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

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Division of Water Resources
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The area covered by this report encompasses ten counties of the North Carolina Southern Coastal Plain, including Bladen, Robeson, Scotland, Hoke, Cumberland, Sampson, Pender, Brunswick, New Hanover, and Columbus Counties. The southwestern part of Duplin County is included as well (figure i). This report continues and connects with a previous regional study of the North Carolina Central Coastal Plain by Lautier, 2001, entitled Hydrogeologic Framework and Groundwater Conditions in the North Carolina Central Coastal Plain.

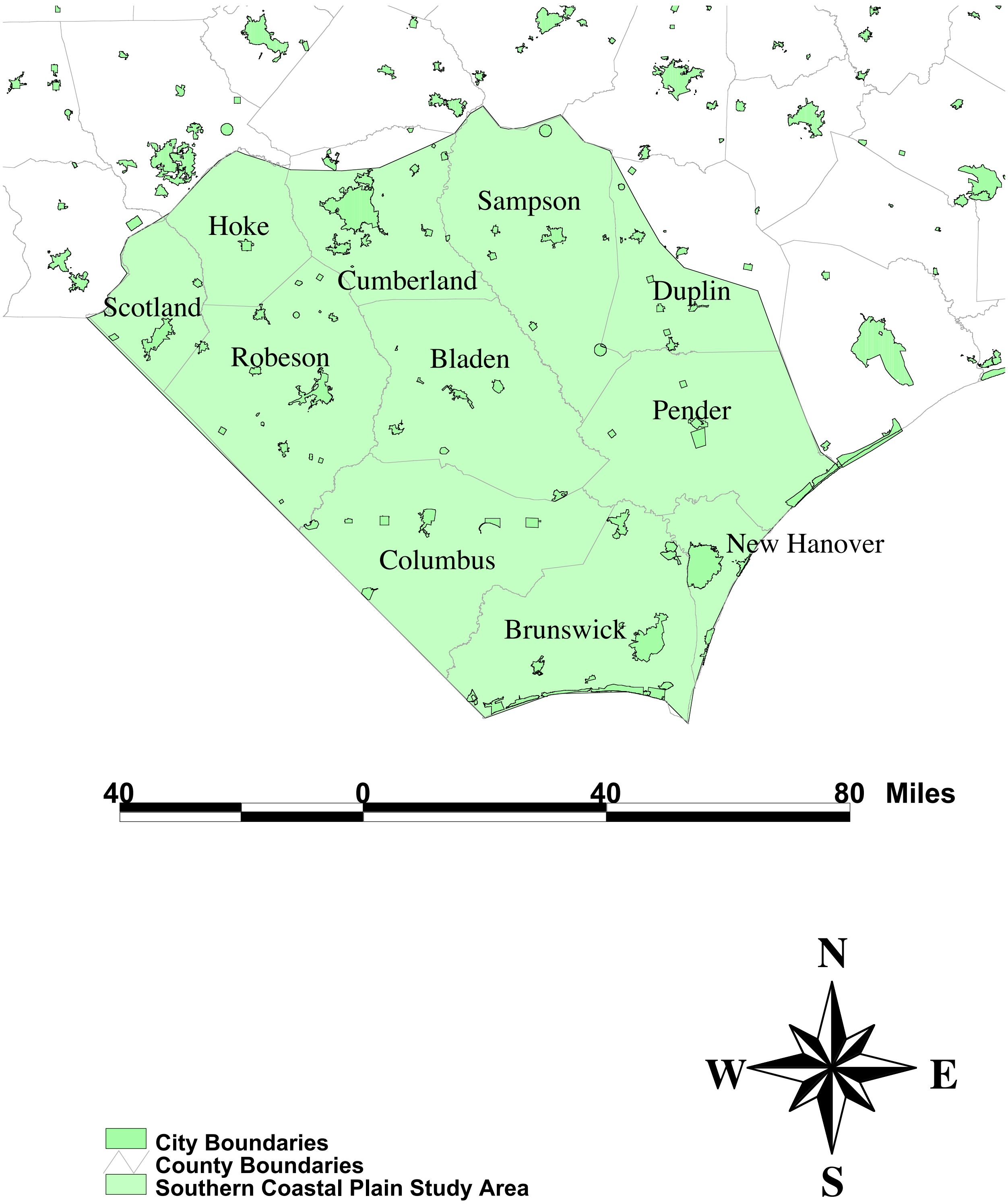
As is the case in the Central Coastal Plain, population growth in the southern counties of the coastal plain has led to increased reliance on ground water for water supply needs. This has fueled the need to understand in more detail, the system of aquifers and confining beds that underlie the region,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

In December, 2002, the Division of Water Resources was asked by the North Carolina Environmental Management Commission to conduct a capacity use investigation of Bladen, Robeson and surrounding counties in order to assess the impact of ground water withdrawals from the Cretaceous aquifers. The results of that study were presented in a report entitled "Southern Coastal Plain Capacity Use Investigation," 2004. This report expands the area and scope of the previous study to include the complete hydrogeologic framework of the aforementioned ten county area.

The study was accomplished by correlation and interpretation of borehole geophysical and lithologic logs, water level and chloride measurements taken from a network of observation 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. In addition, new information has been made available through public and private water system wells that have been drilled in the past few years.

The geology of the North Carolina Southern 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 which rests on an underlying basement complex of Paleozoic age rocks. The basement surface ranges in elevation between 96 and 1,515 feet below sea level within the area of study, and dips southeast at a rate of 40 feet per mile in the northwestern part of the area to 72 feet per mile in the southeast. 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 zero at the fall line to in excess of 1,515 feet in the southern tip of New

Figure i. Study Area: Southern Coastal Plain Hydrogeologic Framework



Hanover County and southeastern-most part of Brunswick County. In a successive manner, older stratigraphic units outcrop or subcrop immediately west of the updip limit of the next younger unit. Deposition occurred in cyclic fashion during alternating transgressions and regressions of the Atlantic Ocean, in marine to non-marine environments.

The sedimentary column of the Southern 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 Southern 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 six 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 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. To the northwest of the pinchout of the Peedee Formation, the confining unit of the Black Creek aquifer may include Pliocene age Yorktown or younger age deposits which directly overly the Black Creek Formation. In this area, the Black Creek aquifer can include permeable beds in the lower part of these younger 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 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.

Figure ii. -Relationship of Geologic and Hydrogeologic Units in the North Carolina Southern Coastal Plain

North Carolina Southern Coastal Plain Geologic Units			North Carolina Southern Coastal Plain Hydrogeologic Units
System	Series	Formation	Aquifers and Confining Units
Quaternary	Holocene	Undifferentiated	Surficial Aquifer
	Pleistocene		
Tertiary	Pliocene	Yorktown Formation	(note: the Yorktown Formation does not overly the Castle Hayne in the study area and is not part of the Castle Hayne confining unit)) Castle Hayne Confining Unit
	Middle Eocene	Castle Hayne Formation	Castle Hayne Aquifer
	Upper Paleocene	Beaufort Formation	Peedee Confining Unit
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

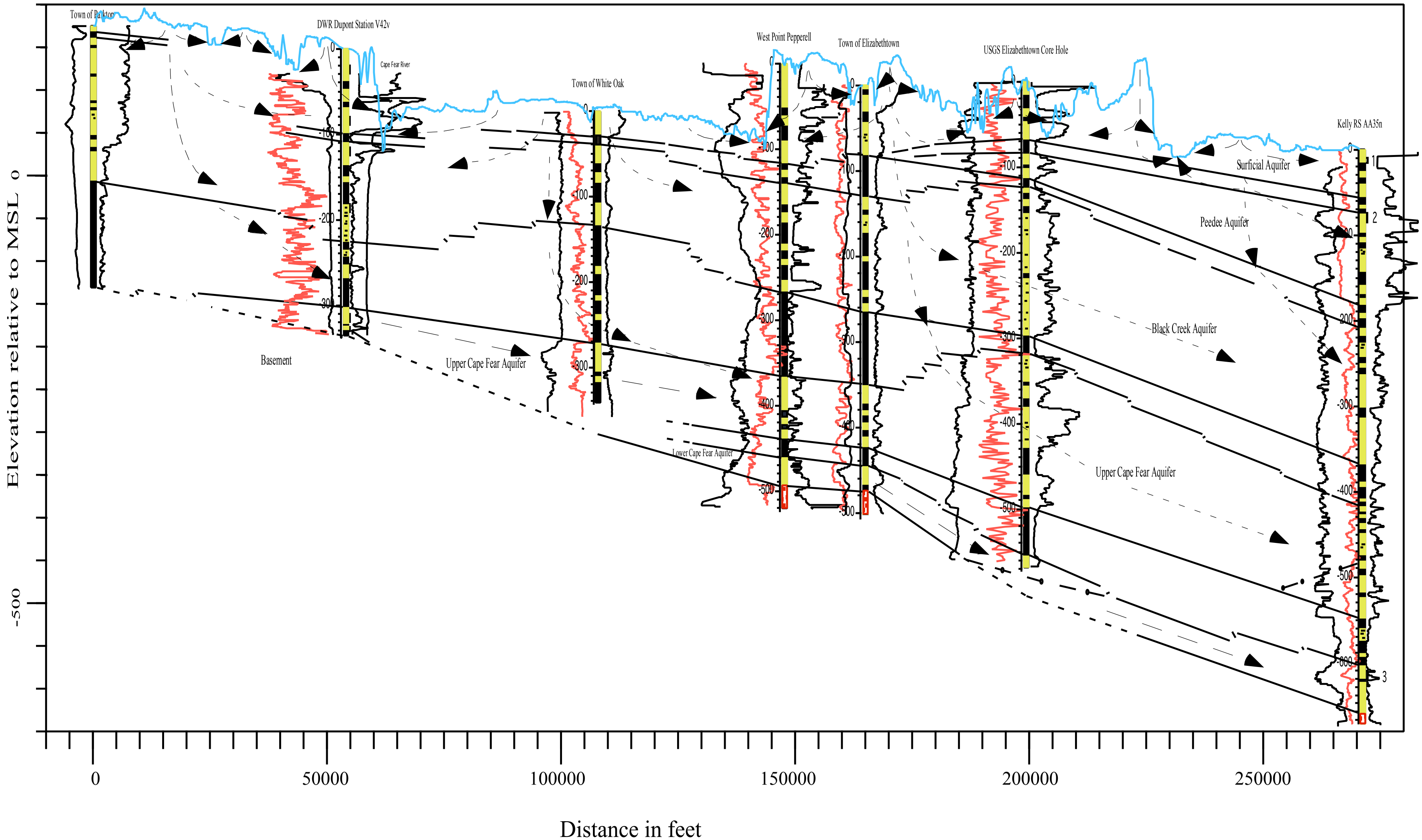
The surficial, or water table aquifer, which is made up primarily of Quaternary age sediments. It also includes parts of older formations depending on the varying age of underlying sediments and the varying stratigraphic position of the uppermost confining layer.

A typical hydrogeologic cross section through the Southern 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.

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 along the coast of New Hanover and Pender Counties, as well as along the fringes of the coastline, and other areas where high tides cause natural intrusion of salt water. 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 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.

The system of six regional aquifers and intervening confining units found in the Quaternary through Cretaceous age sedimentary wedge in the 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.

The results of this study indicate that ample ground water supplies exist in the Southern Coastal Plain to provide for present and future needs, in balance with surface water use. However, it is also clear that careful consideration must be taken in the placement and design of new well fields in order to avoid excessive drawdown situations such as what has occurred in Bladen County in the Black Creek and Upper Cape Fear



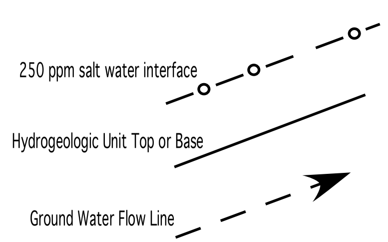


Figure iii. Northwest to Southeast Hydrogeologic Cross Section through Robeson and Bladen Counties, NC showing idealized ground water flow lines and salt water interfaces

Aquifers. Confined aquifers in areas such as Bladen County are particularly sensitive to relatively small pumping volumes due to low aquifer transmissivity. Excessive drawdown can lead to dewatering of a confined aquifer, which will result in compaction, loss of pore space, and permanent loss of yield ability. Moreover, excessive drawdown can lead to salt water encroachment if salt water sources are within reach of a cone of depression, or if a source exists below the zone of pumping. Careful monitoring of aquifers in the Southern Coastal Plain via the Division of Water Resources monitoring network is necessary in order to track water level decline rates, the growth of cones of depression, and changes in chloride concentration in areas affected by pumping. Expansion of this network is badly needed in order to gain adequate coverage of areas experiencing water level declines.

Additional ground water monitoring stations are needed near the cities of Elizabethtown, White Lake and Tarheel in Bladen County to monitor water level declines in the Black Creek and Upper Cape Fear aquifers. Additional monitoring stations are needed in the vicinity of Lumberton in Robeson County to monitor declines in the Black Creek aquifer. Wells are needed in Scotland and Hoke Counties in order to better understand the hydrogeologic framework and monitor Black Creek and Upper Cape Fear aquifer water levels. The Turkey Station in Sampson County needs to be replaced because of well construction problems along with the Magnolia and Red Banks stations in Robeson County. A big gap in the Division of Water Resources monitoring network exists in Pender County, where there is only one station at Burgaw. Additional stations are needed there in order to gain a better understanding of ground water conditions. Monitoring stations are badly needed in New Hanover County on order to monitor stresses on the Peedee and Castle Hayne aquifers, particularly in the northern half where the majority of the population lives and where ground water withdrawals are heaviest.

Introduction

The area covered by this report encompasses ten counties of the North Carolina Southern Coastal Plain, including Bladen, Robeson, Scotland, Hoke, Cumberland, Sampson, Pender, Brunswick, New Hanover, and Columbus Counties. The southwestern part of Duplin County is included as well (figure 1). This report continues and connects with a previous regional study of the North Carolina Central Coastal Plain by Lautier, 2001, entitled Hydrogeologic Framework and Groundwater Conditions in the North Carolina Central Coastal Plain.

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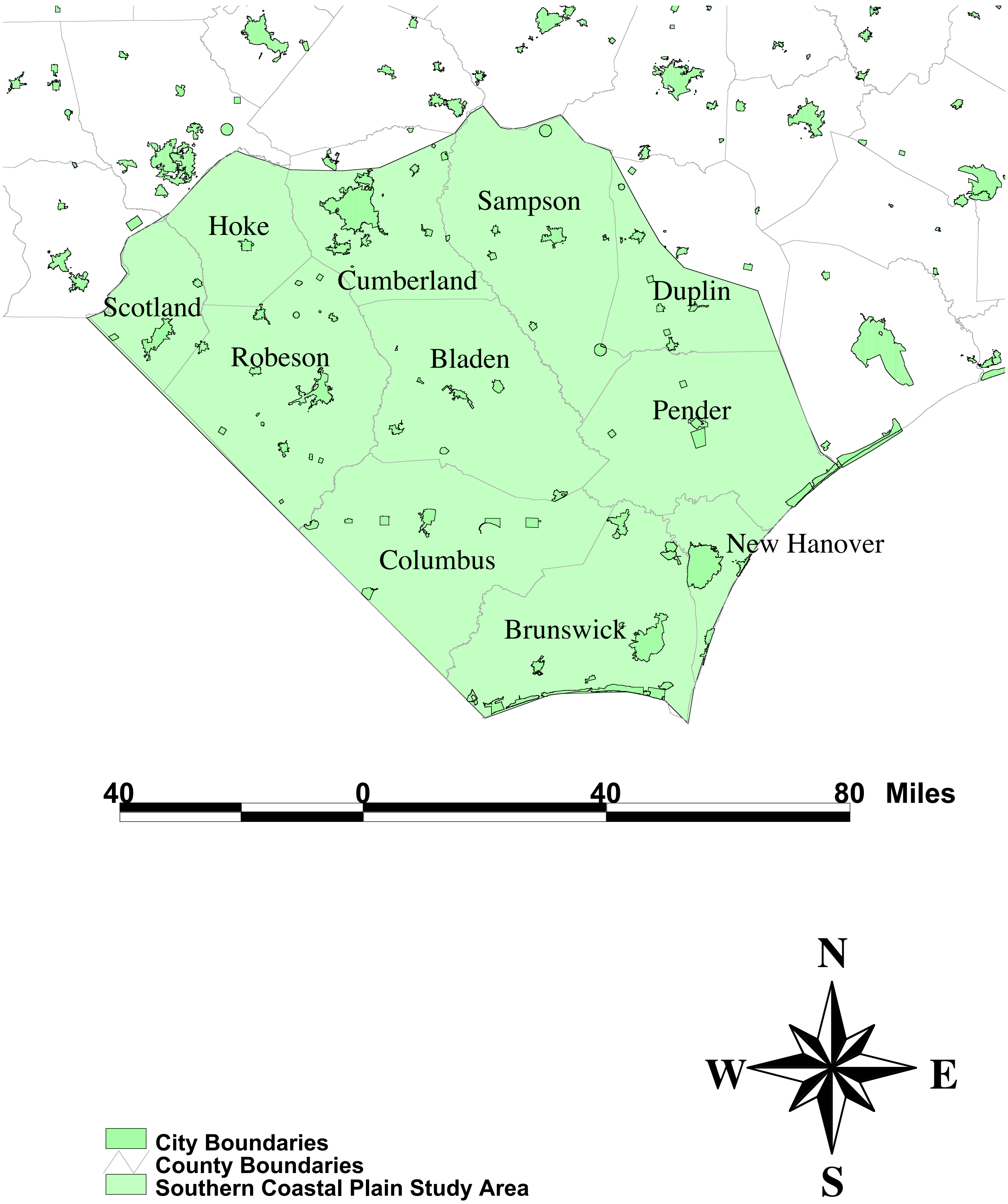
Previous Studies

Of the numerous local and regional geologic and hydrogeologic studies concerning this region that have been published, the ones that most relate to this study are mentioned as follows:

The Wooten Company and Groundwater Management Associates, 2004, A regional study of ground and surface water resources of Bladen, Robeson, Sampson, Columbus, Scotland and Hoke Counties.

Figure 1. Study Area: Southern Coastal Plain Hydrogeologic Framework



Harden, S.L., Fine, J.M., and Spruill, T.B., 2003, A study of the hydrogeology and Ground Water Quality of Brunswick County.

Strickland, A.G., 2000, A study of water level conditions in the Southern Coastal Plain Black Creek aquifer covering the period of 1992 through 1998.

Strickland, A.G., 2000, A study of water level conditions in the Southern Coastal Plain Upper Cape Fear aquifer covering the period of 1994 through 1998.

Lautier, J.C., 1998, A study of New Hanover and eastern Brunswick Counties related specifically to an assessment of potential ground water system impacts from deepening the Wilmington Harbor shipping channel.

Lawrence and Hoffman 1993, A geologic study of basement rocks present beneath the North Carolina coastal plain.

Zarry. L., A., 1991, A subsurface stratigraphic framework study of Cenozoic strata in Brunswick and New Hanover Counties.

Winner and Coble, 1989. A regional hydrogeologic framework study of the NC Coastal Plain aquifer system.

Brown, Miller and Swain, 1972, A regional structural and stratigraphic study of the Atlantic Coastal Plain.

Bain, 1970, A study of the hydrogeology of New Hanover County.

LeGrand, H.E., 1960, A study of the geology and ground water resources of the Wilmington-New Berne area.

Acknowledgements

The author would like to thank the following colleagues in the North Carolina Division of Water Resources-Ground Water Allocation Section, who contributed to this report, either by review, data collection and data entry, assistance with data analysis, discussion, etc. : Nat Wilson, Stephen Webb, Gabrielle Chianese, Blake Rouse, Keith Robertson, Michael Bauer, John Barr, and Mark Gamble.

Hydrogeologic Setting

The geology of the North Carolina Southern 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 which rests on an underlying basement complex of Paleozoic age rocks. The basement surface ranges in elevation between 96 and 1,515 feet below sea level within the area of study, and dips southeast at a rate of 40 feet per mile in the northwestern part of the area to 72 feet per mile in the southeast. 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 zero at the fall line to in excess of 1,515 feet in the southern tip of New Hanover County and southeastern-most part of Brunswick County. In a successive manner, older stratigraphic units outcrop or subcrop immediately west of the updip limit of the next younger unit. Deposition occurred in cyclic fashion during alternating transgressions and regressions of the Atlantic Ocean, in marine to non-marine environments.

The sedimentary column of the Southern 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 Southern Coastal Plain. The relationship of the geologic column to the system of hydrogeologic subdivisions as defined by this study is depicted in figure 2.

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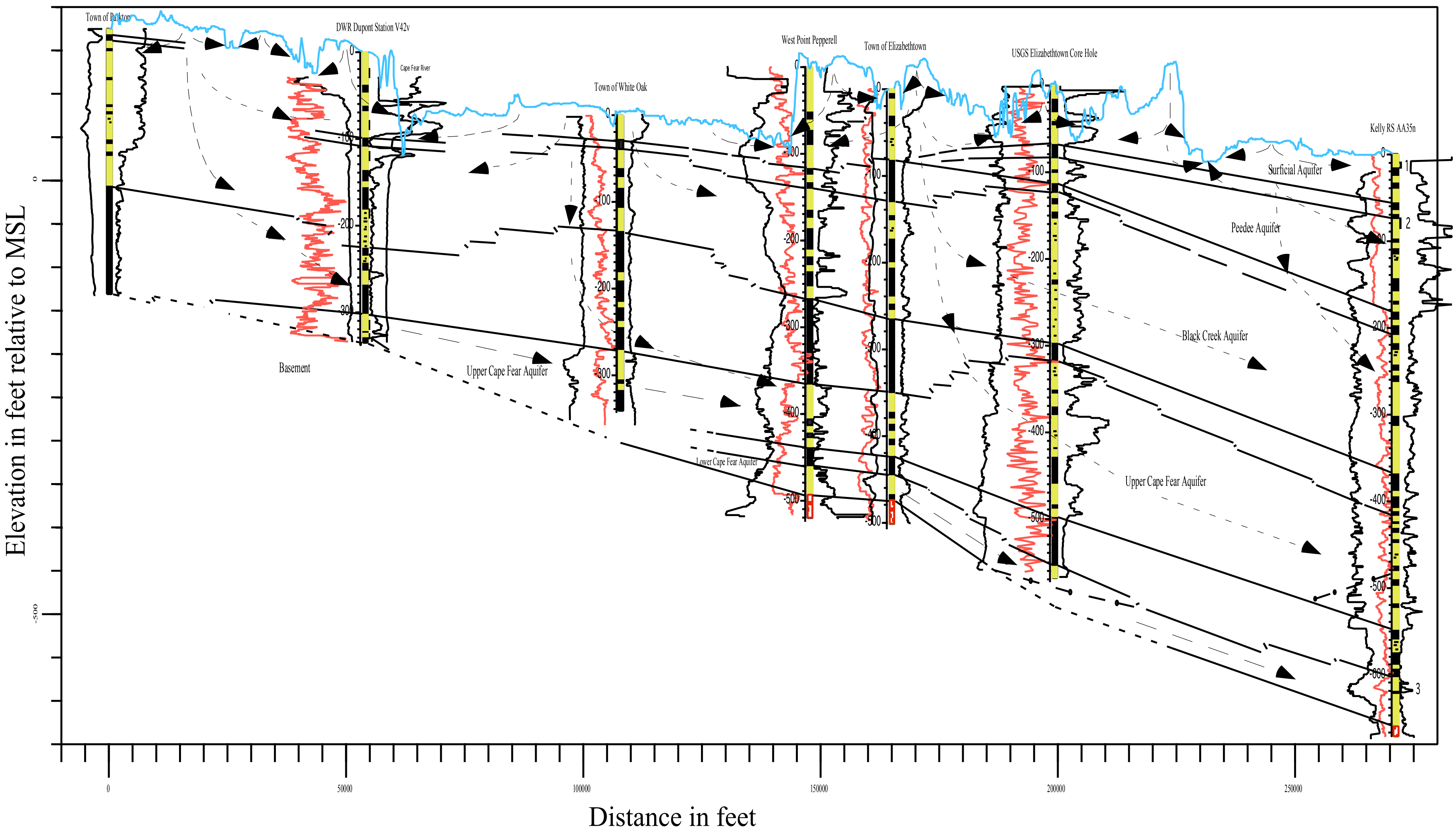
The surficial, or water table aquifer, which is made up primarily of Quaternary age sediments. It also includes parts of older formations depending on the varying age of underlying sediments and the varying stratigraphic position of the uppermost confining layer.

General Description of the Ground Water System

A typical hydrogeologic cross section through the Southern 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 along the coast of New Hanover and Pender Counties, as well as along the fringes of the coastline, and other areas where high tides cause natural intrusion of salt water. 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 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 Southern Coastal Plain (figure 4), recharge occurs predominantly through rainfall, which enters the surficial (or water table) aquifer in the interstream areas. The ten county area receives an



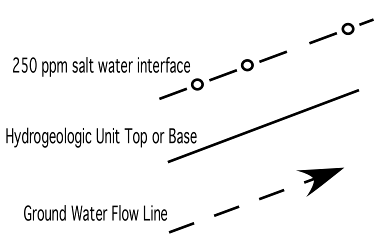


Figure 3: Northwest to Southeast Hydrogeologic Cross Section through Robeson and Bladen Counties, NC showing idealized ground water flow lines and salt water interfaces

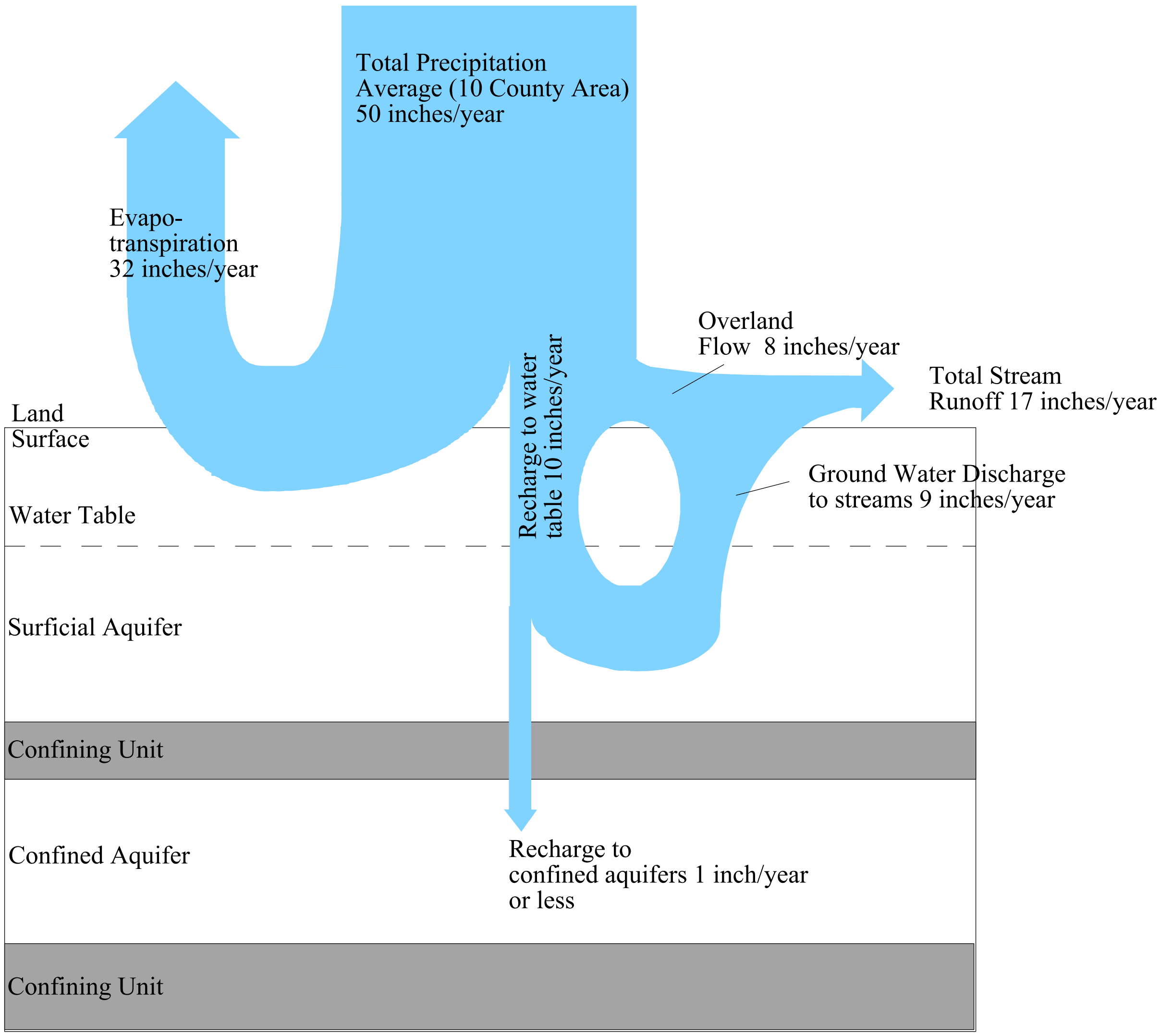


Figure 4. Generalized average water budget model for the NC Southern Coastal Plain ground water system (adapted from Hardin, Fine, and Spruill, U.S. Geological Survey, 2003 and Wilder, 1978)

average of 50 inches of total precipitation per year based on historical records covering the years between 1971 to 2000 (Southeast Regional Climate Center, table 1). Based on a water budget model developed by the U.S. Geological Survey for Brunswick County (Harden, Fine and Spruill, 2003), and using precipitation data averaged for the whole ten county area, it was determined that about 8 inches of the 50 inches of total annual precipitation is lost to overland flow to nearby surface water bodies. Another 32 inches are taken up annually through evapo-transpiration. Of the 10 inches of water that enters the water table as recharge, 9 inches per year flows from recharge to discharge areas such as the Cape Fear, Lumber, South, and Waccamaw Rivers, associated floodplains, and the Boiling Springs Lakes. 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
Brunswick	57.96
New Hanover	57.07
Columbus	50.22
Bladen	48.53
Robeson	47.98
Scotland	48.17
Cumberland	46.6
Sampson	48.58
Pender	54.2
Hoke	no data
Duplin	56.98
10 county average:	51.63

source: Southeast Regional Climate Center

Table 1: Average of Total Annual Precipitation (in inches) from 1971 to 2000 for the North Carolina Southern Coastal Plain

In certain areas of the Southern Coastal Plain deeper confined aquifers are easily over-pumped, and susceptible to excessive drawdown and formation of large cones of depression due to various reasons:

1. Low rates of available recharge water as indicated by the water budget model (one inch or less per year).
2. The presence of thick, low permeability confining layers which slow down the rate of recharge.
3. Low aquifer transmissivity.
4. Poor well field design.

Examples of this have occurred in Bladen County, where pumping of over 3 million gallons per day of ground water from the Black Creek and Upper Cape Fear aquifers at Elizabethtown, White Lake and the Tarheel area produced overlapping cones of depression that cover most of the county, and parts of surrounding counties. The Black Creek aquifer in the Tarheel region is most likely being dewatered as indicated by comparison of the elevation of the top of the aquifer and a map of the potentiomentric surface.

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 2-22) 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 Castle Hayne, Peedee, Black Creek, Upper and Lower Cape Fear aquifers using water level data collected by the North Carolina Division of Water Resources in July and August of 2005.

Hydrogeologic Framework of the Study Area

The system of six regional aquifers and intervening confining units found in the Quaternary through Cretaceous age sedimentary wedge in the 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 aquifer is the uppermost aquifer in the system of aquifers and confining units that comprise the hydrogeologic framework of the Southern Coastal Plain. The surficial aquifer is unconfined and thus, the water table is able to fluctuate with changes in ground water storage. It is the first aquifer to receive recharge, storing water as it moves laterally to rivers, lakes and other discharge areas, and downward in small quantities to deeper, confined aquifers. The rate at which recharge occurs in any given area in the study region is dependant on several factors, including:

- differences in precipitation rates from one area to another.
- variations in soil types and their differing infiltration capacities.
- the position of the water table relative to land surface, which varies over time.
- the slope of the land surface.
- evapotranspiration rates, which vary across the region, and over time.

Heath (1997) reported recharge rates as low as 4 inches per year for the wet, flat uplands which occupy much of the northern and southeastern parts of Brunswick County. In these areas the soil zone is composed of sandy, silty, and clayey loams that range from three to four feet in thickness. The soil surface consists of low to nonpermeable organic matter. Similar rates would apply to much of Columbus, southwestern Bladen, and northwestern Pender Counties according to a North Carolina coastal plain soils map by Tant and others (1974). Heath (1997) indicates that the dry, flat, sloping upland areas that border the wet, flat uplands receive up to 12 inches of recharge per year. The sand hills region of the eastern portion of the study area has highly permeable soils, containing abundant, coarse to medium grained fluvial sands. Recharge rates of 12 inches per year or greater are applicable in this region. The barrier island system along the coastline of New Hanover, Brunswick, and Pender Counties receives recharge rates ranging from 17 to 20 inches per year, assuming similarity to the Cape Hatteras area from a study by Winner (1975).

Over the wide range of the study area, the surficial aquifer is primarily made up of Quaternary age sands with interbedded silts and clays, but can also be composed of older units depending on the stratigraphic position of the first confining bed and where the various, older units are present in the shallow subsurface. The Pleistocene age Waccamaw Formation is part of the surficial aquifer in parts of Brunswick and Columbus Counties as well as the Pliocene age Yorktown Formation in southern Robeson, southwestern Bladen, and easternmost Columbus Counties. The Waccamaw formation is made up of shelly sand with silt and clay, bluish gray to tan in color. The Yorktown formation consists of fine grained sands, shell material, and bluish gray silts and clays. In northern New Hanover County and part of eastern Brunswick County the Castle Hayne formation is part of the surficial aquifer where its confining unit is absent. Uppermost Peedee and Black Creek age sediments can sometimes be a part of the surficial aquifer in their subcrop areas where confining beds are positioned below the tops of the formations. The thickness of the aquifer varies between a minimum of 4 feet and a maximum of 200 feet at Carolina Beach in New Hanover County, where no significant shallow clay layers are present, as indicated by geophysical and lithologic logs.

The presence of saltwater in the surficial aquifer is limited to the Tidewater region of the report area, and is found on the coastal barrier islands that fringe Pender, New Hanover, and Brunswick Counties, the shoreline of sounds behind the barrier islands, and along the upstream limits of saltwater in streams and rivers.

Usage is limited primarily to domestic, as yield and drawdown limitations do not make it viable for municipal, industrial or large-scale agricultural use. The quality of the water is generally poor. The surficial aquifer is, however, used by the town of Salemburg in Sampson County where sands are thick and highly transmissive (Wooten, GMA 2004).

Castle Hayne Confining Unit

The Castle Hayne confining unit is made up of clay, sandy clay, and silt beds that are present in the lower part of the Plio-Pleistocene, the River Bend Formation in southern New Hanover County, and sometimes in the upper part of the Castle Hayne Formation. As illustrated in plate 30, this unit is present only in the eastern-most part of the study area, pinching out along a line trending through eastern Brunswick, northern New Hanover, eastern Pender, and southeastern Duplin Counties. The unit appears to be absent in a large section of northern New Hanover County. Permeable beds that make up the Castle Hayne aquifer extend in some areas, beyond of the limit of the confining unit, and are considered to be part of the surficial aquifer where this occurs.

The confining unit ranges in thickness between zero along its approximate zero thickness line, to 51 feet at Kure Beach in New Hanover County (plate 30).

Castle Hayne Aquifer

The presence of the Castle Hayne aquifer is limited to the eastern part of the study area in eastern Brunswick, New Hanover, and eastern Pender Counties. It is much thinner in the southeastern Coastal Plain than in the central Coastal Plain, achieving a maximum known thickness of 90 feet in eastern Pender and northeastern New Hanover Counties (plate 32). The top of the aquifer dips gently from northwest to southeast at a rate of about 12 feet per mile, and ranges in elevation from between 18 feet above sea level to 130 feet below sea level at Carolina Beach in New Hanover County (plate 31).

The aquifer consists primarily of light gray to white moldic limestones, and bryozoan rich limestones of the Eocene age Castle Hayne Formation, grading downward to calcareous, fine-grained sandstone in the deeper subsurface. It also contains the uppermost part of the Peedee Formation of Cretaceous age in central New Hanover County, the lower part of the River Bend Formation of Oligocene age in southern New Hanover County, and the upper part of the Beaufort Formation of Paleocene age in southeastern Brunswick County. Where these formations are included the aquifer may also contain gray to light brown, silty, fine grained quartz sand, sandy moldic limestone or fine-grained shelly sandstone.

The Castle Hayne limestone is highly prone to sinkhole formation in southeastern Brunswick County, and in Pender and Duplin Counties. The collapse of overlying younger deposits into depressions formed by sinkholes may allow for localized and direct circulation of ground water between the Castle Hayne aquifer and younger, surficial deposits.

The aquifer is recharged by water moving downward from the surficial aquifer at a rate that varies from place to place over the study region. Rates of recharge are dependent on the thickness and vertical hydraulic conductivity of the overlying confining unit, and how much higher the water table elevation is above the elevation of the Castle Hayne potentiometric surface in recharge areas. Analysis of several monitoring station hydrographs showing long term water level trends in both the surficial and Castle Hayne aquifers indicate similar patterns of water level variation (plates 14 and 20). It is apparent that the Castle Hayne aquifer in areas where monitoring data is available is affected by seasonal recharge variations in a similar way as the surficial aquifer, indicating fairly quick recharge from the surficial to the Castle Hayne. Along its western margins where the aquifer is present in the shallow subsurface. direct discharge may occur where stream and river channels incise into the aquifer. In the deeper subsurface upward leakage may occur into surface water bodies where the head is higher in the aquifer. Water level data over the extent of the study region is not sufficient to define the regional potentiometric surface of the aquifer.

Lautier (1998) determined the range of transmissivity of the Castle Hayne aquifer in New Hanover and eastern Brunswick Counties to be between 250 and 10,888 ft^2 per day, with a hydraulic conductivity range of 3.66 to 108.8 ft per day. Storativity varied between .00006 and .0097. This was based on aquifer test analysis of 23 wells and well nests. The U.S Geological Survey (Harden, Fine and Spruill, 2003) determined a transmissivity range of 1,000 to 5,000 ft^2 per day for the Castle Hayne in Brunswick County, based on analysis of 9 aquifer tests. Bain (1970) reported specific capacities in New Hanover County to be in the range of 4 to 50 gallons per minute per foot of drawdown.

The aquifer is used for water supply in many municipal well fields in New Hanover County, including the beach towns, the City of Wilmington, and the County system. There is also some limited industrial and agricultural usage. In Brunswick County, the Castle Hayne is pumped for water supply in the County well field, the City of Southport and at a limited number of other locations for domestic and agricultural purposes. There is some industrial usage of the aquifer in the Southport area. In Pender County, the coastal towns of Topsail Island and Surf City use the aquifer for water supply.

The presence of salt water in the Castle Hayne is limited to areas where pump-induced intrusion and some natural intrusion has occurred along the coastline. It is also likely that the aquifer contains salt water along the fringes of the tidal influenced zone of the Cape Fear River and various streams and creeks in the region.

Peedee Confining Unit

The Peedee confining unit consists of clay and silt beds with some interbedded sand in the upper part of the Cretaceous age Peedee Formation. Overlying beds of the same lithology in the lower part of the Quaternary are also part of the confining unit over portions of the study area, as well as the Paleocene Beaufort Formation in the southeastern parts of Brunswick and New Hanover Counties. Beds of Pliocene Yorktown age may be part of the confining unit in a small southwestern section of the area in Bladen, Robeson and Columbus Counties. The unit ranges in thickness between zero, where it pinches out through the central part of the study area (plate 34) to a maximum of 70 feet in eastern Pender County. Its average thickness is 20 feet. The unit is absent in some down dip wells in New Hanover and Brunswick County as shown on an isopach map of its thickness, allowing direct movement of ground water from overlying sediments.

Peedee Aquifer

The Peedee aquifer is present throughout the southeastern half of the study area, pinching out approximately along a line through southern Robeson, central Bladen, the southern tip of Sampson, and into central Duplin County. It dips to the southeast at a rate of 5 feet per mile, increasing to a rate of 24 feet per mile in New Hanover County (plate 35). The elevation of the top of the aquifer ranges from 38 feet above sea level in southern Robeson County to 219 feet below sea level at Kure Beach in New Hanover County. The top surface of the aquifer is rather hummocky in the central part of the study area, apparently due to an erosional cut and fill surface between Quaternary and Peedee age deposits. The aquifer is generally wedge shaped in profile, thickening toward the southeast to a known maximum of 404 feet in eastern Brunswick County (plate 36).

The aquifer is primarily composed of the Upper Cretaceous age Peedee Formation, the lithology of the which consists of gray or light brown, silty, fine to very fine grained quartz sand with trace quantities of glauconite, phosphorite, oyster shells, and pyrite. In southeastern Brunswick and north central New Hanover Counties, the Rocky Point Member makes up the uppermost part of the Peedee Formation, consisting of gray, sandy, moldic limestone, grading downward to a very calcareous sandstone. The updip limit of the Peedee aquifer extends in some areas, a few miles further to the northwest than the limit of the Peedee Formation as delineated on the North Carolina Geologic Map. The reason for this is that the aquifer contains some upper sands of the Black Creek Formation and probably some lower sands of Quaternary age that directly overly the Peedee Formation.

To the west of the limit of the Castle Hayne aquifer, the Peedee aquifer is directly overlain by the surfical aquifer, and recharge occurs from water moving downward from the surficial aquifer. Some of the ground water monitoring station hydrographs in this area indicate semi-confined conditions, as the water levels in the surficial aquifer are only a few feet higher than the Peedee in recharge areas, and a few feet lower in discharge areas, with similar seasonal effect patterns apparent in the Peedee hydrographs. Examples of this are seen at Rowland, Marietta, Bear Pen, Bolivia, Kelly and other monitoring stations (cross sections I-I', K-K', H-H', and L-L', plates 11, 13, 10, and 14). In the few locations where water level data is available from deeper sands in the Peedee aquifer it is clear that there is a basis for designation of more than one aquifer within the Peedee. Well to well correlation along cross-section lines indicates the widespread continuity of thick clay beds, which probably cause significant hydraulic head differences between interconnected bodies of sand. This is clearly the case at Bear Pen monitoring station (plate 13) where there is a significant head difference between upper and lower Peedee sands. Unfortunately, there is not enough water level data from deeper sands to map the Peedee system in its true complexity.

A regional potentiometric surface map of the Peedee aquifer is presented in plate 50. Comparison of a map of the elevation of the top of the aquifer with the potentiometric surface map indicates a close relationship of highs and lows between the two surfaces. In the area of the Green Swamp in north central Brunswick and eastern Columbus County, water levels are very close to land surface, and are the highest in the eastern section of the study area. This corresponds to higher topographic elevations in an area of wet, flat uplands. Although wet, flat uplands generally correspond to areas of very low recharge (approximately 4 inches per year) as defined by Heath (1997), topographic controls seem to dominate water levels in the Peedee. The potentiometric surface is also affected by cones of depression that have formed in eastern Brunswick County due to the County well field, and pumping from the Peedee in northern Columbus County.

Harden, Fine and Spruill (2003) estimated transmissivity values for the Peedee aquifer in Brunswick County at 21 sites. They found the range to be between 3,000 and 6,000 ft^2 per day, with the highest measurements found in the east central part of the county. Lautier (1998) determined a transmissivity range of 128 to 18,620 ft^2 per day, hydraulic conductivity range of 1 to 243 feet per day, and storativity range of 0.00002 to 0.1 for New Hanover and eastern Brunswick Counties based on measurements at 85 sites. An analysis of aquifer tests for this study indicates a transmissivity range of 42 to 337 ft^2 per day, hydraulic conductivity range of .86 to .975 feet per day, and storativity of 0 .00016 to 0.000463 for the Peedee aquifer from three sites (table 2).

The lower part of the Peedee aquifer contains salt water in the eastern part of the study area as defined by isochlors representing the approximate intersection of the 250 ppm chloride transition zone with the top and base of the aquifer (plate 35). The transition zone is broad and fairly flat lying, underlying virtually all of Brunswick and New Hanover Counties, southeastern-most Columbus, and southeastern Pender Counties. The interface was defined by chloride analysis of water samples and by use of Time Domain Electromagnetic soundings. TDEM cross sectional profiles a-a', b-b' and c-c' (plates 25, 26 and 27) indicate resistivity value ranges of 18 to 288 ohm-meters in the

Table 2. Aquifer Test Data from the Southern Coastal Plain

County	Well/Monitoring Station Name	Screened Interval (in ft.)	Aquifer	Analysis Method	Type of Well	Transmissivity in ft2/day	S	K (ft/day)	Specific Capacity gpm/ft.
Robeson	LITTLEFIELD Y42f4	310-315	Black Creek	Theis	Observation	560	0.000017	14	2.94
Robeson	LITTLEFIELD Y42f6	145-165	Black Creek	Theis	Observation	2941	0.00092	147	25
Bladen	WHITE LAKE PRISON Y38b7	90-100	Black Creek	Theis	Observation	289	0.000104	1.7	4.64
Robeson	REX RENNERT SCHOOL V45u3	65-90	Black Creek	Theis	Observation	1770	0.000122	11.56	19.5
Columbus	LAKE WACCAMAW CC38b10	112-122	Peedee	Theis	Observation	119	0.000463	0.975	3.5
Brunswick	DWR SUNSET HARBOR STATION	84-102	Peedee	Theis	Observation	337	0.00016	0.86	5
Brunswick	DWR CALABASH STATION	496-506	Peedee	Hantush-Jacobs	Pumping	42			0.9
Sampson	DWR MINGO STATION	50-60	Black Creek	Theis	Pumping	294			0.9

fresh water area of the Peedee aquifer and 0 to 15 ohm-meters in the salt water portions of the aquifer. The position of the transition zone is fairly clear due to large differences in resistivity on opposite sides. Resistivities are much higher in the fresh water bearing zone of the Peedee aquifer than in deeper aquifers in this area due to low clay content in the Peedee. The fresh water portions of deeper aquifers have much lower average resistivity due to higher clay content, as recognized on TDEM profiles.

The shallow presence of salt water in this area is probably attributable to low rates of recharge, and the presence of fairly large areas where ground water discharge predominates. Flow occurs down gradient to rivers, floodplains and marshes from the surficial as well as from the Peedee aquifer, and to a lesser extent from deeper aquifers. These conditions allow salt water to remain present in the shallow subsurface because very little water is able to move downward over geologic time to push the salt water interface eastward. Another factor to consider is the position of the shoreline during Pleistocene sea-level fluctuations in the North Carolina Coastal Plain. Meisler (1989) documented a number of areas of shallow salt water occurrence along the coastal plain of the eastern United States and attributed them to the above mentioned factors.

The Peedee aquifer is the principal aquifer used in Brunswick County for municipal water supply via a central county well field. It is also used by New Hanover County through a system of well fields, in conjunction with the Castle Hayne aquifer. In Columbus County the Peedee is used by a number of towns for water supply, including Fair Bluff, Chadbourne, Whiteville, and Bolton. In Bladen County it is used by the towns of Bladenboro and Clarkton.

Black Creek Confining Unit

The Black Creek confining unit is uniformly present over the study area except where it has been incised by streams and rivers in the eastern-most counties. It achieves a maximum thickness of 168 feet in eastern Brunswick County. Over the extent of the study region it maintains an average thickness of 34 feet based on 107 well penetrations.

The confining unit is made up of clay, silt and thin sand interbeds that are present in the upper part of the Black Creek Formation and the lower part of the Peedee Formation. Northwest of the updip limit of the Peedee aquifer, clay and silt beds present in the lower part of the Quaternary make up part of the confining unit.

Black Creek Aquifer

The Black Creek aquifer is present over the entirety of the study region, and is made up of alternating beds of sand and clay of the Upper Cretaceous Black Creek Formation. The sands are generally gray to olive gray in color, fine to medium grained, poorly sorted, and contain variable amounts of glauconite, phosphorite, shell fragments, lignite, and traces of mica, pyrite and marcasite. Clays are generally gray to black in color, and lignitic. Individual sand and clay beds generally range between 10 and 20 feet in thickness across the region. The aquifer includes the Middendorf Formation in Scotland, Hoke, and western Cumberland Counties where it interfingers into the Black Creek Formation and appears to be connected hydraulically. Due to a lack of water level data, it is somewhat uncertain as to whether the aquifer is confined in these counties, or part of the surficial aquifer. Correlation of geophysical logs along cross section O-O' (plate 16) indicates the persistance of clay beds in the upper part of the Middendorf Formation or lower part of the Quaternary. For this reason, the aquifer appears to be confined in the interfluvial areas and under water table conditions in the fluvial valleys where confining beds have been eroded.

The top of the aquifer dips to the southeast at a rate of 8 to 10 feet per mile as exhibited by elevation contours shown in plate 39. It ranges in elevation between 318 feet above sea level in northern Hoke County, to 641 feet below sea level at Kure Beach in southern New Hanover County. The aquifer varies in thickness between 34 feet in central Cumberland County to 312 feet in southern Robeson County with an overall average of 164 feet. The aquifer is unusually thick in central Robeson County due to an apparent embayment in the basement surface as exhibited in cross sections B-B' and C-C' (plates 3 and 4) and an isopach map (plate 40). The thickness of the aquifer changes in irregular patterns due to facies variations between sand and clay that affect where the top and base of the unit is determined from geophysical log correlation.

The Black Creek aquifer is recharged by water moving downward from the Peedee aquifer in the portion of the study area where the Peedee is present. Where the Black Creek is well confined, it is recharged at rates of less than one inch per year (or less than 47,610 gallons per day per square mile). To the northwest of the area where the Peedee aquifer pinches out, the thickness of sediments that overly the Black Creek is reduced, the confining unit is generally thinner, and recharge rates are assumed to be much higher. This depends of course, on the other factors that control recharge to confined aquifers, such as vertical hydraulic conductivity, and hydraulic gradients. In Scotland, Hoke, Robeson and Cumberland Counties, the Black Creek aquifer occurs at a shallow enough level in the subsurface to be incised by rivers and streams, allowing direct discharge of ground water. This is indicated by hydrogeologic cross sections A-A' and O-O' (plates 2 and 16). This relationship is also present along the Cape Fear river in Bladen County as illustrated on cross section H-H' (plate 10).

The aquifer contains salt water in the southeastern part of the study area as defined by isochlors representing the approximate intersection of the 250 ppm chloride transition zone with the top and base of the aquifer (plate 39). Except for its northwestern fringe, virtually all of Brunswick County lies within the salt water zone of the aquifer. All of New Hanover County and the southern half of Pender County lie to the west of the transition zone, and the Black Creek contains only salt water (plate 39). The transition zone was defined by chloride analysis of water samples and by use of

Time Domain Electromagnetic soundings. TDEM cross sectional profiles a-a', b-b' and c-c' (plates 25, 26 and 27) indicate resistivity value ranges of 3.5 to 18.5 ohm-meters in the fresh water area of the Black Creek aquifer and 0 to 6 ohm-meters in the salt water portions of the aquifer (lower resistivity values occur within the freshwater zone due to the presence of clay beds). The position of the transition zone is clear on profile a-a' due to large differences in resistivity on opposite sides.

A potentiometric surface map prepared from water level data collected in July and August of 2005 indicates two areas in Bladen County where prominent cones of depression have developed. In the northwestern part of Bladen County, withdrawals in the area of the Town of Tarheel by Smithfield Foods Inc. have lowered the Black Creek potentiometric surface to a minimum of 36 feet above sea level in an area where the top of the aquifer is 81 feet above sea level. Although water levels within the well field are not reflective of true static conditions, it appears that localized dewatering is taking place at this location. Another cone of depression is evident at Elizabethtown in the central part of Bladen County due to pumping from the city well field and from the nearby town of White Lake. Black Creek water levels appear to be rebounding in this area due to closure of Alamac Knit Fabrics Inc., which was a heavy ground water user. In the eastern part of the study area where the Black Creek is close to the surface, ground water flows in patterns similar to the surficial aquifer, from areas of recharge in the inter-stream areas to discharge areas such as streams, rivers and wetland areas. This natural pattern of flow is disturbed in areas affected by cones of depression. Where the aquifer is deeper and well confined, ground water flow paths are toward the coast in a southeastward direction with some upward flow to the Cape Fear River and other major surface water bodies.

The aquifer is most heavily used in Robeson County, where it is the chief water supply source for the county water system, and the cities of Lumberton, Pembroke, Red Springs, etc., as well as for several industries. Despite the high volume of withdrawals in Robeson County, water levels are not being severely impacted. In Bladen County, the aquifer is sensitive to relatively small volumes of pumping, as evidenced by the aforementioned cones of depression that developed at Tarheel and Elizabethtown. Aquifer tests analyzed for this study are shown in table 2. According to this data, the Black Creek aquifer has a transmissivity range of 289 to 2,941 ft^2 per day. Data from an unpublished GMA/Wooten Company report (2003) indicates an overall range of 500 to 7,209 ft2 per day for Black Creek in the Southern Coastal Plain. This range was calculated from 20 aquifer tests. A test at White Lake Prison monitoring station in Bladen County indicated a very low transmissivity value of 289 ft^2 per day for the Black Creek, in the area of the cone of depression that formed in the Elizabethtown-White Lake area. High transmissivity values in Robeson County (average of 3,850 ft^2 per day from 10 tests), versus low values in Bladen (average of 1,438 ft^2 per day from 4 tests) help to explain why the aquifer drawdown impacts are much less severe in Robeson, despite the high volume of pumping from various locations throughout the County. High transmissivity values in Robeson County are in part, explainable by the high thickness of the aquifer relative to other parts of the study region as indicated by an isopach map (plate 40).

Upper Cape Fear Confining Unit

The Upper Cape Fear confining unit consists of clay, silt, and thin interbedded sands that are part of the Upper Cretaceous age Cape Fear Formation and lower part of the Black Creek Formation. The unit thickens and thins in a non-uniform pattern between 20 and 145 feet across the study area, with an average of 59 feet. Areas of maximum thickness are found in southern Robeson and northern Bladen Counties (plate 42).

Upper Cape Fear Aquifer

The Upper Cape Fear aquifer is composed of alternating beds of sand, clay, and silt which are part of the Upper Cretaceous Cape Fear Formation. The sands are made up of quartz and feldspar, and are fine to coarse grained, subrounded to subangular, poorly sorted with minor to abundant iron oxide staining. Also present are accessory iron oxide minerals such as pyrite, marcasite, and siderite. Fine gravel is present in some well samples. Clay and silt beds are generally red, pink, to yellowish gray in color.

The top of the aquifer ranges in elevation between 38 feet above sea level to 905 feet below sea level at Kure Beach in southern New Hanover County. The top of the aquifer dips to the southeast at a rate that varies from 5 feet per mile to 29 feet per mile in the eastern part of the study area. The unit is wedge shaped in cross sectional profile, thickening generally toward the southeast from a minimum of 44 feet in Robeson County to a maximum of 208 feet in northern New Hanover County. A prominent northwest-southeast trending basement arch is present in the northern part of the study area, the axis of which roughly follows the Cumberland-Sampson and Bladen-Sampson County lines (plate 43). The influence of the basement arch is evident on an elevation map of the top of the Upper Cape Fear aquifer. Elevation contour maps of the underlying Lower Cape Fear aquifer and confining unit do not express the influence of the arch due to a lack of well penetrations of sufficient depth in this area.

A potentiometric surface map prepared from water level data collected in July and August of 2005 reveals a very large cone of depression that covers western Bladen, eastern Robeson, southern Cumberland, and western Columbus Counties. Combined pumping from the Black Creek and Upper Cape Fear aquifers (1,974 gallons per day) at Smithfield Foods Inc. near Tarheel in Bladen County, and from the Elizabethtown-White Lake area (903,000 gpd) has produced large cones of depression in both aquifers. Upper Cape Fear water levels at the center of the Smithfield Foods cone of depression have been drawn down to approximately 114 feet below sea level. Due to reductions in the volume of water withdrawn from the Upper Cape Fear aquifer, water levels have been recovering at Smithfield Foods since early 2001 (SCP Cap Use Inv., 2004). Because of a lack of water level data specific to the Upper Cape Fear aquifer, the effects of pumping in the Elizabethtown-White Lake area are not apparent on the map. Reductions in pumping rates have occurred there because of the closure of Alamac Knit Fabrics, which pumped large volumes of water from the Upper Cape Fear and Black Creek aquifers combined. Water levels in the Upper Cape Fear aquifer are being affected in Columbus and southern Robeson Counties by pumping from South Carolina. This is apparent on hydrographs from the Boardman, Marietta, Nakina and Clarendon stations, which indicate slow, steady declines in an area of the study region where little to no pumping from the Upper Cape Fear occurs. Under natural conditions, ground water flow lines in this aquifer would point generally southeastward toward the coast, or toward other areas of major natural discharge. Instead, due to pumping and formation of large cones of depression, natural gradients have been altered and much of the flow is toward pumping centers.

The Upper Cape Fear aquifer is particularly sensitive to pumping because it is well confined by thick overlying clay beds which highly limit the amount of vertical recharge (plate 42). The aquifer is also relatively thin in the Tarheel-Elizabethtown area, which limits transmissivity, and large cones of depression are able to form due to relatively low volume pumping (plates 44 and 52). Careful well field design, including adequate spacing between wells is necessary to prevent excessive drawdown in this aquifer.

In Sampson County at the Ivanhoe and Six Runs monitoring stations the aquifer is under artesian flowing pressure. At these locations water level elevations are a few feet above land surface, and are under minimal influence from pumping centers. At Calabash monitoring station in southwestern Brunswick County, the Upper Cape Fear water level is about 13 feet above land surface, again, indicating flowing artesian pressure. Areas where this occurs are where ground water discharge is taking place. Hydraulic heads are at a higher elevation in deeper aquifers than in shallow, thus an upward component of flow is occuring at a very slow rate through the subsurface under the prevailing hydraulic gradient.

The Upper Cape Fear aquifer is used in Sampson County by the towns of Clinton, Garland, Roseboro, and Turkey and also by the town of Parkton in Robeson County. In Bladen County, as mentioned earlier, it is used for municipal supply by Elizabethtown and White Lake, and by Smithfield Foods, Inc. for industrial purposes. Table 3 from GMA-Wooten Co. (2004) lists the volumes of ground water used for industrial, agricultural and domestic purposes in Bladen, Columbus, Robeson and Sampson Counties. Due to limitations of the survey it is unknown how much ground water is withdrawn from individual aquifers.

The aquifer contains salt water in Brunswick, New Hanover, southern Columbus, southeastern Duplin, and most of Pender Counties as indicated by the location of the fresh water-salt water transition zone delineated in this study (plate 43). The transition zone was defined by chloride analysis of water samples and by use of Time Domain

Electromagnetic soundings. TDEM cross sectional a-a', b-b' and c-c' (plates 25, 26 and 27) indicate resistivity value ranges of 5 to 10.5 ohm-meters in the fresh water area of the Upper Cape Fear aquifer and 0 to 4 ohm-meters in the salt water portions of the aquifer. Low average resistivity values in the fresh area of the aquifer are apparently due to a high percentage of clay, which suppresses values of electrical resistivity. For this reason, the position of the transition zone is rather subtle based on interpretation of TDEM response.

Lower Cape Fear Confining Unit

The Lower Cape Fear confining unit is made up of red, pink to yellow-brown colored silts, clays, and thin sand interbeds of the Upper Cretaceous Cape Fear Formation. The Lower Cape Fear aquifer is separated from the Upper Cape Fear aquifer on the basis of significant hydraulic head differences observed at several ground water monitoring stations. Hydrographs from screens positioned above and below the confining unit are shown on hydrogeologic cross sections F'-F", I-I' (plates 8 and 11). The confining unit pinches out approximately along a line though southeastern Robeson, western Bladen, central Sampson, and northern Duplin Counties. The unit is present only to the east of the dashed line. Thickness of the confining unit varies from zero where its updip limit occurs, to a maximum of 146 feet at Supply monitoring station in Brunswick County. Its average thickness across the study region is 55 feet, based on 41 well penetrations.

Lower Cape Fear Aquifer

The Lower Cape Fear Aquifer is lithologically similar to the Upper Cape Fear with the exception that it contains in its lower part, reworked materials from the underlying basement. Sediments that comprise the aquifer are part of the Upper Cretaceous Cape Fear Formation.

According to an elevation contour map, the top of the aquifer dips to the southeast at a rate that varies from 9 feet per mile to 31 feet per mile in the eastern-most section of the study area (plate 47). The approximate updip limit of the aquifer corresponds to the same updip limit line of the confining unit. The average thickness is 151 feet, with a range between zero where it pinches out, to 430 feet near the town of Southport in Brunswick County.

The Lower Cape Fear aquifer is the deepest aquifer in the study region and is thus recharged at the lowest rate. It pinches out against the basement surface as exhibited in cross sections F-F', H-H' I-I', P-P', and U-U' (plates 7, 10, 11, 17 and 22) and thus, does not appear anywhere in the shallow subsurface where it can receive higher recharge rates.

The aquifer is used very little in the study region, due mostly to the fact that it contains salt water over the majority of the area. The position of the fresh water-salt water transition zone occurs in southern Bladen, the southern tip of Sampson, and southern-most Duplin Counties. Consequently, the area of fresh water occurrence between the transition zone and the up dip limit if the aquifer is rather limited, although the aquifer might provide a viable source of water for the population within that area. It is used in conjunction with other aquifers by the towns of Clinton in Sampson County, and Elizabethtown in Bladen County. The only aquifer test information available is reported in Peek and Heath (1973). A 24 hour test was performed at the Hercules Inc. site, north of Wilmington, in New Hanover County in 1968, which yielded a transmissivity value of 9,000 gpd/ft or 1,206 ft^2/day.

Water level data is available from six monitoring stations in the Southern Coastal Plain Counties. Existing data indicates that the aquifer is under anomalous artesian flowing pressure in the southeastern part of the study area, as presented in the following table.

County	Monitoring Station	Height of Lower CF Aquifer water level above land surface (August, 2005)	elev. rel. to MSL
Brunswick	Bear Pen	30.77	+91.11
Brunswick	Sunset Harbor	63.7	+89.1
Brunswick	Calabash	53.29	+101.27
Columbus	Waccamaw	14.5	+77.93
Bladen	Kelly	40.62	+70.94
Sampson	Six Runs	6.63	+68.12

The resulting potentiometric surface map (plate 53) drawn from water levels at these well sites indicates a rather anomalous high centered at Calabash monitoring station. Ground water flow lines emanating from the high at Calabash are to the northwest, north and northeast. Under non-pump influenced conditions, the general ground water flow direction in a deep confined aquifer such as the Lower Cape Fear would be southeastward, and generally perpendicular to aquifer elevation contours. High heads in the Lower Cape Fear aquifer can not be explained by high recharge rates or proximity to recharge area because the aquifer pinches out against the basement surface at deep depths as indicated by cross sections I-I', F-F', H-H', P-P', and U-U' (plates 11, 7, 10, 17, and 22). Under these conditions recharge rates are certainly very low.

The anomalous nature of hydraulic heads in this area were recognized and discussed by Peek and Heath (1973) and Peek and Register (1975). Peek and Register (1975) attributed the anomalous pressures to a rise in elevation of the land surface in southeastern North Carolina related to seismic activity, and the resulting compression of sediments. Other possible causes such as high recharge rates, osmotic pressure, high geothermal gradient, and natural gas were ruled out. A reevaluation of bench mark data used to arrive at the conclusion that land surface had been rising has proven that, if anything, land surface has slowly been subsiding. This has been proven to be in case in the Central North Carolina Coastal Plain, where subsidence has occurred as a result of heavy pumping from Cretaceous aquifers (North Carolina Division of Water Resources). There is no question that high temperatures are not responsible for the anomalous head conditions in the Lower Cape Fear aquifer as the water temperatures at the well sites range in the low to mid 70s in degrees Fahrenheit.

Of the possible causes of anomalous pressure introduced by Peek and Register (1975), natural gas accumulation seemed the most likely. The idea was tested using a GEM–500 Landfill Gas Monitor to conduct well site analysis of methane (CH_4) concentrations. The GEM-500 measures CH_4 as a percent by volume. Ground water monitoring wells in the test area are equipped with spigots by which a pressure gauge may be attached to measure pressure in pounds per square inch. Values measured are then converted to total hydraulic head using a multiplier of 2.31 feet/psi. At each well tested a short hose was attached to the spigot and then bent upward to direct the water flow into an inverted plastic container with an opening just large enough to accept the spout of the hose. After the water was allowed to flow into the container for 10 minutes the GEM-500 probe was inserted into the top of the container for 2 to 3 minutes in order to measure the percentage of CH_4. Subsequently, at each site, another small plastic container was filled with water, then agitated, and allowed to sit in sunlight for a period of 20-25 minutes. The cap was then removed and the GEM-500 probe was quickly placed inside to measure CH_4 percentage. The results of each test are presented in table 3. As the table indicates, methane gas was detected by the GEM-500 at several monitoring sites. Where detected, CH_4 levels range between .1 percent at Kelly Station to 5.8 percent at Bear Pen Station. It is interesting to note that a 3.5 percent reading was taken from the Upper Cape Fear aquifer monitoring well at Calabash, which currently shows a head of 13.22 feet above land surface. The 5.8 percent maximum reading was taken from the Lower Cape Fear aquifer well at Bear Pen Station, which displays a head of 30.77 feet above land surface.

Monitoring Station	Aquifer	topographic quad/well no.	Screened Interval in feet below ls	test 1 %CH4	test 2 %CH4
Calabash	Lower Cape Fear	hh39j2	1042-1052	0.5	2.1
Calabash	Upper Cape Fear	hh39j6	810-820	3.5	not measured
Sunset Harbor	Lower Cape Fear	gg34s2	1294-1304	0.1	0.6
Bear Pen	Lower Cape Fear	ee36k2	1038-1048	5.8	0.7
Kelly	Lower Cape Fear	aa35n2	610-620	0	0.1
Lake Waccamaw	Lower Cape Fear	cc38b7	668-678	0	0
Six Runs	Lower Cape Fear	y35t4	370-380	0	0
Six Runs	Black Creek	y35t5	63-83	0	0
Six Runs	Upper Cape Fear	y35t6	240-266	0	0
Six Runs	Black Creek	y35t7	196-206	0	0
Six Runs	Upper Cape Fear	y35t8	258-268	0	0
Ivanhoe	Black Creek	y34p4	328-338	0	0

Table 3: Methane Concentration by volume at selected well locations in the North Carolina Southern Coastal Plain

The following observations can be made about the methane findings:

1. It is unknown at this time whether or not these levels reflect the actual concentrations in the aquifers. An in situ method such as those available through geophysical logging techniques and use of the Archie equation would allow for direct measurement. Follow up work with laboratory measurements of ground water samples and other analysis methods will be necessary.

2. Detectable levels of CH_4 were found in the area of highest head located on the Lower and Upper Cape Fear potentiometric surface maps. No methane was detected at Six Forks, Lake Waccamaw and Ivanhoe Stations, which are located several miles to the north. By the process of

elimination, one could ascertain that pressures related to methane gas accumulation are wholly or partially the cause of the highest head values at Calabash, Sunset Harbor and Bear Pen. Localized methane accumulation could have occurred due to a permeability barrier related to diagenetic factors or facies variations from sand to clay.

3. There are two types of methane, biogenic and thermogenic. Biogenic methane is formed by the breakdown of carbon dioxide by bacteria in the presence of hydrogen to form CH_4. Biogenic methane is a common constituent of ground waters around the world (Gorody, Baldwin and Scott, 2005). Thermogenic methane is formed by the thermal breakdown of organic material from marine source beds. It is unknown at this time whether the methane was formed in the deeper subsurface by thermogenic means and migrated upgradient to its present position, or if it was generated through a biogenic process.

Further investigation of these findings will be conducted by the Division of Water Resources in order to gain additional information about methane concentrations and their influence on hydraulic head in this area.

Basement

The Quaternary through Cretaceous age sediments of the Southern Coastal Plain are underlain by a basement complex of pre-Mesozoic rocks which vary in type between volcanic, plutonic, and metamorphic. Also included are slightly metamorphosed sedimentary rocks such as mudstone, siltstone, and greywacke (Lawrence and Hoffman, 1993).

According to a structural map of its elevation (plate 49), the basement surface dips to the southeast at a rate that varies from 10 feet per mile in the western portion of the area, to 35 feet per mile near the coast. Available data indicates that its elevation ranges between 200 feet above sea level in northwestern Hoke and Scotland Counties, to 1,525 feet below sea level near Southport in New Hanover County.

In 2004, the Division of Water Resources installed two monitoring stations in southeastern Cumberland County, the DWR Bushy Lake Station and Cedar Creek Firetower Station. Pilot holes at both sites encountered basement material (slightly metamorphosed mudstone) at much shallower depths than was expected from correlation of regional borehole data. An updated contour map (plate 49) reveals the existence of an arch on the basement surface in Cumberland and Bladen Counties, the axis of which approximately follows the Cape Fear River. It is possible that this is a northward, more prominent extension of the Cape Fear Arch, which is visible on the southwestern part of the map by a slight bowing of contours along the Cape Fear River underneath New Hanover, Brunswick, Pender, Columbus, and Sampson Counties.

The morphology of the basement surface has a strong affect in some areas on the thickness patterns of overlying sediments. Examples of this are illustrated on cross section b-b' (plate 3) which clearly shows thinning of the sediment column over a basement high. Thickening of the sedimentary section occurs in a basement low that is visible in southern Robeson County on a structural map (plate 49) and cross section C-C' (plate 4).

Summary and Conclusions

Population growth in the Southern 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 Southern 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 six regionally significant aquifers and the intervening confining units that separate them. Included are the surficial, Castle Hayne, 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 ground water supplies exist in the Southern Coastal Plain to provide for present and future needs, in balance with surface water use. However, it is also clear that careful consideration must be taken in the placement and design of new well fields in order to avoid excessive drawdown situations such as what has occurred in Bladen County in the Black Creek and Upper Cape Fear

Aquifers. Confined aquifers in areas such as Bladen County are particularly sensitive to relatively small pumping volumes due to low aquifer transmissivity. Excessive drawdown can lead to dewatering of a confined aquifer, which will result in compaction, loss of pore space, and permanent loss of yield ability. Moreover, excessive drawdown can lead to salt water encroachment if salt water sources are within reach of a cone of depression, or if a source exists below the zone of pumping. Careful monitoring of aquifers in the Southern Coastal Plain via the Division of Water Resources monitoring network is necessary in order to track water level decline rates, the growth of cones of depression, and changes in chloride concentration in areas affected by pumping. Expansion of this network is badly needed in order to gain adequate coverage of areas experiencing water level declines.

Additional ground water monitoring stations are needed near the cities of Elizabethtown, White Lake and Tarheel in Bladen County to monitor water level declines in the Black Creek and Upper Cape Fear aquifers. Additional monitoring stations are needed in the vicinity of Lumberton in Robeson County to monitor declines in the Black Creek aquifer. Wells are needed in Scotland and Hoke Counties in order to better understand the hydrogeologic framework and monitor Black Creek and Upper Cape Fear aquifer water levels. The Turkey Station in Sampson County needs to be replaced because of well construction problems along with the Magnolia and Red Banks stations in Robeson County. A big gap in the Division of Water Resources monitoring network exists in Pender County, where there is only one station at Burgaw. Additional stations are needed there in order to gain a better understanding of ground water conditions. Monitoring stations are badly needed in New Hanover County on order to monitor stresses on the Peedee and Castle Hayne aquifers, particularly in the northern half where the majority of the population lives and where ground water withdrawals are heaviest.

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