,660 feet below sea level in eastern Dare County (plate 29). In areas where the Beaufort confining unit is missing, the sands of the Beaufort Formation are part of the Castle Hayne Aquifer.

Beaufort Aquifer

The Beaufort Aquifer is present over most of the area of study except in areas where its confining unit is missing. It is principally comprised of highly glauconitic sand and sandy limestone beds present within the Beaufort Formation of Paleocene age. The difference in hydraulic head between the Beaufort and Castle Hayne Aquifers is generally only a few feet, and it appears that the effectiveness of confinement between the two aquifers is only slight.

The top of the aquifer, as displayed by a contour map of its elevation, slopes gently toward the east-southeast at a rate of 19 feet per mile in the westernmost counties, and increases to approximately 30 feet per mile in the east. The top ranges in elevation from sea level to more than 1,710 feet below sea level in eastern Dare County. The thickness of the aquifer varies between essentially zero where its confining bed is missing, to a maximum observed thickness of 242 feet in Carteret County.

The Beaufort Aquifer contains salt water in concentrations greater than 250 ppm over more than 75 per cent of the study area. The western boundary of the interface (where the isochlor intersects the base of the aquifer) occurs along a sinuous line running from north to south near the Washington-Martin County line through western Beaufort County, into northwestern Craven County, trending a few miles to the west of the City of New Bern. The intersection of the interface with the top of the aquifer is in approximate parallel orientation, and occurs generally about 5 miles to the east (plate 31). The narrow area occupied by the transition zone attests to the sluggish circulation of ground water through this aquifer and its low transmissivity.

The Beaufort Aquifer lies directly underneath the Castle Hayne Aquifer, and is thus affected by dewatering operations at the PCS Phosphate mine. This is indicated by a potentiometric surface map shown on plate 51, displaying a water level at the closest well to the excavation of 66.96 feet below sea level. However, it may be assumed that the water level directly underneath the excavation is close to 150 feet below sea level.

Peedee Confining Unit

The Peedee confining unit is made up of clay and slit beds that are present in the upper part of the Peedee Formation of Upper Cretaceous age and sometimes possibly in the lower part of the Beaufort Formation. This unit is defined primarily by geophysical and drillers log correlations across the study area due to limited information from monitoring stations where screens are available to observe long term head differences between the Beaufort and Peedee Aquifers. In addition, the large volume withdrawal from the PCS mine area has caused the water levels in the Peedee and Beaufort Aquifers to equilibrate with the Castle Hayne over most of Beaufort and surrounding counties (figures 13, 14, 16, and 17). Long term water level differences are observed, however, at the DWR Croatan and Clarks stations in Craven County.

The elevation of the top of this unit is everywhere below sea level in the study area, and ranges between 60 feet in western Beaufort to 1,786 feet below sea level in Carteret County. Available well data indicates that the unit thickens eastward to a maximum of 116 feet. The unit is absent in the northern part of the study area to the north of a line approximating the limit of the Peedee Aquifer (plate 34).

Peedee Aquifer

The Peedee Aquifer within the study area contains alternating beds of sand and clay that primarily make up the Upper Cretaceous Peedee Formation, although the aquifer may contain some sediments from the underlying Black Creek Formation or overlying Beaufort Formation in some areas. On some borehole geophysical logs, sands within the Peedee Aquifer appear to be thick and massive as illustrated in the DWR Bath and Winsteadville Station wells on cross section C-C' (plate 4). In other wells, as shown on regional cross sections, beds of sand of 10 to 20 foot thickness alternate with sections of clay. Sands are fine to coarse grained, slightly glauconitic and fossiliferous. Clays are generally dark brown in color and contain minor amounts of sand. The aquifer is known to contain only saline ground water in this area and could only be considered viable as a source of water for aquaculture farms or for treatment by reverse osmosis. Because of the fact that it is a salty aquifer in this area, little information is available about its hydraulic properties. Chloride concentrations in the aquifer vary between 1,204 and 19,360 ppm in DWR observation wells, and generally increase coastward. The fresh water salt water transition zone in the Peedee traverses the study area along the western fringe in Beaufort and northern Craven Counties (plate 35).

The top of the aquifer ranges in elevation from 120 feet below sea level in western Beaufort County to 1,842 feet below sea level in eastern within the limits of available well information. An elevation map indicates that it dips to the southeast at a rate of 16 feet per mile in Beaufort and northern Craven Counties, but steepens to approximately 37 feet per mile in eastern Carteret County. The thickness of the aquifer ranges between zero where its northern limit occurs, to a maximum of 395 feet in Pamlico County. In two oil company wells in Carteret County, permeable sediments are absent and the thickness of the aquifer is zero on an isopach map displayed on plate 36. A northward pinchout of the aquifer is shown as a dashed line on plates 35 and 36, and occurs where the Peedee Formation is either absent or part of the Upper Cape Fear confining unit in Washington, Tyrrell, and northern Dare Counties, and a small section of northern Beaufort County.

A regional potentiometric surface map of the Peedee Aquifer is shown on plate 52. Evident on the map are the effects of the dewatering operation on lowering water levels in the Castle Hayne Aquifer. This initially increased the negative head differential between the Peedee and Castle Hayne and allowed upward flow and a cone of depression to form in the Peedee. Over time, water levels in the Peedee equilibrated with the Castle Hayne and have dropped lower than the Castle Hayne at the DWR Godley Station (figure 17). The center of the cone of depression shown on the map is at the Godley Station, which exhibits a Peedee water level of –73.43 feet, with a corresponding level of –67.8 feet in the Castle Hayne. The actual center of the cone of depression in the Peedee is closer to the town of Aurora where the water level in the Castle Hayne has been drawn down to 150 feet below sea level to dewater the current PCS mine excavation. However, the DWR Aurora Station does not include a well screen in the Peedee Aquifer and the map does not show what should be the deepest Peedee water level.

Black Creek Confining Unit

The Black Creek confining unit generally consists of a very thick section of dark brown to blackish sandy clay that occurs in the upper part of the Black Creek Formation of Upper Cretaceous Age. The unit may also include clay beds in the lower part of the Peedee Formation. Geophysical logs in the study area indicate that the unit varies in thickness between 292 feet in the southern part of the study area (plate 37) to zero where it pinches out to the north in Washington, Tyrrell, northern Beaufort, northern Hyde and northern Dare Counties. Substantial differences in hydraulic head between the Peedee and Black Creek Aquifers have been observed historically at DWR monitoring stations in the area as illustrated in hydrographs on regional cross sections (plates 2 through 14). The elevation of the top of the unit varies between 193 and 1,604 feet below sea level as shown on (plate 37). The unit is absent in the northern part of the study area to the north of a line approximating the limit of the Black Creek Aquifer (plate 38).

Black Creek Aquifer

The Black Creek Aquifer is made up of alternating layers of white fine to coarse grained, lignitic sand and dark clay that vary in total thickness across the study area between 372 feet and zero where the unit pinches out to the north in Washington, Tyrrell, northern Beaufort, northern Hyde and northern Dare Counties. This unit is almost entirely within the Black Creek Formation of Upper Cretaceous Age. Over the majority of the area it contains ground water which exceeds 250 ppm chloride concentration. It contains fresh water in the DWR Clarks monitoring station well in Craven County in the western part of the study area and also at Wilmar. Interestingly, the overlying Peedee Aquifer at Clarks station contains salt water, while the Black Creek is fresh as shown in cross section E-E' (plate 6). This is perhaps due to a higher transmissivity of the Black Creek Aquifer in this vicinity, which has allowing better circulation of ground water than in the Peedee. Thus, the fresh water/salt water interface has migrated further eastward than in the overlying Peedee. Chloride concentrations vary over the study area between 192 ppm (DWR Clarks Station) and 16,435 ppm from six different measurement locations.

In several deep oil and gas wells drilled in the eastern part of the study area, and in particular, Carteret County, sands in the Black Creek Aquifer are completely missing and the equivalent unit is near 100 per cent clay. This is also the case in a number of wells drilled in northern Beaufort County as shown on an isopach map of the aquifer thickness (plate 40). The lack of permeability of Black Creek sediments in these areas would likely impede the coastward movement of salt water through the aquifer.

The elevation of the top of the Black Creek Aquifer varies between 299 and 1,690 feet below sea level across the area, dipping southeastward at a rate of 19 feet per mile to a maximum of 34 feet per mile on the Atlantic shoreline (plate 39).

As mentioned in the previous discussion of the effects of ground water withdrawals at the PCS Phosphate Quarry in Beaufort County, the potentiometric surface of the Black Creek Aquifer (plate 53) has been impacted due to a major drawdown of water levels in the Castle Hayne Aquifer and the large negative head gradient that was created between the Black Creek and Castle Hayne underneath the pumping center. This allowed increased upward movement of ground water over what would have occurred naturally in a ground water discharge area. Thus, water levels have been slowly declining in the Black Creek Aquifer underneath the mine site since July, 1965. This is illustrated by hydrographs from DWR monitoring stations (figures 13-17) and a potentiometric surface map of the aquifer (plate 53). The effects of pumping in the Central Coastal Plain are contributing to the decline as well, and the cones of depression merge in this area. It is anticipated that water levels will eventually equilibrate with the Castle Hayne, as they already have at the DWR Bonnerton monitoring station. Sands in the Black Creek Aquifer pinch out a few miles to the north of the mine site in northern Beaufort County as shown on an isopach map (plate 40). The permeability barrier to the north more than likely allows drawdown to occur at a higher rate in the Black Creek Aquifer underneath the mine site.

Upper Cape Fear Confining Unit

The Upper Cape Fear confining unit is defined in this study by head differences observed between the Black Creek and Upper Cape Fear Aquifers at the DWR Scuppernong and Clarks monitoring stations in Washington and Craven Counties. It is principally defined by correlation of the clay section that makes up this unit from well to well using borehole geophysical logs. Except for the wells at Clarks and Scuppernong, there are no other station sites where differences in hydraulic head may be observed. This unit is principally within the Cape Fear Formation of Upper Cretaceous Age. In the northern part of the study area where the Peedee and Black Creek Aquifers pinch out, clay beds which principally comprise these formations are likely a part of the Upper Cape Fear confining unit. The elevation of the top varies between 344 and 1,931 feet below sea level across the study area with the deepest penetration in Dare County (plate 41). The thickness of the unit varies between 12 and 450 feet as shown by an isopach map (plate 42). It is thickest in Dare and Carteret Counties, and thinner in the westernmost part of the area, and through Pamlico County.

Upper Cape Fear Aquifer

The Upper Cape Fear Aquifer within the study area contains fresh water only in westernmost Beaufort County in its upper portion, where the county is traversed by the fresh water/salt water interface (plate 43). The aquifer ranges in elevation between 469 feet to 2,394 feet below sea level where the deepest penetration occurs in Carteret County. It dips to the southeast at a rate of 28 feet per mile in the western counties, increasing to approximately 36 feet per mile along the coastline. The Upper Cape Fear Aquifer is made up of permeable sediments of the Cape Fear Formation of Upper Cretaceous Age. It is comprised of interbedded sands, clays, and silts that were deposited in alternating marine to nonmarine environments of deposition. Where nonmarine in origin in up dip areas, sands commonly are interbedded with layers of gravel, and are reddish to tan colored from the presence of iron oxides. Where the unit is marine in origin in the eastern part of the study area, sands alternate with beds of shell limestone and dolomite.

Two DWR monitoring stations have wells that are screened in the Upper Cape Fear Aquifer, including the Scuppernong Station in Washington County, and the Clarks Station in Craven County. The well at Scuppernong is affected by a large cone of depression formed due to withdrawals from the Franklin, Virginia area as evidenced by a decline of 12.55 feet since March, 1978. This well is probably near the limits of the cone of depression, as the effects are much more pronounced in wells to the north of the Albemarle Sound in Gates, Hertford, Bertie, Chowan, Perquimans, and Pasquotank Counties (Lautier, 1998).

Lower Cape Fear Confining Unit

The Lower Cape Fear confining unit consists of a thick section of clay and silt beds that are regionally correlative in the middle of the Cape Fear Formation. It occurs at an elevation ranging from 667 to 3,122 feet below sea level across the study area, dipping to the east-southeast at an average rate of 38 feet per mile. It thickens prominently toward the coast from 22 feet to a maximum of 320 feet in Dare County. There is virtually no water level information to help with the identification of this unit. It is defined exclusively by correlation with wells to the west of the study area.

Lower Cape Fear Aquifer/Lower Cretaceous Aquifer System Undifferentiated

The Lower Cape Fear confining unit is underlain by a wedge of sediments ranging in age from Upper to Lower Cretaceous and possibly Triassic/Jurassic (Brown, Miller and Swain, 1972). This sediment wedge ranges in thickness from approximately 800 to 5,300 feet from western Beaufort County to Cape Hatteras, consisting of alternating layers of sand, clay, silt, limestone, dolomite and various combinations of these lithologies. No attempt has been made in this study to subdivide the sedimentary section below the Lower Cape Fear confining unit into component aquifers and confining units due to the lack of water level and stratigraphic information necessary to ensure the reliable identification and correlation of units. In coastal plain counties to the west of the study area, the Lower Cape Fear Aquifer directly overlies the basement surface and probably includes some sediments of Lower Cretaceous age. Within the study area sediments of Lower Cretaceous age thicken dramatically toward the coastline, thus accounting for their great thickness underneath Cape Hatteras. Resistivity measurements from borehole geophysical logs and time domain electromagnetic surveys indicate that these sediments are highly saline beneath the study area.

Basement

The Quaternary through Triassic age sediments of the East Central North Carolina Coastal Plain are underlain by a basement complex of pre-Mesozoic rocks which vary in type between volcanic and plutonic (Lawrence and Hoffman, 1993).

A structural map of the basement elevation indicates that it dips steeply to the east- southeast at a rate of approximately 105 feet per mile (plate 48). Data from the few wells that penetrate the basement surface indicate that it ranges in elevation between 1,871 below sea level in Beaufort County to 9,854 feet below sea level underneath Cape Hatteras in Dare County.

Status of DWR Monitoring Well Network in the East Central Coastal Plain and Recommendations for Improvement

A number of replacement wells are needed at this time in order to improve the DWR monitoring network in the study area. The Belhaven monitoring station, constructed between 1966 and 1973, was abandoned sometime after 1984. A replacement station in the general vicinity is needed not only to monitor water levels, but to track the potential westward migration of the fresh water salt water transition zone in the Castle Hayne Aquifer (plate 9, cross section H-H'). The Winsteadville monitoring station in Beaufort County includes a well screened in the Castle Hayne Aquifer from 250 to 430 feet below land surface (plate 4, cross section C-C'). The screen apparently crosses the fresh water salt water transition zone as indicated by an elevated chloride level of 246 ppm. The screen is so wide however, that it is impossible to delineate where the transition zone occurs within the 180 foot screen. The well should be replaced by two wells with narrower screens, one upper, and one lower to better track changes that may occur in the transition zone due to pumping in Beaufort County. This will also provide head information in upper and lower Castle Hayne zones to help understand its hydraulic properties between the lower sandy section, and upper limestone section. A lower Castle Hayne Aquifer well is needed at the Bath monitoring station in Beaufort County in order to help track the potential westward movement of the transition zone (plate 4, cross section C-C'). At the Southside monitoring station in Beaufort County, the lower Castle Hayne well, which was constructed with an open hole between 280 and 370 feet below land surface, was left ungrouted between land surface and 200 feet. The chloride concentration in this well is 740 ppm, while the level in the upper Castle Hayne well is 56 ppm. The close proximity of the station to the Pamlico River as a source of

salt water and the fact that the lower Castle Hayne well was left ungrouted leaves open the question of whether the high chloride level in the well is due to salt water intrusion from the river, or westward migration of the Castle Hayne transition zone. In order to be valuable as a monitoring site for tracking any possible westward shift in the Castle Hayne salt water transition zone due to mining activities, a new monitoring station should be constructed further south of the river. The Yorktown Aquifer well (147-156') at Hydeland Station needs to be replaced for two reasons. The well was grouted from 0 to 20 feet and left open from 20 feet to the top of the screen. The surficial aquifer well at Hydeland has a chloride concentration of 1,000 ppm due to salt water intrusion from a nearby source. Thus, salt water from the surficial aquifer was able to move down around the casing to pollute the Yorktown screen zone from 147 to 156 feet, which showed a chloride level of 301 ppm. This problem was discovered by means of a nearby TDEM sounding which showed a resistivity value indicative of fresh water at the level of the Yorktown screen zone. A TDEM sounding was conducted next to the DWR Sladesville Station in Hyde County which showed a resistivity of 54 to 73 ohm-meters adjacent to the screen zone of the Castle Hayne monitoring well. Resistivity of this magnitude typically indicates the presence of fresh water. The last measured chloride value from Oct. 1999 was 5400 ppm. An earlier sample from 1977 indicated a 480 ppm chloride concentration. It is apparent that the well has a construction problem that is allowing salt water from a nearby source
to move into the screen zone.

Conclusions

Population growth in the North Carolina Coastal Plain has led to increased reliance on ground water for water supply needs. This has fueled the need to understand in more detail, the system of aquifers and confining beds that underlie the region, and in particular how the aquifers are being affected by current pumping conditions. A better and more detailed understanding of the hydrogeologic framework will allow for development of strategies for dealing with water level declines in the confined aquifers of the Coastal Plain.

This study was accomplished by correlation and interpretation of borehole geophysical and lithologic logs, water level and chloride measurements taken from a network of observation and other types of wells, aquifer test data, and time domain electromagnetic soundings. Much additional information has been made available from new ground water monitoring station sites that have been added to the North Carolina ground water monitoring network by the Division of Water Resources Moreover, new information has been made available through public and private water system wells that have been drilled in the past few years.

The hydrogeologic system in the study region, from basement to land surface, consists of eight regionally significant aquifers and the intervening confining units that separate them. Included are the surficial, Yorktown, Castle Hayne, Beaufort, Peedee, Black Creek, Upper and Lower Cape Fear aquifers. Each aquifer was mapped and described in as much detail as available data would allow in order to define them in terms of regional elevation, thickness and lateral distribution, hydraulic properties, relationship to stratigraphic units, ground water movement, and chloride distribution. The approximate position of 250 parts per million chloride interfaces was plotted, where applicable on cross sections and elevation maps prepared for the study. Water level data from a regional network of monitoring wells was used to construct up-to-date potentiometric surface maps for each of the confined aquifers in the study region.

The results of this study indicate that ample fresh, ground water supplies exist in the surficial, Yorktown and Castle Hayne Aquifers in the study region. The Yorktown and Castle Hayne Aquifers are more prolific and high yielding in the East Central Coastal Plain counties than any other place where they are present in the Coastal Plain.

Large scale mine dewatering operations and resultant withdrawals from the Castle Hayne Aquifer in Beaufort County have produced a large cone of depression that has been discussed in numerous earlier reports. What has not been discussed is the impact on deeper, salt water bearing aquifers that underlie the Castle Hayne Aquifer, and the apparent water level declines that are occurring in the Beaufort, Peedee, and Black Creek Aquifers. This report has discussed these issues in detail.

This study has also identified numerous places in the region where improvements are needed in the existing Division of Water Resources ground water monitoring network either due to improperly constructed wells, incomplete stations, or areas where additional stations are needed.

REFERENCES

Brown, P.M., and others Geologic Map of North Carolina, North Carolina Department of Natural Resources and Community Development, Division of Land Resources, Geological Survey Section, 1985.

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.

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.

Harshbarger, J.W. Analysis of Ground Water Systems in the Beacham Savanna Area, Beaufort County, North Carolina (confidential report to Bear Creek Mining Company, Washington, North Carolina), (1963)

Heath. R.C.. 1994. Ground-Water Recharge in North Carolina: Unpublished report prepared for the North Carolina Division of Water Quality, Aquifer Protection Section, 44 p.

Heath, R.C. 1980, Basic Elements of Ground-Water Hydrology With Reference to Conditions in North Carolina: U.S. Geological Survey Water Resources Investigations Open File Report 80-44, 86 p.

Heath, R.C., 1994, Ground-Water Recharge in North Carolina: Unpublished report prepared for the NC-DWQ Aquifer Protection Section, 44 p.

Ingram, R.L., 1987, Peat Deposits of North Carolina: North Carolina Geological Survey Section Bulletin 88, 84 p.

Interim Report on Groundwater Conditions in Capacity Use Area No. 1 Central Coastal Plain, North Carolina, 1976, North Carolina Division of Environmental Management, Groundwater Section, 55 p.

Keyes, W.S., 1990, Borehole Geophysics Applied to Ground-Water Investigations, in: Techniques of Water Resources Investigations, U.S. Geological Survey, Book 2, Chapter E2, 149 p.

Kimrey, J.O., 1965, Description of the Pungo River Formation in Beaufort County, North Carolina, U.S. Geological Survey Bulletin No. 79, 131 p.

Lautier. J.C., 1998, Hydrogeologic Framework and Ground Water Resources of the North Albemarle Region, North Carolina, North Carolina Department of Environment and Natural Resources, Division of Water Resources, 61 p.

Lawrence, D.P., and Hoffman, C.W., Geology of Basement Rocks Beneath the North Carolina Coastal Plain, North Carolina Department of DEHNR, Division of Land Resources, Geological Survey Section, Bulletin 95, 59 p.

Miller, J.A., 1982, Stratigraphy, Structure, and Phosphate Deposits of the Pungo River Formation of North Carolina, North Carolina Department of Natural Resources and Community Development, Division of Land Resources, Geological Survey Section, Bulletin 87, 32 p.

NC Groundwater Section, 1974, Status Report on Groundwater Conditions in Capacity Use Area No. 1 Central Coastal Plain, North Carolina, North Carolina Department of Natural and Economic Resources, 146 p.

Nelson, P.F., 1964, Geology and Ground-Water Resources of the Swanquarter Area, North Carolina, NC Department of Water Resources, Division of Ground Water, Ground Water Bulletin No. 4, 79 p.

North Carolina Ground Water Division, William F. Guyton and Associates, and others, 1971, Report on Hydrogeology and Effects of Pumping from Castle Hayne Aquifer System, Beaufort County, North Carolina, 52 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, North Carolina Dept. of Natural and Economic Resources, Division of Resource Planning and Evaluation, Groundwater Section, 33 p.

Stephenson. L.W., and Johnson, B.L., 1912, The Water Resources of the Coastal Plain of North Carolina, in Clark, W.B., Miller, B.L. Stephenson, L.W., Johnson, B.L. and Parker, H.N., The Coastal Plain of North Carolina; North Carolina Geological and Economic Survey, v.3, pt.2, p. 333-509.

Wilder, H.B., Robinson, T.M., and Lindskov, K.L., 1978, Water Resources of Northeast North Carolina: U.S. Geological Survey Water-Resources Investigation 77-81, 113 p.

Wilson, Nathaniel C., Roanoke Island 1993 Ground Water Monitoring Report, Division of Water Resources, NC Department of Environment, Health, and Natural Resources, May 1994, 23 p.

Winner, M.D. Jr. and Simmons C.E., 1977, Hydrology of the Creeping Swamp Watershed, North Carolina, with reference to potential effects from stream channelization: U.S. Geological Survey Water Resources Investigation 77-26, 54 p.

Winner, M.D., and Coble, R.W., 1996, Hydrogeologic Framework of the North Carolina Coastal Plain, U.S. Geological Survey pp. 1404-1, 150 p.