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

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North Carolina Department of Environment and Natural Resources
Division of Water Resources
September 2012

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Executive Summary

This report is the latest 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, Southern, and East Central Coastal Plain (Lautier, 1998, 2001, 2006, 2009).

The study area is situated in the Northwest Coastal Plain between the Fall Line and the Chowan River, including the following Counties: Halifax, Northampton, Hertford, Bertie, Martin, and the eastern part of Edgecombe (figure i).

Recent information collected in this area from water supply wells, a U.S. Geological Survey core hole in Bertie County, and several new NC-DWR ground water monitoring station sites has provided the basis for a new interpretation of the hydrogeologic framework. In addition, it is important to understand the effects of stresses incurred on the aquifer system due to pumping from industrial, municipal and agricultural well fields located in the study region. Of particular interest is the recent recovery of water levels observed due to reductions in pumping from the deeper Cretaceous age aquifers in Southeast Virginia in the vicinity of Franklin. This was due to the closure in June, 2008 of the International Paper Company facility, which withdrew up to 35 million gallons per day of ground water during 50 or more years of operation.

The area of study is situated in the northern part of the Inner Coastal Plain as defined by Stuckey (1965). Here the topography is flat to gently rolling except where streams have eroded and dissected the landscape. The land surface slopes gently toward the southeast. Elevations vary from 150 feet near the fall line in northern Northampton County, to just above sea level adjacent to the Albemarle Sound and along the southernmost extent of the Chowan River. The major river basins in the eastern part of the region contain large floodplains and swamps which are widespread in Martin and Bertie Counties. The major Rivers, the Roanoke and Chowan, dissect the land surface on their courses to the Albemarle Sound.

The most prominent physiographic features of this region, and over much of the North Carolina Coastal Plain for that matter, are the Pleistocene terrace deposits. They form irregular belts extending northeast to southwest across the Coastal Plain (Mundorff, 1946). The terraces were formed during still stands of sea level at various times during the Pleistocene Epoch between ten thousand and 2 million years ago. The highest terraces are believed to be the oldest, and the lower are successively younger. Each terrace is generally separated from the next higher one by a pronounced scarp, which marks the shoreline of the sea that formed it (Mundorff, 1946).

Underlying the Holocene and Pleistocene sediments of the study area is a wedge of Tertiary and Cretaceous Age sediments and sedimentary rock which range in thickness from zero where they pinch out along the Fall Line to approximately 1,500 feet

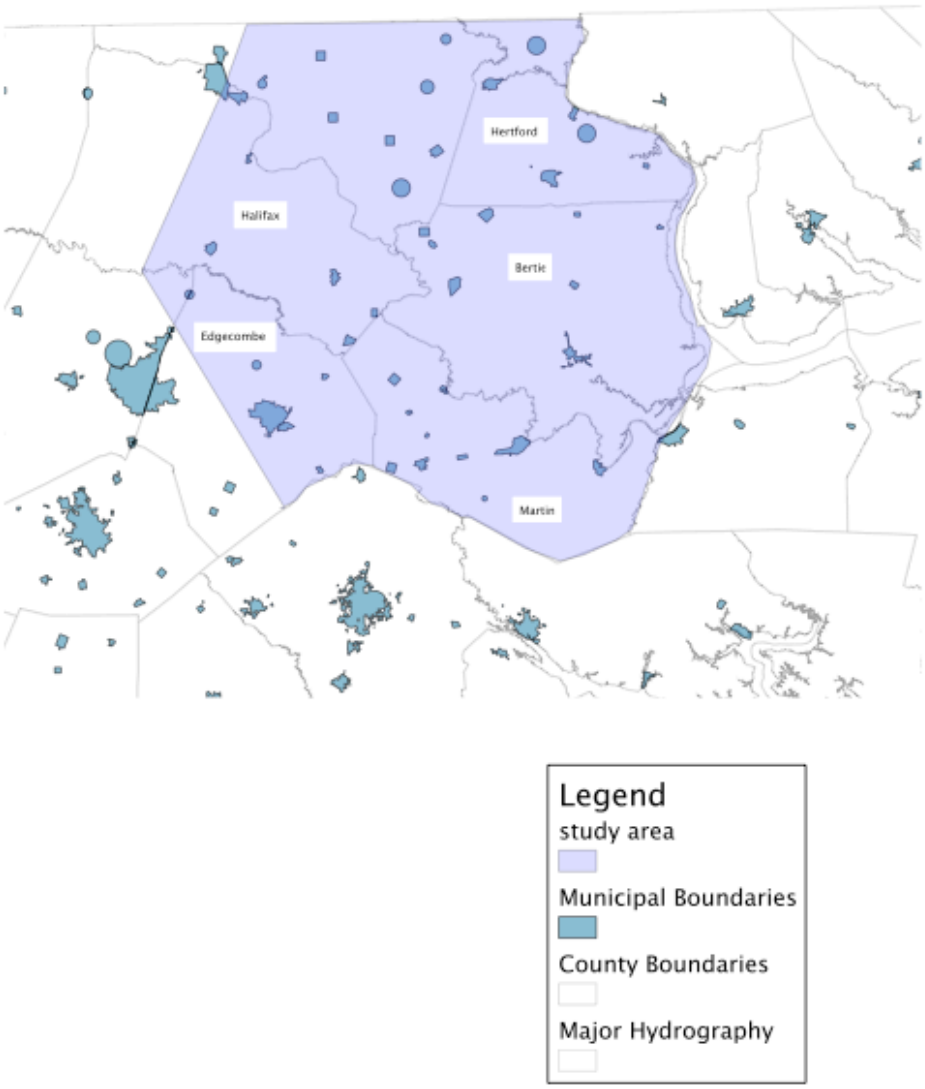

Figure i
Area of Study in the North Carolina Northwestern Coastal Plain

underneath the Chowan River. The sediment wedge is comprised of layers and lenses of sand, clay, silt, limestone, gravel, shell material, and combinations thereof. Triassic Age sedimentary rock was encountered in a U.S. Geological Survey core hole near the Town of Windsor in Bertie County at a depth of 1,026 feet below land surface. Triassic strata are composed of reddish brown colored sandstone, conglomerate, silt, and clay (Weems and others, 2007).

The sedimentary column of the Northwestern 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 Northwestern 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 nine regionally significant aquifers and the intervening confining units that separate them. They are mentioned from oldest to youngest as follows:

The Lower Cretaceous aquifer, which is comprised along with its confining unit, of sediments of Lower Cretaceous Age. The Lower Cretaceous Aquifer is underlain by sediments of Triassic age. Triassic age sediments are probably localized, and limited in presence to fault bounded basins in the basement rock. Where Triassic Age sediments are missing, as evidenced by a few basement penetrations in the area, the basement surface directly underlies the Lower Cretaceous Aquifer.

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 and confining unit, which correspond to the upper part of the Cape Fear Formation .

The Black Creek aquifer, which corresponds primarily to the Black Creek Formation. The confining unit is made up of clay or silt beds of variable age that overly the Black Creek Formation.

The Peedee aquifer, which is made up of the Peedee Formation. This aquifer is present only in Martin County and the southern fringe of Bertie County. The confining unit is generally present in the Beaufort Formation or upper part of the Peedee Formation.

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

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

Hydrogeologic Framework and Ground Water Conditions in the North Carolina Northwestern Coastal Plain, July, 2012.
North Carolina Dept. of Environment and Natural Resources
Division of Water Resources

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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. 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. It also includes a lower sandy section of the overlying Pungo River Formation and an upper sandy section of the underlying Beaufort Formation. The confining unit occurs in the overlying Pungo River Formation. Where the Pungo River Formation is absent the confining unit is present within the Yorktown Formation.

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.

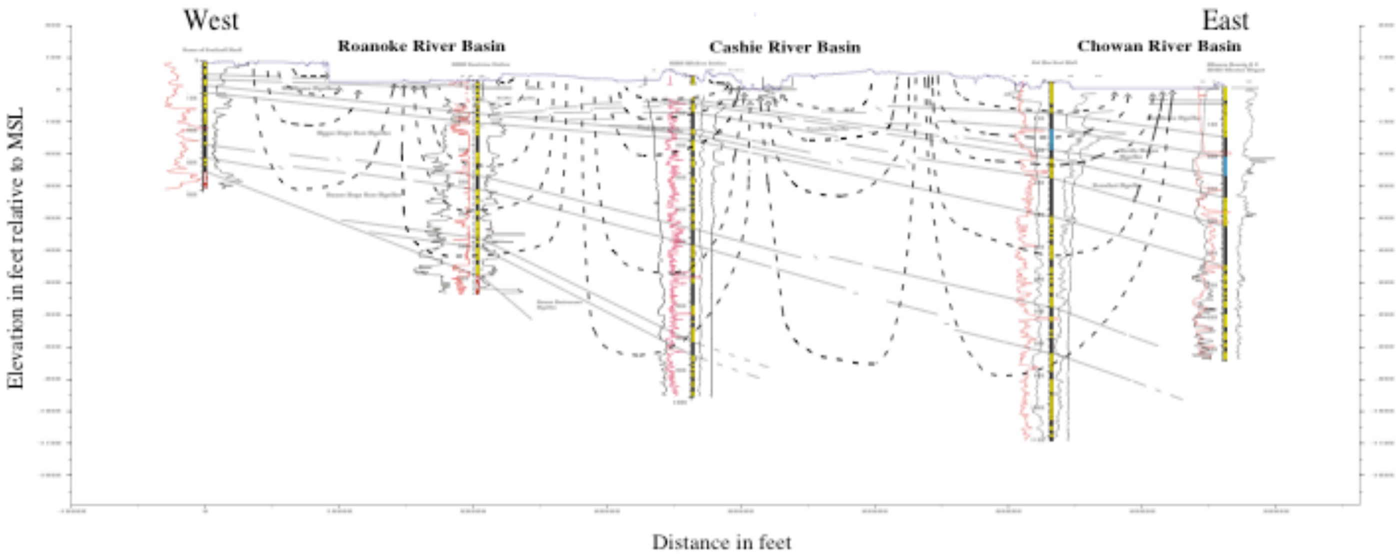
A typical hydrogeologic cross section through the Northwest Coastal Plain is shown in figure iii, exhibiting the complexity of ground water flow patterns and saltwater interfaces in relation to hydrogeologic units. Ground water flows in a rather complex three-dimensional pattern through the subsurface in a multilayered Coastal Plain environment. Flow occurs laterally through aquifers from recharge to discharge areas along flow lines 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.

General Description of the Ground Water System

Some of the aquifers within the study region 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 along the fringes of the Albemarle Sound, 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. Saltwater 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.

Of particular interest in the study area are the water level declines that have been occurring in the deeper Cretaceous age aquifers due to withdrawals of up to 43 million gallons per day from the Union Camp Corp. (later International Paper Co.) well field in Franklin, Virginia and other nearby sources. Due to the size and extent of the cones of depression, water levels in the Lower Cape Fear and Lower Cretaceous Aquifers have been declining at a rate of about 1 to 2 feet per year in the northern Coastal Plain of North Carolina since heavy pumping began in the late 1940s. The closure of plant operations in 2008 caused water levels in these aquifers to rebound in North Carolina as indicated by DWR monitoring stations.

The system of nine regional aquifers and intervening confining units found in the Quaternary through Triassic age sedimentary wedge in the Northwestern 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.



Ground Water Flow Line

Aquifer and Confining Unit Boundary

Figure iii. West to East Hydrogeologic Cross-Section through Halifax, Bertie, and Chowan Counties, North Carolina, showing idealized ground water flow lines.

Introduction

This report is the latest 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, Southern, and East Central Coastal Plain (Lautier, 1998, 2001, 2006, 2009).

The study area is situated in the Northwest Coastal Plain between the Fall Line and the Chowan River, including the following Counties: Halifax, Northampton, Hertford, Bertie, Martin, and the eastern part of Edgecombe (figure 1).

Recent information collected in this area from water supply wells, a U.S. Geological Survey core hole in Bertie County, and several new NC-DWR ground water monitoring station sites has provided the basis for a new interpretation of the hydrogeologic framework. In addition, it is important to understand the effects of stresses incurred on the aquifer system due to pumping from industrial, municipal and agricultural well fields located in the study region. Of particular interest is the recent recovery of water levels observed due to reductions in pumping from the deeper Cretaceous age aquifers in Southeast Virginia in the vicinity of Franklin. This was due to the closure in June, 2008 of the International Paper Company facility, which withdrew up to 35 million gallons per day of ground water during 50 or more years of operation.

Previous Studies

Several local and regional geologic and hydrogeologic reports have been published in this area. The ones that most closely relate to this study are mentioned as follows, starting with the earliest. Reports by Byers (2008) and Groundwater Management Associates (2004) are unpublished.

Mundorff (1946) conducted a study of ground water supplies, aquifer quality and use in relation to the geologic framework of Edgecombe, Halifax, Nash, Northampton, and Wilson Counties.

Brown (1959) discussed the geology and ground water resources of Bertie, Hertford, Northampton, and Martin Counties, as well as other surrounding counties using lithologic descriptions of well cuttings, outcrop descriptions and other information from local water supply wells.

Wyrick (1966) produced a report on the ground water resources of Martin County. A hydrogeologic framework was constructed using lithologic descriptions of

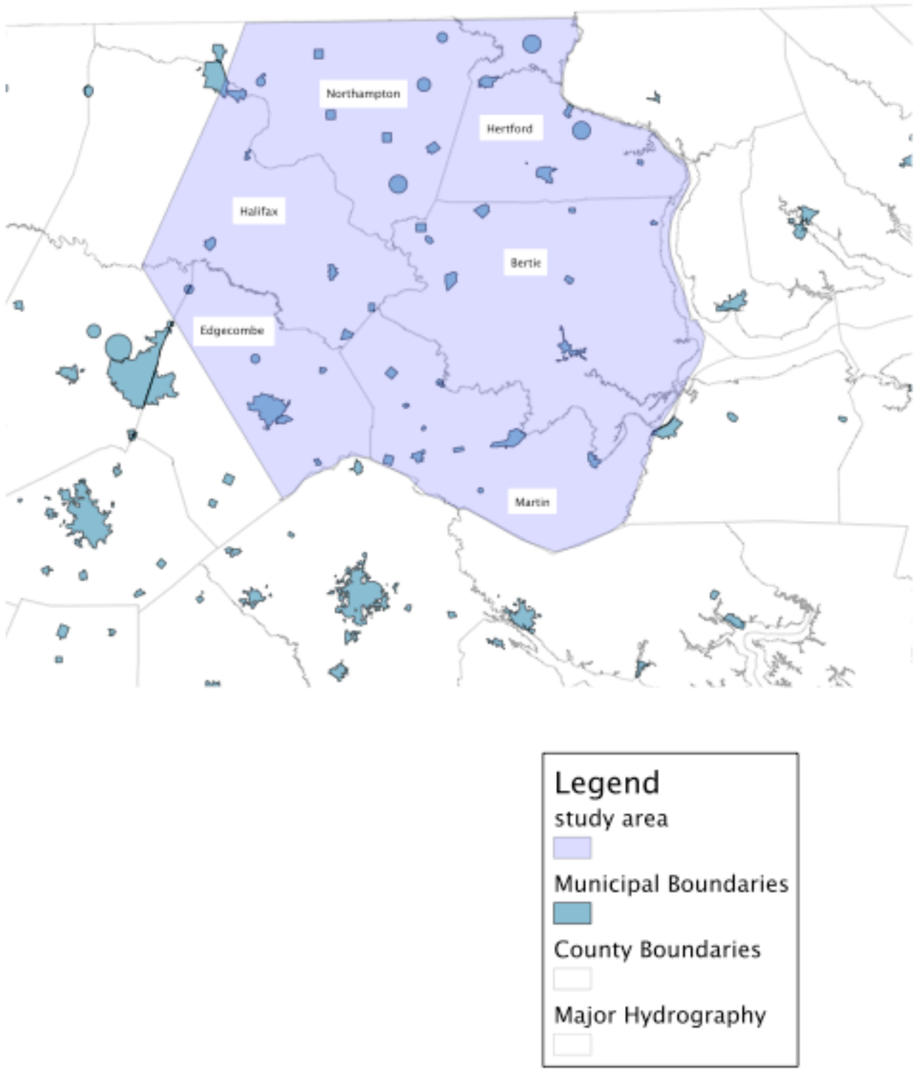


Figure I
Area of Study in the North Carolina Northwestern Coastal Plain

well cuttings and borehole geophysical logs. Water quality and yield information from water supply wells in the County was presented.

Wilder, Robinson and Lindskov (1978) studied the surface water and ground water resources of Northeast North Carolina, and discussed the basic hydrogeologic framework, supply potential and quality of surface and ground water, stream flow characteristics, and surface water/ground water interaction. A water budget model of the area was also presented, covering much of the present study area in Northampton, Hertford, and Bertie Counties.

Winner and Coble (1996) mapped and characterized the major aquifers and confining units across the entire North Carolina Coastal Plain as part of a U.S. Geological Survey Regional Aquifer System Analysis of the North Atlantic Coastal Plain.

Groundwater Management Associates (2004), a Greenville, NC based consulting firm, provided a hydrogeologic evaluation of Northampton and Halifax Counties.

Weems and others (2007) described the physical stratigraphy and geophysical data of the US Geological Survey Hope Plantation core, near the Town of Windsor, in Bertie County. This added much needed information on the subsurface stratigraphy of the region.

Byers (2008) completed a masters thesis project in Bertie County in which he described the hydrogeologic framework and ground water resources. The thesis research was carried out at East Carolina University Dept. of Geological Sciences, Greenville, NC.

Acknowledgements

The author would like to thank colleagues in the North Carolina Division of Water Resources Ground Water Management Branch 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, Paul Williams, and Tony Butz. 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.

Hydrogeologic Setting

The area of study is situated in the northern part of the Inner Coastal Plain as defined by Stuckey (1965). Here the topography is flat to gently rolling except where streams have eroded and dissected the landscape. The land surface slopes gently toward the southeast. Elevations vary from 150 feet near the fall line in northern Northampton County, to just above sea level adjacent to the Albemarle Sound and along the southernmost extent of the Chowan River. The major river basins in the eastern part of the region contain large floodplains and swamps which are widespread in Martin and Bertie Counties. The major Rivers, the Roanoke and Chowan, dissect the land surface on their courses to the Albemarle Sound.

The most prominent physiographic features of this region, and over much of the North Carolina Coastal Plain for that matter, are the Pleistocene terrace deposits. They form irregular belts extending northeast to southwest across the Coastal Plain (Mundorff, 1946). The terraces were formed during still stands of sea level at various times during the Pleistocene Epoch between ten thousand and 2 million years ago. The highest terraces are believed to be the oldest, and the lower are successively younger. Each terrace is generally separated from the next higher one by a pronounced scarp, which marks the shoreline of the sea that formed it (Mundorff, 1946).

Underlying the Holocene and Pleistocene sediments of the study area is a wedge of Tertiary and Cretaceous Age sediments and sedimentary rock which range in thickness from zero where they pinch out along the Fall Line to approximately 1500 feet underneath the Chowan River. The sediment wedge is comprised of layers and lenses of sand, clay, silt, limestone, gravel, shell material, and combinations thereof. Triassic Age sedimentary rock was encountered in a U.S. Geological Survey core hole near the Town of Windsor in Bertie County at a depth of 1,026 feet below land surface. Triassic strata are composed of reddish brown colored sandstone, conglomerate, silt, and clay (Weems and others, 2007).

The sedimentary column of the Northwestern 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 Northwestern 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 nine regionally significant aquifers and the intervening confining units that separate them. They are mentioned from oldest to youngest as follows:

The Lower Cretaceous aquifer, which is comprised along with its confining unit, of sediments of Lower Cretaceous age. The Lower Cretaceous Aquifer is underlain by sediments of Triassic age. Triassic age sediments are probably localized, and limited in presence to fault bounded basins in the basement rock. Where Triassic Age sediments are missing, as evidenced by a few basement penetrations in the area, the basement surface directly underlies the Lower Cretaceous Aquifer.

The Lower Cape Fear aquifer, which is comprised along with its confining unit, of the lower part of the Cape Fear Formation of Upper Cretaceous age.

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

North Carolina Northwestern Coastal Plain Geologic Units			North Carolina Northwestern Coastal Plain Hydrogeologic Units
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	Miocene	Pungo River Formation	
			Castle Hayne Confining Unit
	Eocene	Castle Hayne Formation	Castle Hayne Aquifer
			Beaufort Confining Unit
	Paleocene	Beaufort Formation	Beaufort Aquifer
Upper Cretaceous			Peedee Confining Unit
		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			Lower Cretaceous Aquifer

The Upper Cape Fear aquifer and confining unit, which correspond to the upper part of the Cape Fear Formation of Upper Cretaceous age.

The Black Creek aquifer, which corresponds primarily to the Black Creek Formation of Upper Cretaceous age. The confining unit is made up of clay or silt beds of variable age that overly the Black Creek Formation.

The Peedee aquifer, which is made up of the Peedee Formation of Upper Cretaceous age. This aquifer is present only in Martin County and the southern fringe of Bertie County within the area of study. 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 Paleocene age Beaufort Formation. The confining unit is made up of the upper part of the Beaufort Formation. The aquifer may also include sands in the Peedee Formation in some areas.

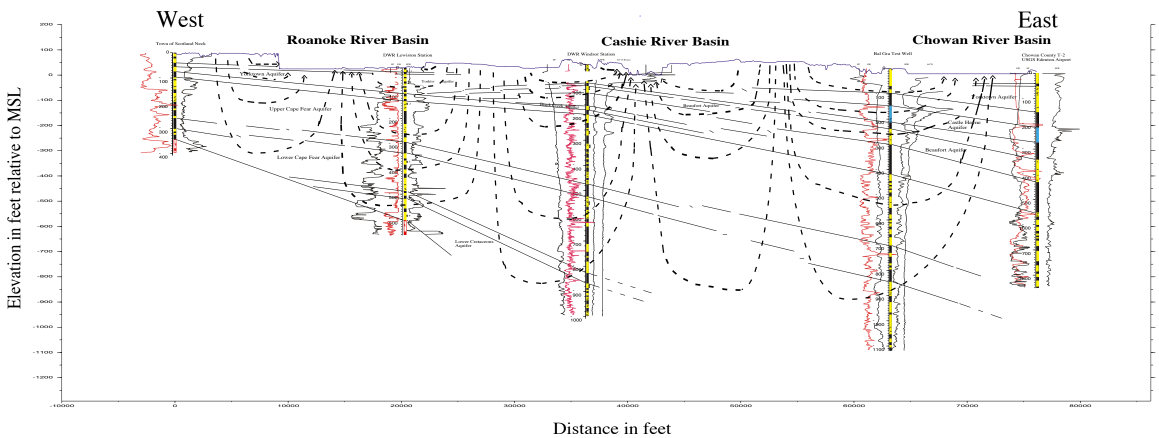
The Castle Hayne aquifer is comprised primarily of the Eocene age Castle Hayne Formation. It also includes a lower sandy section of the overlying Pungo River Formation (Middle Miocene) and an upper sandy section of the underlying Beaufort Formation. The confining unit occurs in the overlying Pungo River Formation. Where the Pungo River Formation is absent the confining unit is present within the Yorktown Formation.

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 Northwest Coastal Plain is shown in figure 3, exhibiting the complexity of ground water flow patterns and saltwater 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 flow lines 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.



Ground Water Flow Line

Aquifer and Confining Unit Boundary

Figure 3. West to East Hydrogeologic Cross-Section through Halifax, Bertie, and Chowan Counties, North Carolina, showing idealized ground water flow lines.

Some of the aquifers within the study region 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 along the fringes of the Albemarle Sound, 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. Saltwater 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.

In order to develop a generalized water budget model for the report area, average annual precipitation data was obtained from the Southeast Regional Climate Center and is presented in table 1.

COUNTY	Annual Precipitation in Inches
Hertford	47.92
Bertie	47.37
Martin	48.56
Northampton	46.51
Halifax	45.09
Edgecombe	46
6 County Average:	46.9

Table 1: Average of Total Annual Precipitation (in inches) from the years of 1872 to 2011 for the North Carolina Northwestern Coastal Plain (period of record varies within time frame depending on measurement station)

Annual base flow and runoff amounts were calculated using a model developed by Arnold and others, 1999. Simulations were performed using four US Geological Survey stream gauges, the results of which are presented in table 2.

Gauge	**Average annual base flow in inches per year**	**Average annual surface runoff in inches per year**
Cashie River at SR 1257 Near Windsor, Bertie Co. 1987-2012	6.85	6.39
Ahoskie Creek at Ahoskie NC, Hertford Co. 1950-2012	10.8	6.65
Ahoskie Creek Tributary at Poortown, NC, Hertford Co.		

1963-1973	3.57	5.9
Ahoskie Creek near Rich Square, Northampton Co. 1964-1973	4.7	6.98
Average	6.5	6.5

Table 2: Average Annual Base Flow and Runoff Calculated at four USGS Stream Gauges in the Northwestern Coastal Plain using an automated base flow separation and recession analysis model developed by Arnold and others, 1999.

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 six county area receives an average of 47 inches of total precipitation per year based on historical records covering the years between 1872 to 2011 (Southeast Regional Climate Center, table 1). Using a computer model developed by Arnold and others, 1999, it was determined that about 13 inches of the 47 inches of total annual precipitation is lost to overland flow and ground water discharge to nearby surface water bodies, or 27 per cent. Another 33 inches (70 per cent) are taken up annually through evapo-transpiration. Of the 7.5 inches of water that enters the water table as recharge, 6.5 inches per year flows from recharge to discharge areas such as the Roanoke and Chowan Rivers, 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 shallow ground water system is occurring.

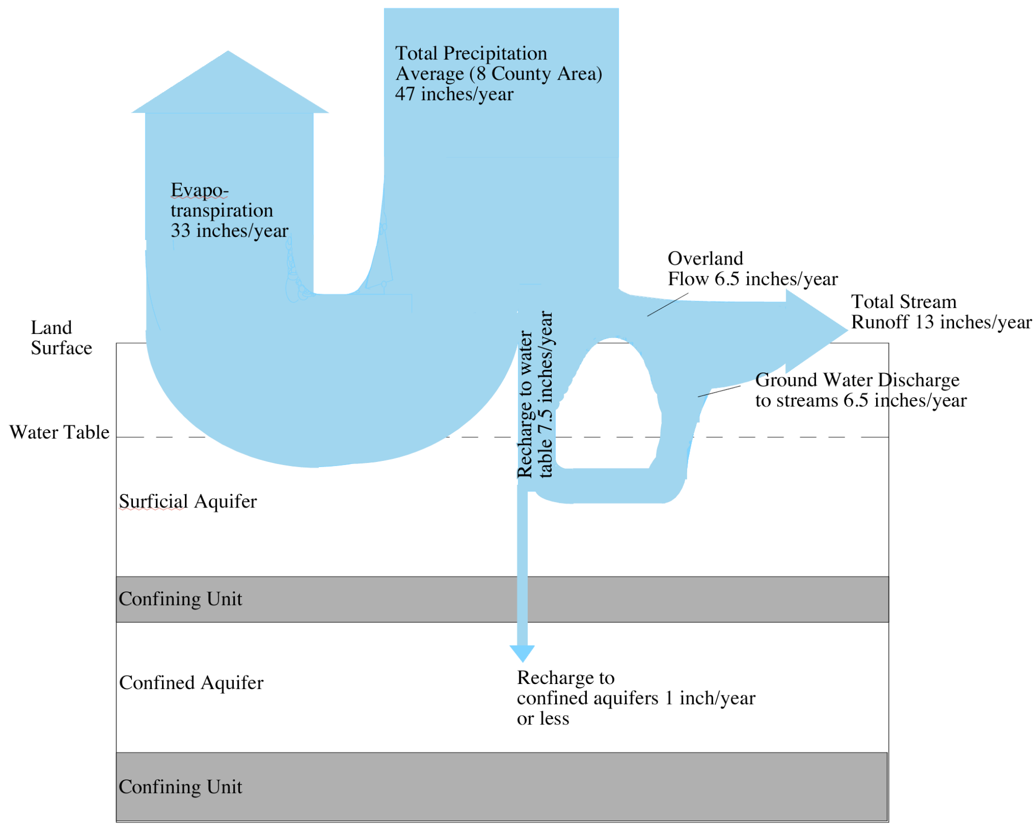


Figure 4. Generalized average water budget model for the
North Carolina Northwestern Coastal Plain ground water system

This model does not vary appreciably from one presented by Wilder, Robinson, and Lindskov (1978) for Northeastern North Carolina, which included Bertie, Halifax and part of Northampton County.

Of particular interest in the study area are the water level declines that have been occurring in the deeper Cretaceous age aquifers due to withdrawals of up to 43 million gallons per day from the Union Camp Corp. (later International Paper Co.) well field in Franklin, Virginia and other nearby sources. Due to the size and extent of the cones of depression, water levels in the Lower Cape Fear and Lower Cretaceous Aquifers have been declining at a rate of about 1 to 2 feet per year in the northern Coastal Plain of North Carolina since heavy pumping began in the late 1940s. The closure of plant operations in 2008 caused water levels in these aquifers to rebound in North Carolina as indicated by DWR monitoring stations. This is discussed in detail later in this report.

Methods Used for Investigation of the Subsurface

The following tools and techniques were used to separate the Quaternary through Triassic 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 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 INTERPIX 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 INTERPIX smooth modeling allows for a maximum of 60 layers. INTERPIX 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, although improvements have been made to the previous processing software, TEMIX XL. This software could only produce a maximum of 19 smooth model layers.

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 Black Creek, Upper Cape Fear, Lower Cape Fear, and Lower Cretaceous Aquifers using water level data collected by the North Carolina Division of Water Resources in February through March, 2012.

Hydrogeologic Framework of the Study Area

The system of nine regional aquifers and intervening confining units found in the Quaternary through Triassic age sedimentary wedge in the Northwestern 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 Northwestern 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 the Chowan and Roanoke Rivers and their tributaries, swamps and floodplains, and other surface water bodies. It also moves down gradient in recharge areas into deeper confined aquifers. 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 20 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 Halifax and Northampton County. 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 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. The top of the aquifer corresponds to the land surface, with a variation in thickness between 4 and 75 feet. Maximum thickness was observed in the DWR Windsor Monitoring Station in Bertie County, where no significant clay layer is present down to 75 feet below land surface.

Due to variations of soil types and infiltration capacities, vegetation, land use, and slight differences in climate, recharge rates to the surficial aquifer vary considerably within the area covered in this report. A general soil map of North Carolina by Tant and others (1974) indicates that the study region is primarily covered by soils exhibiting good to moderate infiltration capacity. Heath (1994) estimated that soils with good infiltration capacity have recharge rates of 400,000 gpd/sq. mile, and soils with moderate infiltration capacity, 200,000 gpd/sq. mile. Base flow calculations presented earlier in this report indicate that average annual recharge to the surficial aquifer is approximately 7.5 inches per year.

The presence of salt water in the surficial aquifer is limited to the downstream sections of the Chowan and Roanoke Rivers, and their lower tributaries where tidal effects in the Albemarle Sound allow inland movement of salt water. During periods of high tide, the head in a river or sound may be higher than the adjoining water table, allowing salt water to migrate. The effects of advection and dispersion create a saltwater fringe in the surficial aquifer adjacent to the surface water body.

The surficial aquifer is used to a limited degree as a domestic source of water with yields that range around 10 or less gallons per minute (Mundorff, 1946). The aquifer in many areas contains objectionable amounts of iron.

Yorktown Confining Unit

The Yorktown confining unit is made up of a series of discontinuous clay and silt beds of Pliocene and Quaternary age. As illustrated by a set of regional cross sections that were constructed for this study (plates 1 through 10), the confining unit is often missing due to erosion in stream and river valleys or due to nondeposition. In areas where the confining unit is missing the Yorktown Formation is part of the surficial aquifer. The unit achieves a maximum thickness of 41 feet in a Perdue Farms Inc. well in Bertie County as displayed by an isopach map (plate 13). Available well data indicates that the unit ranges in elevation between 94 feet above sea level in western Northampton County, to 15 feet below sea level in eastern Bertie County (plate 12).

Yorktown Aquifer

The Yorktown Aquifer is principally composed of the Yorktown Formation of Pliocene age. In the easternmost parts of Hertford, Bertie and Martin Counties, where the up dip limit of the Middle Miocene Pungo River Formation occurs (Miller, 1982), this unit makes up the lower part of the Yorktown Aquifer. The lithology of the Yorktown Aquifer is described as dark greenish gray to bluish colored beds of very fine to fine grained, silty, clayey and micaceous quartz sand. The sands are commonly interbedded with silt, and contain abundant shell material due to their shallow marine origin. The sands alternate with beds of clay and silt, which are also greenish gray in color due to the presence of glauconite. Where the Pungo River Formation makes up the lower part of the aquifer, the lithology is also composed of diatomaceous yellow-green clays and fine to medium grained, clayey quartz sands with traces of phosphate. The clay and phosphate in the Pungo River sands impart a brown color (Miller, 1982).

Sands within the Yorktown Aquifer are discontinuous in nature, as evidenced by poor well to well consistency and correlation on electric and gamma ray logs. The lenticular nature of the sands gives the aquifer poor hydraulic connection over large areas. The aquifer contains so much clay that the permeability is low and ground water yields from wells are limited. Better yields may be obtained where lenses of cleaner sand occur such as at the DWR Cremo Station or the Town of Rich Square well no. 4. Most ground water usage in this area is from the deeper Cretaceous age aquifers, although the

Yorktown was used in this region more frequently in the past according to a report by Mundorff (1946). The City of Halifax in Halifax County at one time operated two wells in the Yorktown which yielded 15 gallons per minute each. The town of Scotland Neck operated a 59.5 foot well which yielded 205 gallons per minute. The town of Rich Square obtained a yield of 120 gallons per minute from a 76 foot well, and 250 gallons per minute from another well at 40 to 70 feet in the Yorktown/Surficial Aquifer (Mundorff, 1946). Since the Yorktown is the first confined aquifer in the system, available drawdown is limited due to its shallow occurrence. However, recharge rates are higher than to the deeper aquifers, and the Yorktown is semi-confined as indicated by hydrographs over much of the North Carolina Inner Coastal Plain.

An isopach map (plate 15) of the Yorktown aquifer indicates that it is thickens from west to east to a maximum of 122 feet near the Chowan River in Bertie County. The unit is absent in areas where its confining unit is missing due to erosion or non-deposition, and the equivalent sediments are part of the overlying surficial aquifer. In the Roanoke River Basin, Yorktown and Quaternary Age sediments are almost entirely eroded away in some locations, as illustrated in cross section B-B' and H-H' (plates 3 and 9). The unit ranges in elevation from over 82 feet above sea level in western Northampton County, to approximately 40 feet below sea level along the southeastern boundary of the study region.

Well and tdem data indicate that the freshwater-saltwater interface in the Yorktown Aquifer occurs east of the Chowan River. The interface is documented in a report by this author on the North Albemarle region (Lautier, 1998). It is likely that the Yorktown contains saltwater along the tidal influenced sections of the Chowan and Roanoke Rivers, tributaries, estuaries and the Albemarle Sound.

Recharge to the Yorktown Aquifer is from the overlying surficial aquifer in inter-stream areas where water levels are higher in the surficial than the Yorktown. In areas where the Yorktown confining unit is missing, direct hydraulic communication occurs between the two aquifers. Ground water discharges directly from the Yorktown into rivers and streams that have incised the aquifer as illustrated on regional cross sections (plates 2 through 10).

Castle Hayne Confining Unit

The Castle Hayne confining unit is present only in the easternmost part of the study area, and pinches out through eastern Hertford, central Bertie, and eastern Martin Counties (plate 16 and 17). This unit is made up of clay and silt beds present in the lower part of the Pungo River Formation. West of the pinch out of the Pungo River Formation, the lower Yorktown Formation makes up the Castle Hayne confining unit. The unit ranges in elevation from 44 feet to over 90 feet below sea level under the Chowan River, and has a maximum thickness of 70 feet.

Castle Hayne Aquifer

Eastern Martin, Bertie and Hertford Counties contain the westernmost extent of the Castle Hayne Aquifer as shown in plates 18 and 19. As discussed in an earlier report by this author covering the hydogeologic framework of the North Albemarle Region (Lautier, 1998), the Castle Hayne Aquifer is made up of a lower sand zone in the Pungo River Formation of Middle Miocene Age, the Middle Eocene Castle Hayne Formation, and sands in the upper part of the Beaufort Formation of Paleocene Age. These three units are considered to be hydraulically connected due to a lack of presence of confining beds to separate them. The middle layer, the Castle Hayne Limestone, pinches out to the east of the Chowan River from Valhalla in Chowan County and further northward. To the south, the up dip extent of the limestone was encountered in a town test well at Windsor in Bertie County as shown on cross section C-C' (plate 4). The dashed line representing the up dip limit of the Castle Hayne Aquifer therefore approximates where the upper and lower units either pinch out or are no longer a separate hydraulic unit.

East of the up dip limit of the Castle Hayne Formation, the aquifer contains from top to bottom, a lower phosphatic sand zone of the Pungo River Formation, the shelly, sandy limestone of the Castle Hayne, and the glauconitic upper sands of the Beaufort Formation. West of the up dip limit of the Castle Hayne limestone, the lithologies of the lower section of the Pungo River and upper section of the Beaufort Formation are predominant.

Two tests of the Castle Hayne Aquifer were conducted by Groundwater Management Associates and discussed in separate reports (GMA, 1999, 2010). A test performed on a well for the Town of Windsor in Bertie County indicated a transmissivity value of 1340 ft2/day and specific capacity of 5 gallons per minute per foot of drawdown. An estimation was made that a production well in the Castle Hayne Aquifer should be capable of producing 200 gallons per minute using approximately 46 feet of drawdown. It was reported that the Castle Hayne Aquifer contained iron at 0.4 mg/L and manganese at 0.06 mg/L, exceeding the secondary EPA Drinking Water Standards. A pump test of well SW-1 at Nucor Steel in Hertford County indicated a specific capacity of 56 gallons per minute per foot of drawdown (table 3).

The fresh water/saltwater transition zone in the Castle Hayne Aquifer occurs to the east of the Chowan River and outside of this report area, as documented in Lautier (1998), and Winner and Coble (1996). To the west of the transition zone and including this report area, the aquifer contains fresh water.

Table 3: Aquifer Test data from the North Carolina Northwestern Coastal Plain

County	Well Name	Well Number	Screened interval (ft bls)	Aquifer	Analysis Method	Pumping or Observation Well	Transmissivity in ft2/day	Storativity	K (in ft/day)	Specific Capacity gpm/ft
Hertford	Hertford County Well No. 4	No. 4	275-315	Upper Cape Fear	Jacobs Straight Line	Pumping	5,034	na	21	85.5
Martin	Penco Products Well No. 6	No. 6	365-395,405-425	Upper Cape Fear	Jacobs Straight Line	Pumping	1,338	na	4.5	6.8
Martin	Martin Co. Beargrass Test Well		271-296	Black Creek	Jacobs Straight Line	Pumping	324	na	3.3	0.98
Martin	Martin Co. Obs. Well No.2	No.2	450-505	Upper Cape Fear	Jacobs Straight Line	Pumping	2710	na	8	21.7
Bertie	Town of Windsor		77-107	Castle Hayne	Cooper-Jacob/Theis	Pumping	1340	na	26.8	4.19
Hertford	Nucor Steel	SW-1	130-185	Castle Hayne		Pumping				56

The Castle Hayne has seen minor usage by industries and municipalities in the report area due mainly to the fact that the deeper Cretaceous Age aquifers supply water of better chemical quality and with greater yields. According to well construction data in the area it is used to a limited degree as a domestic source of water. It was also used by a few small towns in the past, such as Colerain in Bertie County. The Town of Jamesville in Martin County currently uses both the Castle Hayne and Beaufort Aquifers with a reported maximum withdrawal of 150 gallons per minute per well. Elsewhere, yields are in the 50 to 65 gallon per minute range. In easternmost Martin County, and just to the west of the Town of Plymouth, Washington County, Domtar Paper Company withdraws up to 1.4 million gpd from 11 wells in the Castle Hayne Aquifer. Some of this usage is from the Yorktown Aquifer. Yields for the Castle Hayne are comparatively lower in the Northwestern Coastal Plain due to the fact that its does not have the desirable thickness or optimal hydraulic properties found further to the south, in Beaufort and Washington Counties.

Beaufort Confining Unit

The Beaufort confining unit is made up of clay and silt beds present in the upper part of the Beaufort Formation of Paleocene age, and in some places, in the lower part of the Yorktown or Pungo River Formations. Available well data indicates that the unit ranges in elevation between 13 feet above sea level to 215 feet below sea level at the southeastern border of the study region (plate 20). The unit thickens eastward to a maximum of 40 feet underneath the Chowan River (plate 21). It pinches out, along with the underlying aquifer through eastern Northampton, western Bertie, Hertford, and Martin Counties.

Beaufort Aquifer

The Beaufort Aquifer is composed of glauconitic, shelly quartz sands and silt/clay interbeds which are greenish grey in color. Sands in the aquifer are also slightly phosphatic, which produces negative gamma ray curve shifts on borehole geophysical logs. The aquifer is made up primarily of the Paleocene Beaufort Formation. It presence is limited to the eastern half of the study area, pinching out along the same line as described earlier where its confining unit is missing. As indicated on regional cross sections (plates 1 through 10) the aquifer alternates in composition from a single bed of sand to a group of sand layers and clay/silt interbeds.

The unit ranges in elevation from slightly above sea level where its up dip limit occurs, to 237 feet below sea level beneath the Chowan River (plate 22). It thickens generally eastward to a maximum of about 100 feet in the vicinity of the Hertford/Gates County line (plate 23).

The Beaufort Aquifer has been used to a limited degree by small towns, and as a domestic source of water. It is referred to on many old drillers reports as a green sand aquifer. This is due to its high glauconite content, which imparts a green color in drill cutting samples. Reported yields are in the 35 to 50 gallon per minute range. The aquifer becomes salty at variable distances to the east of the Chowan River, and outside of the area covered by this report (Lautier, 1998, Winner and Coble, 1996).

Peedee Aquifer and Confining Unit

The Peedee Aquifer and associated confining unit are present in the study area only in eastern Martin County, and possibly in south central Bertie County. The Peedee Formation, which principally comprises the aquifer, was not encountered in the U.S. Geological Survey Hope Plantation core hole near Windsor, Bertie County (Weems and others, 2007). Regional cross sections prepared for this report indicate that the aquifer and confining bed pinch out along the boundary between Martin and Bertie County and near the junction between Martin, Washington, and Beaufort Counties (cross sections: plates 1-10, maps: plates 24-27). The aquifer is not present in the DWR Gold Point monitoring station near Robersonville, in western Martin County. It is thickest in the east central part of Martin County in a town of Williamston well, which encounters an 84 foot section. It thins abruptly northward, eastward, and westward toward a line of approximate pinch out (plate 27). The top of the aquifer ranges in elevation between 82 feet below sea level and above, to over 200 feet below sea level, dipping from northwest to southeast (plate 26). The confining unit is a maximum of 20 feet thick near the town of Bear Grass, thinning in the same directions toward an approximate line of pinch out as shown in plate 25.

The aquifer is principally comprised of the Peedee Formation of Upper Cretaceous age. The aquifer consists of grey to dark green clayey, glauconitic sand, and dark green clay interbeds. Shell fragments are common. The Peedee confining unit is made up of clay and silt beds present in the upper part of the Peedee Formation and possibly in the lower part of the Beaufort Formation.

A saltwater transition zone is present in the Peedee Aquifer in eastern Martin County as shown on plate 26. The transition zone trends northeast to southwest between the towns of Williamston and Jamesville and to the east of the town of Bear Grass. To the east of the isochlor representing the intersection of the transition zone with the top of the aquifer, ground water is entirely salty in the Peedee. Within the transition zone the upper part of the aquifer is fresh, and the lower part is salty. The transition zone is also apparent on Tdem resistivity profile a-a' (figure 13) where resistivity is less than 10 ohm meters, indicating the presence of salt water.

The Peedee is not a heavily used aquifer in Martin or Bertie County. A survey of available well construction data does not indicate that any wells exclusively tap it. There may be a number of wells that are screened in the deeper Cretaceous aquifers that are gravel packed through the Peedee and thus yield a portion of total production from this aquifer.

Black Creek Aquifer and Confining Unit

The Black Creek Aquifer and confining unit are present in southern Edgecombe County, south central Bertie County, and over most of Martin County, as indicated on plate 28-31. The aquifer and confining unit are principally made up of the Upper Cretaceous age Black Creek Formation, although the confining unit can also be composed in part, of clay and silt beds present in the lower Peedee Formation. In areas where the Peedee Formation is missing, the lower part of the Beaufort Formation can also make up all or part of the confining unit.

In the Town of Williamston well field the Black Creek Aquifer is described as medium to coarse-grained, clean quartz sand with some feldspar, alternating with clayey fine-grained glauconitic sand. In Williamston, the aquifer consists of a single sand bed of about 35 feet average thickness, with thin clay and silt interbeds. At the DWR Beargrass monitoring station, the aquifer is described as medium grey, well sorted and rounded quartz sand, alternating with medium greenish-grey silty, glauconitic, fine sand with shell fragments. Some greenish-grey clay and silt interbeds are present, making up about 10 percent of the aquifer. At DWR Gold Point station the aquifer contains more silt and clay, and is only about 50 percent sand. To the north, in the U.S. Geological Survey Hope Plantation core hole in Bertie County, the Black Creek is composed of fine to very fine-grained quartz sand, slightly phosphatic and glauconitic, slightly silty and clayey, with pyrite nodules and lignite. Thin clay and silt interbeds are also present, with a total aquifer thickness of 28 feet. The Black Creek Group equivalent in the USGS core hole is referred to in Weems and others (2007) as the Tar Heel Formation. In this core hole the aquifer is near the northern limit (plates 30-31).

In 2011, the NC Division of Water Resources installed a monitoring station near the USGS Hope Plantation core hole site, referred to as the Windsor Station. An average head difference of approximately 30 feet is observed between the Black Creek and overlying Beaufort Aquifer, and 10 feet between the Black Creek and underlying Upper Cape Fear Aquifer (hydrograph, figure 5). As illustrated on cross section H-H' (plate 9), the aquifer pinches out northward toward the DWR Cremo Station. Cross section C-C' (plate 4) shows the eastward pinch out of the aquifer toward Bal Gra, near the Chowan River. The Black Creek Formation is still present eastward and northward but becomes predominantly clay, and comprises the Upper Cape Fear confining unit. In some areas to the east, and particularly east of the Chowan River, the uppermost sands of the Upper

Cape Fear Aquifer may be part of the Black Creek Formation. This is a perfect example of why the mapping of hydrogeologic units has to do with the continuity of permeable versus non-permeable units and how they are connected in three dimensions in the subsurface. The assignment of geologic formation names to aquifers and confining beds can thus be misleading. In cases like this, a formation such as the Black Creek is an aquifer over much of the North Carolina Coastal Plain, but becomes mostly a confining bed in the northern-most counties of the Coastal Plain.

An elevation map of the top of the Black Creek Aquifer indicates that it dips northwest to southeast from approximately 27 feet above sea level in eastern Edgecombe County to over 250 feet below sea level in eastern Martin and southern Bertie County (plate 30). It has a maximum thickness of 118 feet at the DWR Gold Point monitoring station in western Martin County, and thins westward, northward, and eastward toward an approximate line of pinch out shown on an isopach map (plate 31). The confining unit ranges in elevation from 47 feet above sea level to over 200 feet below sea level across the same area, and is thickest (70 feet) at the Town of Windsor in Bertie County as shown by an isopach map (plate 29).

A fresh water-salt water transition zone occurs in the aquifer in the eastern part of Martin County, extending into part of southern Bertie County as depicted on plate 30. The aquifer is entirely fresh in the Town of Windsor well field, Bertie County, and the Town of Williamston and Beargrass community in Martin County. The transition zone to the east is defined solely by time domain electromagnetic survey data, as there is no available well data to define the salty portion of the aquifer. Tdem profile a-a' (figure 13) suggests the presence of salt water where resistivity drops below 10 ohm meters.

A 24 hour pump test was performed in Martin County at the Town of Bear Grass test well by Groundwater Management Associates Inc. Using a Jacobs straight line analysis, a transmissivity of 324 ft2/day for the Black Creek Aquifer was calculated. Specific capacity was determined to be 0.98 gallons per minute per foot of drawdown.

The Black Creek Aquifer is used in Martin County for municipal supply by the town of Williamston and Martin County water system. Wells are generally screened in both the Upper Cape Fear and Black Creek Aquifers in order to obtain the best yields.

Upper Cape Fear Aquifer and Confining Unit

The Upper Cape Fear Aquifer and confining unit are present across the entire study region, the western boundary of which is the fall line. The aquifer and confining unit are made up of the upper part of the Cape Fear Formation of Upper Cretaceous Age. The confining unit is partially composed over regions of variable extent of clay beds in the lower part of the Yorktown, Beaufort, or Black Creek Formations depending on which directly overlies the Cape Fear Formation.

In the USGS Hope Plantation core hole, the Upper Cape Fear Aquifer is described by Weems and others (2007) as generally very fine to medium grained quartz sand, yellow to brown to reddish in color, with silt and clay matrix common. Sands are generally thin, and are interbedded with clayey silt, which makes up about 50 per cent of the aquifer at this location. In the Town of Williamston well field, the aquifer is described as medium to coarse grained quartz and feldspar sand, interbedded with red to orange to yellow, mottled, clayey siltstone. Individual sand beds range in thickness from between 60 feet to only a few feet, and clay/siltstone content is around 50 per cent. In the northern part of the study area, at the DWR Como Station in Hertford County, the aquifer contains numerous gravel and coarse-grained sand beds which make up about 60 per cent of its thickness. Electric and gamma ray log correlation indicates that individual sand bodies are discontinuous, and occur as lenses and stringers in cross sectional profile. However, the three-dimensional distribution of sand in the aquifer allows for widespread transmission of drawdown effects as indicated by a potentiometric surface map (plate 46) and hydrographs (figures 5-11). The aquifer is defined by distinctive hydraulic head differences that occur between the overlying and underlying aquifers as indicated by several DWR monitoring station sites.

An elevation map of the top of the Upper Cape Fear Aquifer indicates that it dips northwest to southeast from approximately 78 feet above sea level in Halifax County to over 400 feet below sea level in easternmost Martin County (plate 34). It exhibits a maximum thickness of 341 feet at the DWR Bear Grass monitoring station in south central Martin County, and pinches out along with its confining unit near the fall line. The confining unit ranges in elevation from 94 feet above sea level to over 300 feet below sea level across the same area, and is thickest (121 feet) near the Chowan River in eastern Bertie County.

Water levels in the Upper Cape Fear Aquifer have been declining slowly in the study area since measurements began in the early 1980s. Unlike the deeper Lower Cape Fear and Lower Cretaceous Aquifers, water levels in the Upper Cape Fear have not rebounded due to the closing of the International Paper Mill near the town of Franklin, Virginia in 2008. This is indicated in hydrographs at DWR monitoring stations at Como, Sunbury, and Cremo (figures 9, 16, and 8). As interpreted by this author in a study of the North Albemarle region of Northeastern North Carolina, (Lautier, 1998) the Upper Cape Fear aquifer pinches out between the Virginia border and the International Paper Company well field. Drawdown effects in the aquifer have otherwise been produced by widespread, ongoing usage in the present study region and in southeastern Virginia border counties to the south of where the aquifer pinches out. The Upper Cape Fear is used by a number of towns, county water systems, farms, and industries in the study area for water supply. Some of the larger users according to the State of NC local water supply plans include the Town of Williamston in Martin County, which pumps a little over 3 million gallons maximum per day from the Black Creek/Upper Cape Fear Aquifers combined. The Bertie County regional water system pumps 4 million gallons per day maximum from 13 wells. The Hertford County water system pumps 2.2 million gallons per day from a 4 well system. Nucor Steel in Hertford County pumps approximately 900,000 gallons per day (average daily withdrawal) from 10 wells in the Upper Cape Fear Aquifer.

A potentiometric surface map of the Upper Cape Fear Aquifer indicates prominent ground water flow toward the northeast in response to pumping from the aquifer in and Hertford, Northampton, Gates, and southern Virginia Counties. Ground water flow occurs to the south in response to pumping in southern Bertie and Martin Counties. The area of eastern Halifax and northern Bertie has maintained an area of higher elevation on the potentiometric surface that is bounded by cones of depression to the northeast and south.

A few aquifer tests were available to calculate hydraulic parameters on the Upper Cape Fear Aquifer, and are reported in table 3. Transmissivity ranges from 1,338 to 5,034 ft2/day and specific capacity from 6.8 to 85.5 gallons per minute per foot of drawdown. Since the aquifer tests were calculated on pumping wells without observation wells, storativity values could not be calculated.

A saltwater/freshwater transition zone is present within the Upper Cape Fear Aquifer through the eastern part of the study region, as shown in plate 34. The transition zone trends northeast to southwest through easternmost Hertford, central Bertie and Martin Counties, and is defined by chloride sample data and tdem surveys. To the east of the transition zone, the Upper Cape Fear Aquifer contains salty ground water in excess of 250 ppm chloride. There has been an apparent westward shift of the transition zone toward the Nucor Steel Corp. well field near the town of Cofield, Hertford County. This is indicated by chloride values near the 250 ppm threshold in the vicinity of the well field. Tdem resistivity profiles a-a’, b-b’ and c-c’ (figures 13, 14 and 15) suggest the approximate position of the fresh water/salt water transition zone where resistivity values are less than 10 ohm meters, indicating the presence of salt water in the aquifer.

Lower Cape Fear Aquifer and Confining Unit

The Lower Cape Fear Aquifer and confining unit are present across the entire study region, the western boundary of which is the fall line. The aquifer and confining unit are made up of the lower part of the Cape Fear Formation of Upper Cretaceous Age.

The Lower Cape Fear Aquifer has a similar lithology as the Upper Cape Fear except for the presence of marine sediments in the lower part of the aquifer. These sediments include alternating layers of limestone, coquina, silt, clay, and very fine to fine-grained sand. This marine section is referred to as the Clubhouse Formation (Upper Cretaceous) by the U.S. Geological Survey in Weems and others (2007), although this designation has not been formally recognized in North Carolina nomenclature. The aquifer is defined by distinctive hydraulic head differences that occur between the underlying Lower Cretaceous Aquifer and the overlying Upper Cretaceous Aquifer as indicated by several DWR monitoring station sites (figures 5-12), and potentiometric surface maps (plates 46-48).

An elevation map of the top of the Lower Cape Fear Aquifer indicates that it dips northwest to southeast from approximately 139 feet below sea level in Halifax County to over 823 feet below sea level in easternmost Martin and Bertie Counties (plate 34). It exhibits a maximum thickness of 288 feet at the USGS Windsor core hole in central Bertie County, although it thickens further eastward toward the eastern boundary of the study area. The aquifer and confining unit pinch out near the fall line. The confining unit ranges in elevation from 49 feet below sea level to over 700 feet below sea level across the same area, and is thickest (146 feet) near the Chowan River in eastern Bertie County.

Unlike the Upper Cape Fear Aquifer, the Lower Cape Fear Aquifer was directly affected by the cessation of pumping from the International Paper Co. facility in Franklin, Virginia in late 2008. Water level measurements began in the Northwestern Coastal Plain ground water system at the DWR Sunbury monitoring station in Gates County in August 1967. As time progressed, additional monitoring sites were added through present, including the latest DWR Windsor station constructed in 2011. Analysis of Lower Cape Fear Aquifer decline rates at monitoring sites closest to the Virginia pumping center indicate that in the late 1960s, water levels were declining at a rate of 4 to 5 feet per year. Large scale pumping from Franklin, Virginia began in the late 1940s with the opening of the Union Camp Paper Mill (later International Paper). Over the long term from August 1967 to late 2008, water levels dropped at Sunbury at an average rate of 1.7 feet per year. At the DWR Como station in northern Hertford County the water level declined approximately 1 foot per year from late 1981 to the end of 2008. The impact of ground water withdrawals in Virginia are apparent in North Carolina as far south as the DWR Scuppernong station in northern Washington County, and DWR Gardner Chicod Station in southern Pitt County. There is only limited usage of the Lower Cape Fear Aquifer in the northern NC Coastal Plain, mainly due to the fact that it contains saltwater over a large area. The Lower Cape Fear is used by Perdue Farms and by the Town of Aulander in combination with shallower aquifers in western Bertie County. The Upper Cape Fear and shallower aquifers provide adequate supplies to meet demand for municipal, industrial and agricultural usage.

The slow, steady, uninterrupted water level decline rates in the Lower Cape Fear Aquifer observed at DWR station sites are a footprint of the extensive cone of depression that has emanated from southeastern Virginia pumping (plate 47). It is also indicative of the very low storativity of an aquifer that is able to transmit drawdown effects over such a large distance. The closure of the International Paper well field became evident on DWR hydrographs at Como and Sunbury at the end of 2008. Since the recovery began, water levels have rebounded 27 feet at Como (to pre-1982 levels when water level measurements began) and 9 feet at Sunbury (to 2001 levels). Recovery became evident as far south as DWR Four Mile Desert Station in Perquimans County in early 2012, as well as DWR Morgans Corner in Pasquotank County, and DWR Cremo and Roxobel Stations in northern Bertie County starting in 2012. In contrast, recoveries are not evident in southern Bertie, Martin County, or Pitt County, where water levels have continued a slow decline. This can be explained by the fact that withdrawals continue to occur from the Lower Cape Fear aquifer equivalent in southeastern Virginia border counties, which continue to affect North Carolina water levels. A potentiometric surface map of the aquifer indicates that in contrast with the Upper Cape Fear Aquifer, the primary direction of ground water flow is to the northeast toward pumping centers in Virginia. Also evident on the potentiometric surface is an isolated low in Northwestern Bertie, southwestern Hertford and southeastern Northampton Counties, caused evidently by agricultural pumping and the Town of Aulander well field.

In a report by this author on the hydrogeologic framework of the North Albemarle region (Lautier, 1998), a Jacobs distance drawdown analysis was performed using pumping data from the Lower Cape Fear equivalent aquifer in southeastern Virginia. Water levels were plotted for the Como, Sunbury and Parkville (now Four Mile Desert) stations against the approximate center of pumping. A value of 22,388 ft2 per day was calculated for transmissivity, 56 feet per day for hydraulic conductivity, and 0.00319 for storativity.

A saltwater/freshwater transition zone occurs in the Lower Cape Fear Aquifer through the central part of the study region. The transition zone trends northeast to southwest through southern Hertford, central Bertie, eastern Martin Counties, and through the southeastern tip of Edgecombe County. To the east of the transition zone the aquifer contains nothing but saltwater at a concentration of 250 parts per million and greater. TDEM resistivity profiles a-a’, b-b’ and c-c’ suggest the approximate position of the fresh water transition zone where resistivity values are less than 10 ohm meters, indicating the presence of salt water.

Lower Cretaceous Aquifer and Confining Unit

The Lower Cretaceous Aquifer and confining unit are present in the eastern half of the study area, pinching out along an approximate line through western Martin, easternmost Halifax, easternmost Northampton, and northernmost Hertford Counties as depicted in plates 40-43. The aquifer and confining unit are made up of non-marine, fluvial-deltaic sediments of Lower Cretaceous Age. Only 9 wells penetrate this aquifer and confining unit in the study area.

In the USGS Hope Plantation core hole the lithology of the Lower Cretaceous aquifer consists of fine to very coarse, yellowish-brown to greenish-gray, quartz sand with minor clay and silt matrix, thin quartz gravel beds, and clayey silt interbeds. Sands are generally only a few feet in thickness. The lower part of the aquifer contains abundant clayey silt with thin sand interbeds. In contrast, the DWR Lewiston station pilot hole lithology consists of abundant, thickly bedded, medium to coarse white sand. Sands in the lower part of the aquifer contain feldspar. Some clayey silt beds are present, but the aquifer is about 70 per cent sand. At DWR Como Station in Hertford County the aquifer contains 8 to 10 foot fine to coarse-grained sand beds with thin clay and silt interbeds, Colors are described as combinations of red, brown, and yellow. The aquifer is defined by distinctive hydraulic head differences that occur with the overlying Lower Cape Fear Aquifer, as depicted on hydrographs (figures 5, 7, 8, 9, 11 and 12) and potentiometric surface maps (plates 47 and 48).

An elevation map of the top of the Lower Cretaceous Aquifer indicates that it dips northwest to southeast from slightly above 400 feet below sea level in eastern Halifax and Northampton Counties to over 1000 feet or more below sea level in easternmost Martin and Bertie Counties (plate 42). It exhibits a maximum thickness of 322 feet at the DWR Cremo Station in central Bertie County, although it thickens further eastward toward the eastern boundary of the study area. The confining unit ranges in elevation from above 400 feet below sea level to over 1000 feet below sea level across the same area, and exhibits a maximum measured thickness of 79 feet at DWR Cremo Station. It likely exceeds this thickness further eastward toward the Chowan River and the Martin-Washington County border. The aquifer pinches out against the basement surface along a line that roughly parallels the border between Hertford and Northampton, Bertie and Halifax Counties. The approximate pinch out line then trends further southward through eastern Martin County (plate 43).

A saltwater-freshwater transition zone occurs in the aquifer that trends northeast to southwest through central Hertford and Bertie Counties and slightly into northern Martin County where the aquifer pinches out (plate 42). The aquifer contains fresh water only in western Hertford and Bertie Counties, along with small sections of eastern Northampton, Halifax, and Northwest Martin Counties. This is only documented area of the North Carolina Coastal Plain where the Lower Cretaceous Aquifer contains fresh water. Further south in the East Central Coastal Plain it contains nothing but saltwater (Lautier, 2009).

No usage of the Lower Cretaceous Aquifer in the report area has been documented in this study, although a potentiometric surface map (plate 48) indicates that some usage may occur in western Bertie County due to agricultural related withdrawals.

In this area a narrow trough occurs in the potentiometric surface that plunges northeastward toward Virginia. Otherwise, the primary influence on the potentiometric surface is pumping from Virginia, which causes northeasterly flow to predominate. Similar to the Lower Cape Fear Aquifer, the low storativity of the Lower Cretaceous Aquifer has allowed widespread drawdown effects. Drawdown is observed as far south as the DWR Bear Grass station in central Martin County. At the DWR Cremo Station, decline rates in this aquifer have occurred at a similar rate as the Lower Cape Fear (figure 8). The cessation of pumping from International Paper Co. in Franklin, Virginia has had apparent effects on the decline rate at the Cremo, Roxobel, Windsor, and Lewiston Stations in Bertie County (figures 5-8). Cessation of drawdown is not evident further south at the DWR Bear Grass Station where water levels continue to decline at a rate of approximately one foot per year (figure 11). The Bear Grass Station is located near the perimeter of the cone of depression and is not yet affected by the cessation of pumping from International Paper Company. However, it is still impacted by other pumping from western Bertie County and across the Virginia State line.

Basement/Triassic Rock

East of the fall line, which forms the western boundary of this report area, the lithology of the underlying basement surface is made up of felsic volcanics, mudstone, volcanic sediments, intermediate volcanics, and mafic volcanics (Lawrence and Hoffman, 1993). The elevation of the basement surface ranges between 200 and 1750 feet below sea level across the area. An interesting exception to this elevation range occurs in the USGS Hope Plantation core hole, near the town of Windsor, Bertie County. Triassic age sediments were encountered in this core hole at a depth of 1,026 feet below land surface (966 feet below sea level). Lithology consists of clayey, reddish brown silt, fine to very coarse reddish brown sandstone, and varicolored conglomerate (Weems and others, 2007). Basement rock was not encountered in this core hole to a depth of 1,094 feet below land surface, or 1,034 feet below sea level. Triassic beds of similar lithology were also encountered in the DWR Windsor Station pilot hole, located 550 feet to the east of the USGS core hole. DWR pilot holes at Lewiston and Cremo to the west and north in Bertie County, and at Gold Point and Beargrass to the south in Martin County, did not encounter Triassic sediments before penetrating the basement surface. One must speculate that the Triassic unit encountered is restricted to a narrow fault controlled basement low, as depicted on cross section H-H' (plate 9).

In the western part of the study area, and to the west of the Lower Cretaceous salt water transition zone, suitable yields of fresh water may be obtained from basement rock where adequate fracturing or schistosity have developed. An in depth discussion of basement well yields in relation to lithology and depth range is provided by Mundorff (1946). Mundorff reported yields in the range of 1 to 300 gallons per minute in wells from 80 to 300 feet deep in slates and schists. He reported much lower yields in wells that penetrated granite, due to limited joint and fracture development over parts of the area.

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

A few additional DWR ground water monitoring stations are needed in the area covered by this report in order to build upon the understanding of the hydrogeologic framework. Moreover, additional stations would improve the coverage and monitoring of ground water level response to various pumping stresses on the aquifers from agricultural, industrial and municipal sources. In particular, the effects of stresses from across the Virginia State line are important to monitor, as well as the status of recovery of water levels in the deeper aquifers from the cessation of pumping from International Paper Co. in Franklin, Virginia. Additional monitoring sites would also help to map and monitor the positions of saltwater-freshwater interfaces.

Monitoring network coverage is adequate in Bertie County as a result of construction of the new DWR station at Windsor and the completion of Roxobel station, along with the existing Cremo and Lewiston stations. However, additional coverage is needed in Edgecombe County, northern Martin County near the Town of Oak City, southeastern Halifax, southern Hertford, and eastern Northampton Counties. An additional monitoring well is needed in the Lower Cretaceous Aquifer at the DWR Como Station in northern Hertford County.

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. Additional information has been made available from new DWR ground water monitoring station sites at Windsor, Bertie County and Caledonia Prison, Halifax County, as well as some new wells installed at the pre-existing Roxobel Station in Bertie County. Moreover, new information has been made available through public and private water system wells that have been drilled in the past few years. The US Geological Survey core hole at Hope Plantation, near the town of Windsor in Bertie County, added much needed stratigraphic information to the study area. The descriptions of this core hole (Weems and others, 2007) helped in the identification and correlation of hydrogeologic units in this present study.

The hydrogeologic system in the study region, from basement to land surface, consists of nine 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 and Lower Cretaceous 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.

Of particular interest in the study area are the water level declines that have been occurring in the deeper Cretaceous age aquifers due to withdrawals of up to 43 million gallons per day from the Union Camp Corp. (later International Paper Co.) well field in Franklin, Virginia and other nearby sources. Due to the size and extent of the cones of depression, water levels in the Upper and Lower Cape Fear and Lower Cretaceous Aquifers have been declining at an average rate of about 1 to 2 feet per year in the northern Coastal Plain of North Carolina since heavy pumping began in the late 1940s. The closure of plant operations in 2008 caused water levels in the Lower Cape Fear and Lower Cretaceous aquifers to rebound in North Carolina as indicated by DWR monitoring stations. The ongoing recovery of water levels should prevent the threat of aquifer dewatering, a condition that would have been inevitable in the distant future. However, the recovery could be reversed if additional high volume pumping occurs in southeastern Virginia or in the northern North Carolina Coastal Plain.

This study has also identified numerous places in the region where additional DWR ground water monitoring stations are needed in order to improve coverage of water level trends and knowledge of the hydrogeologic framework.

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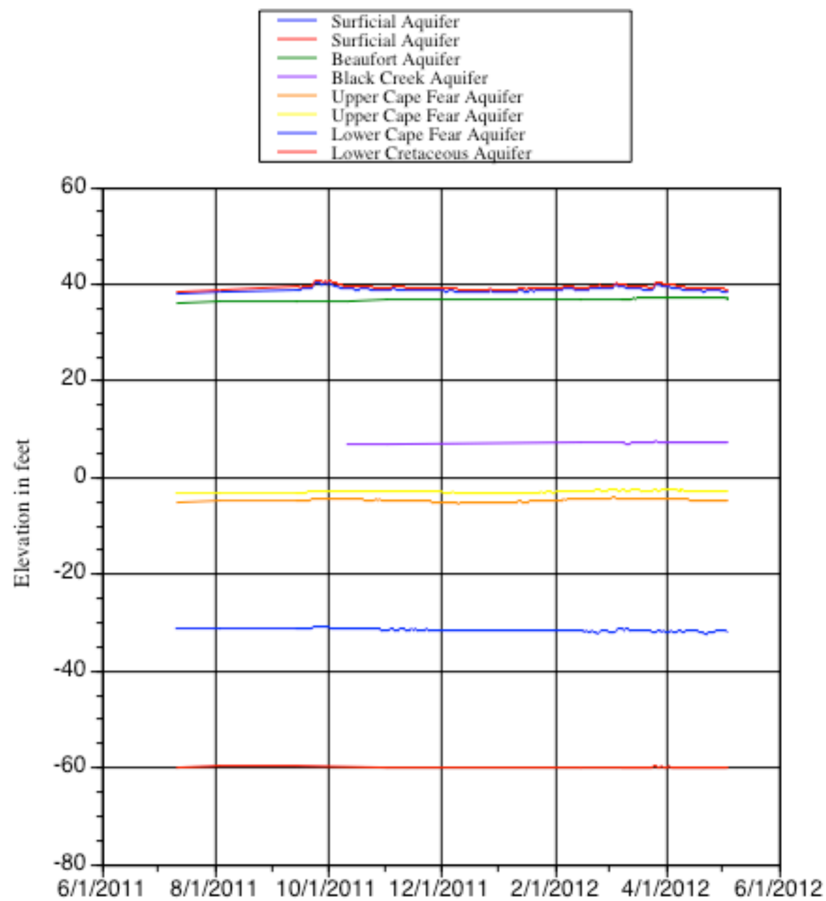


Figure 5: Hydrograph: DWR Windsor Monitoring Station, Bertie County

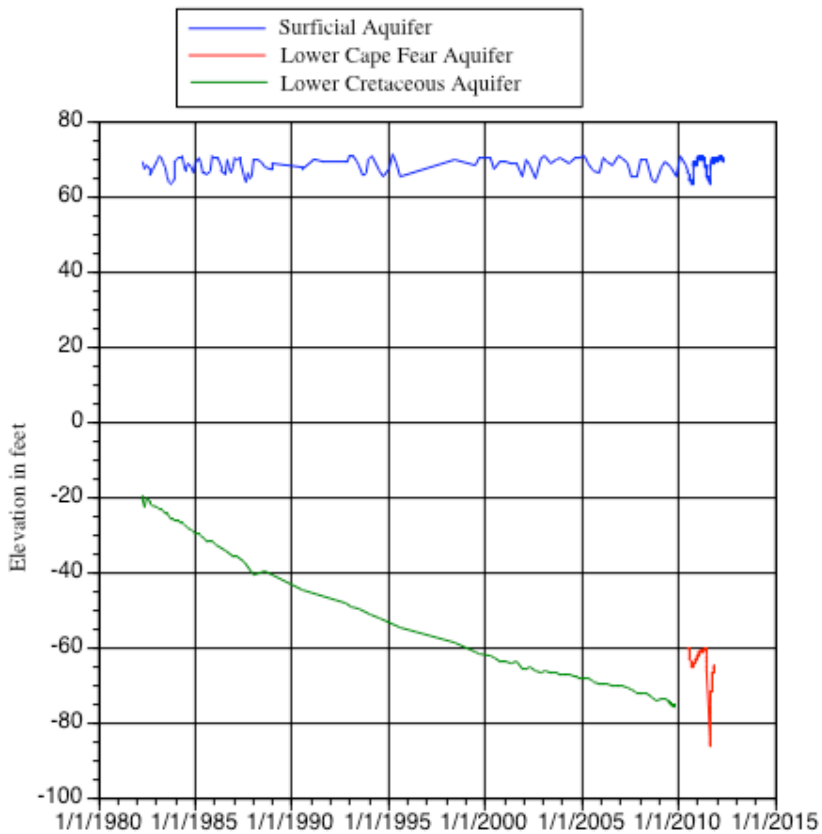


Figure 6: Hydrograph: DWR Roxobel Monitoring Station, Bertie County

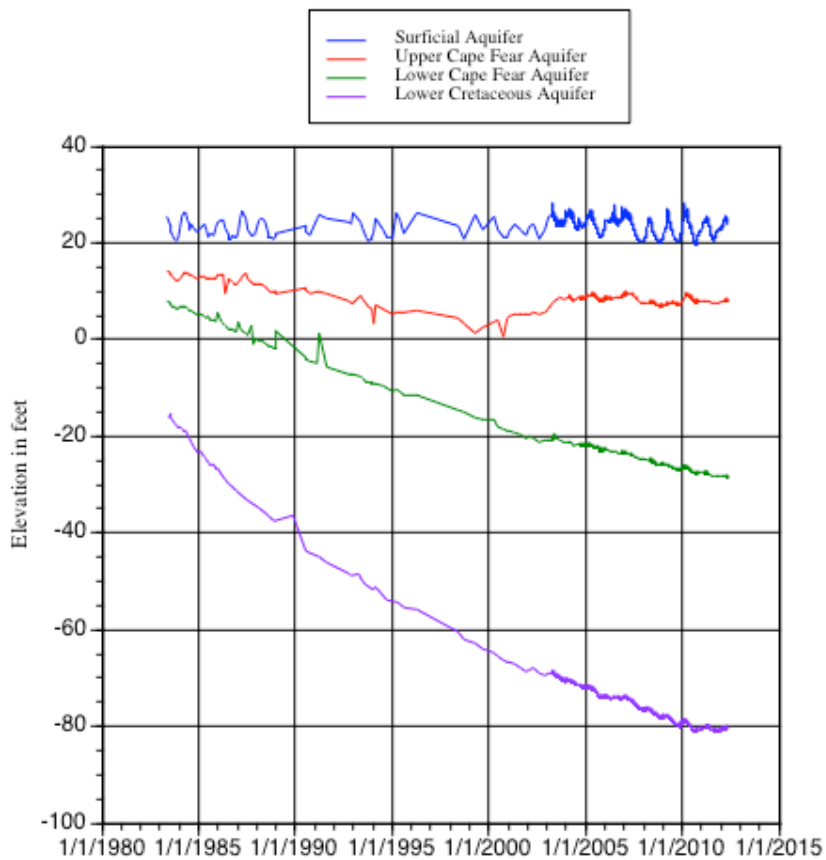


Figure 7: Hydrograph: DWR Lewiston Monitoring Station, Bertie County

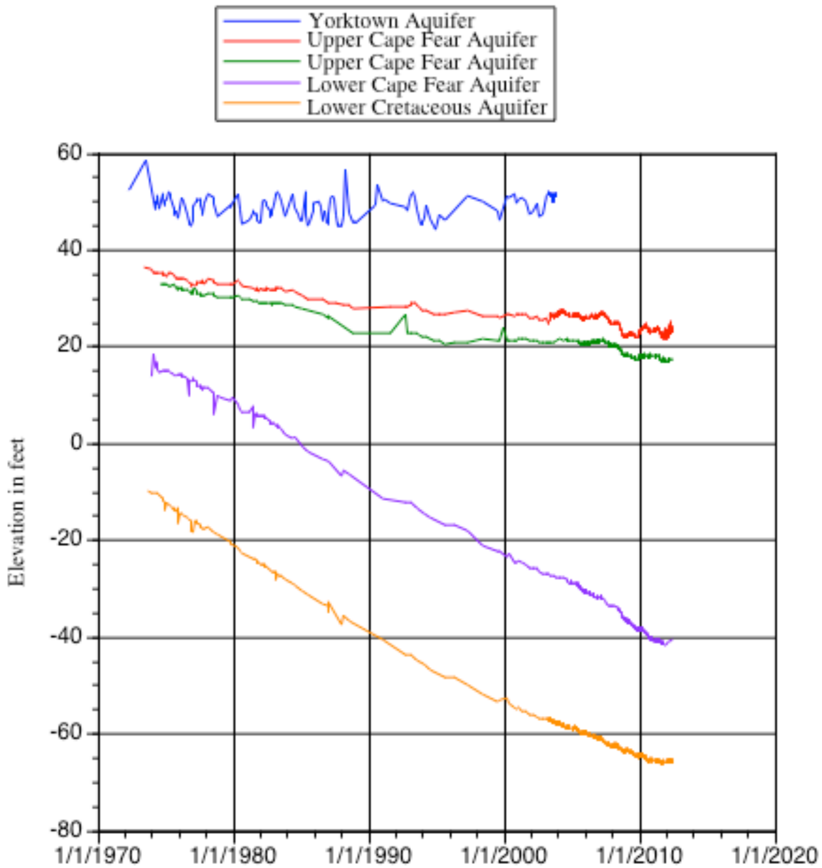


Figure 8: Hydrograph: DWR Cremo Monitoring Station, Bertie County

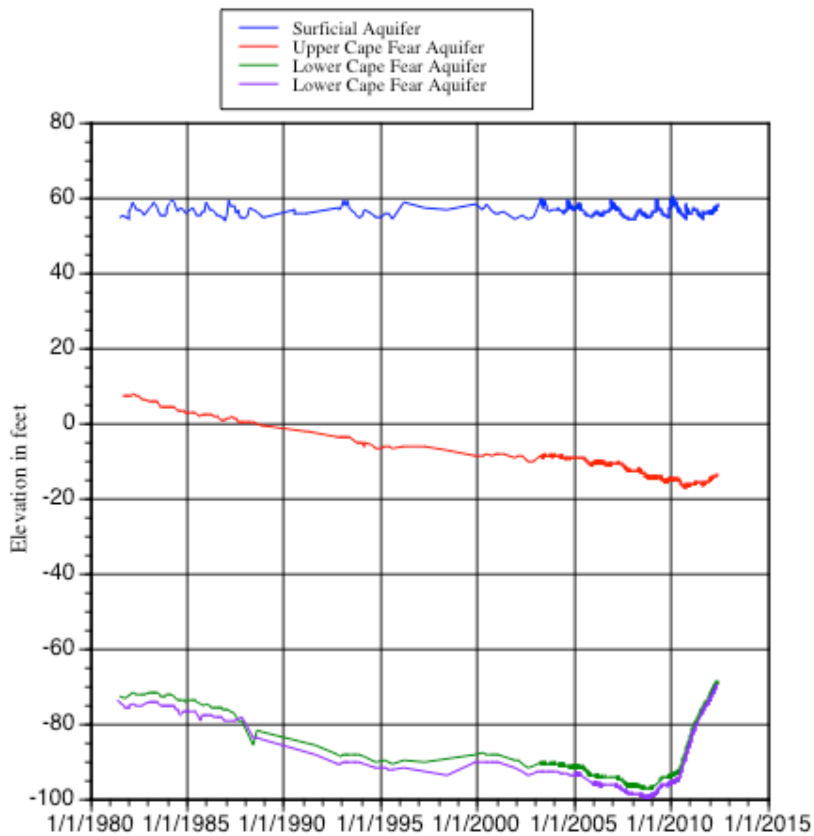


Figure 9: Hydrograph: DWR Como Monitoring Station, Hertford County

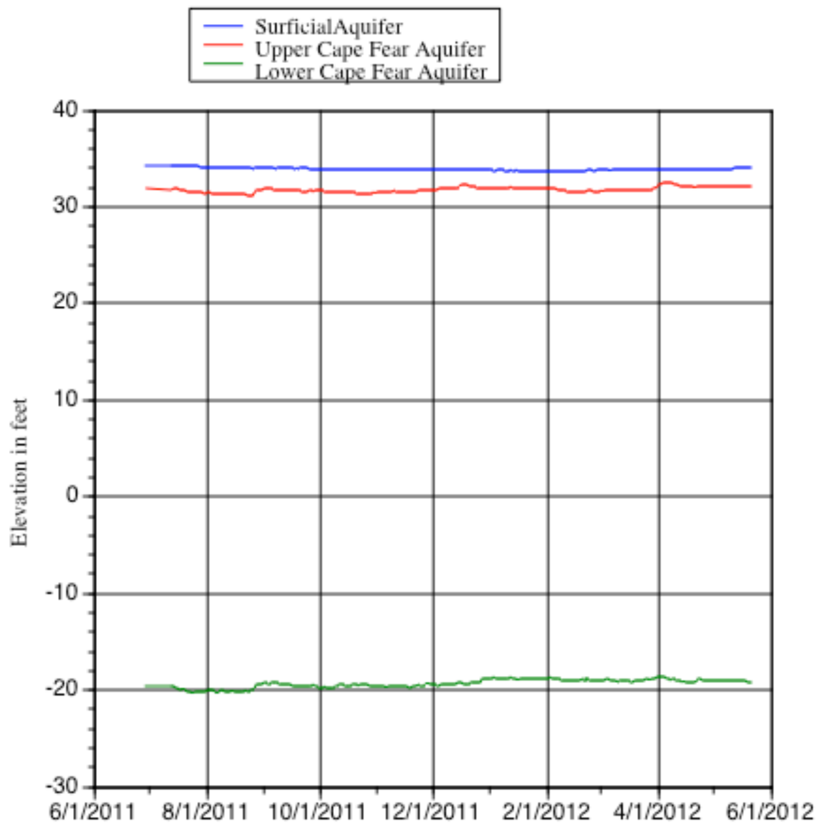


Figure 10: Hydrograph: DWR Caledonia Monitoring Station, Halifax County

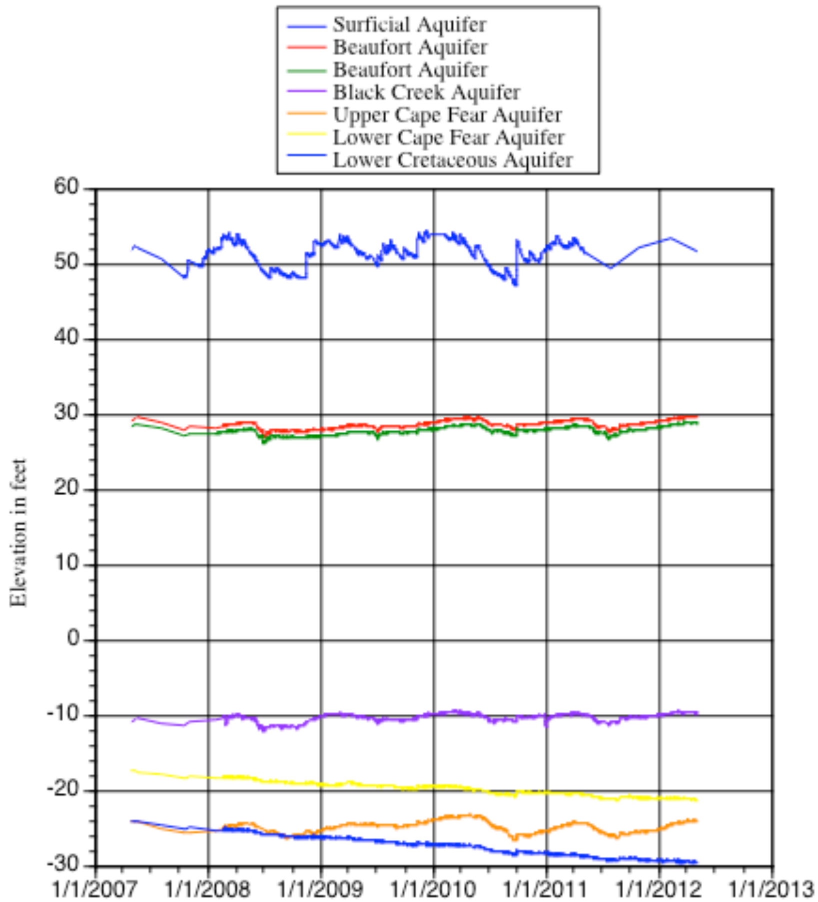


Figure 11: Hydrograph: DWR Bear Grass Monitoring Station, Martin County

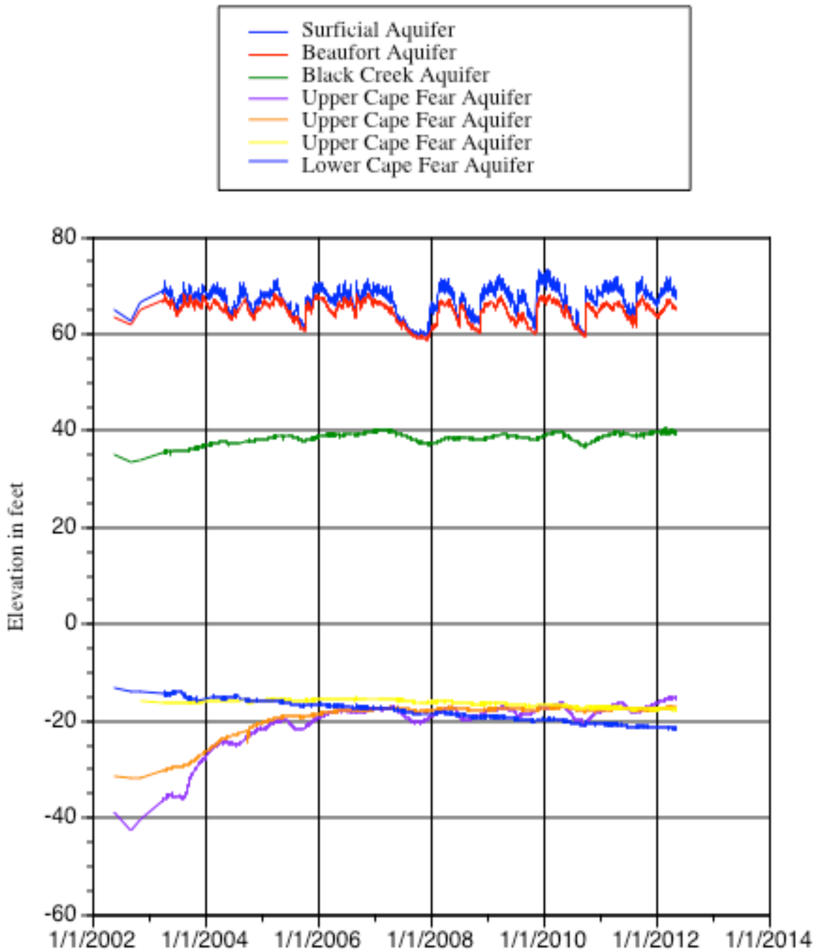


Figure 12: Hydrograph: DWR Gold Point Monitoring Station, Martin County

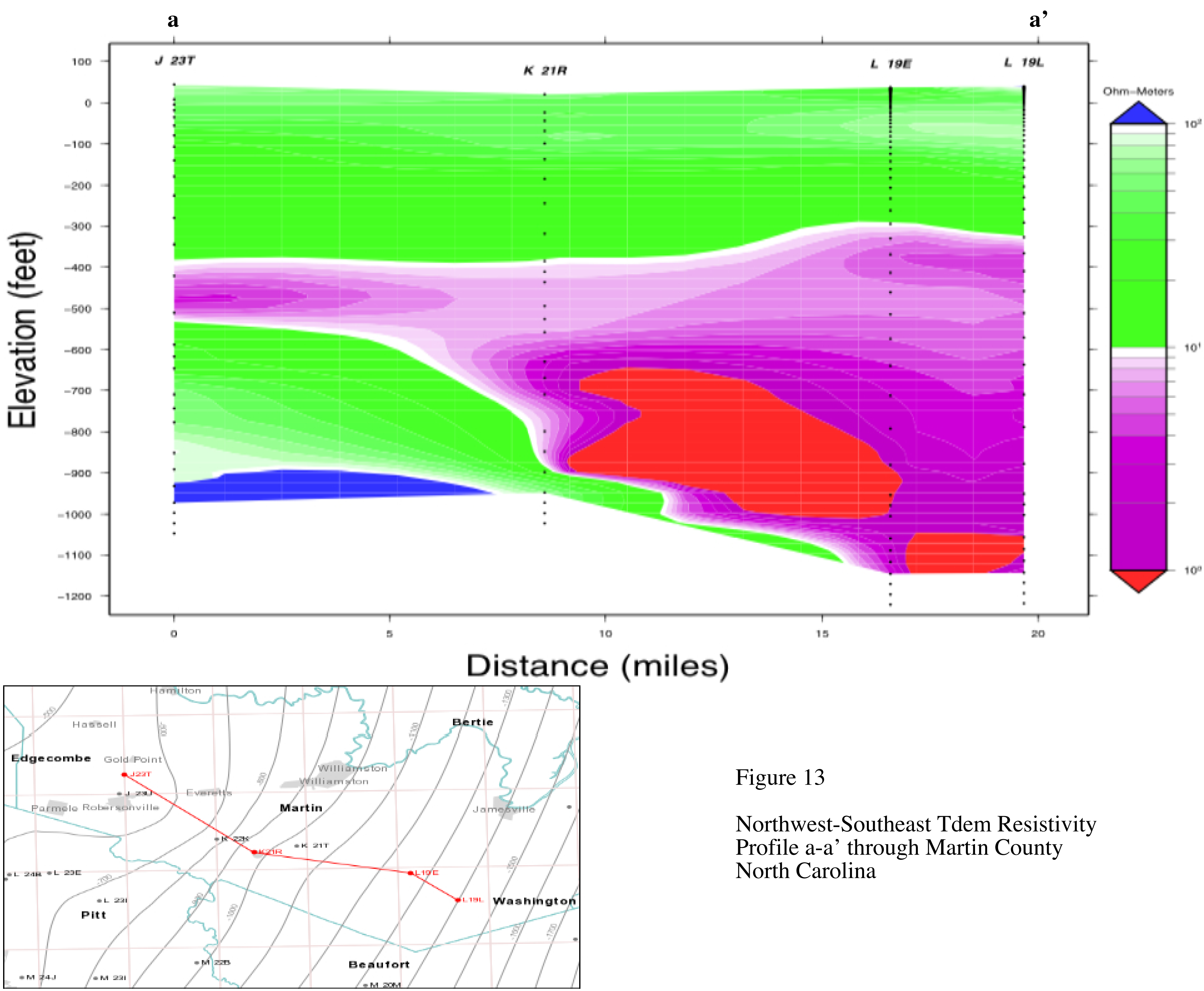
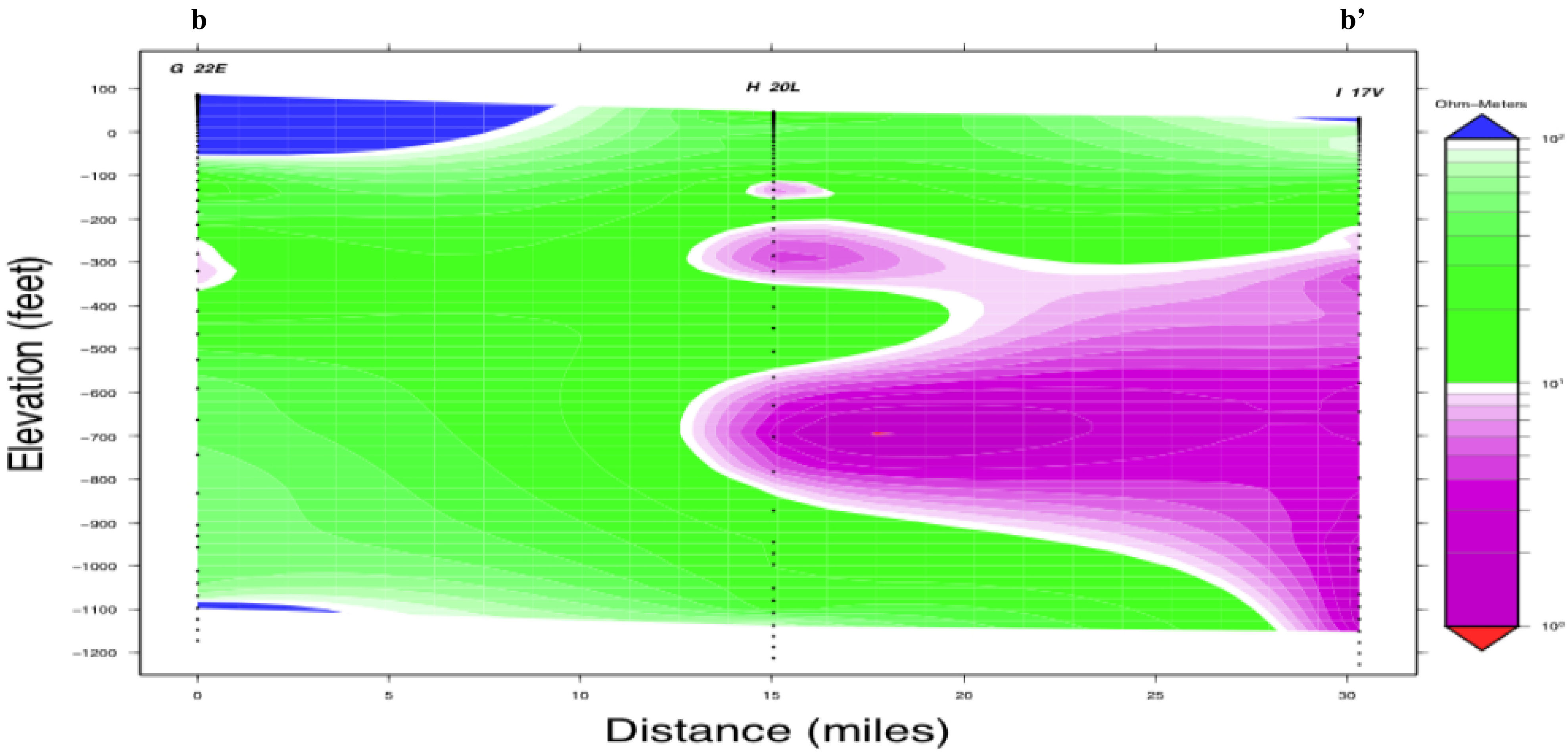


Figure 13

Northwest-Southeast Tdem Resistivity Profile a-a' through Martin County North Carolina



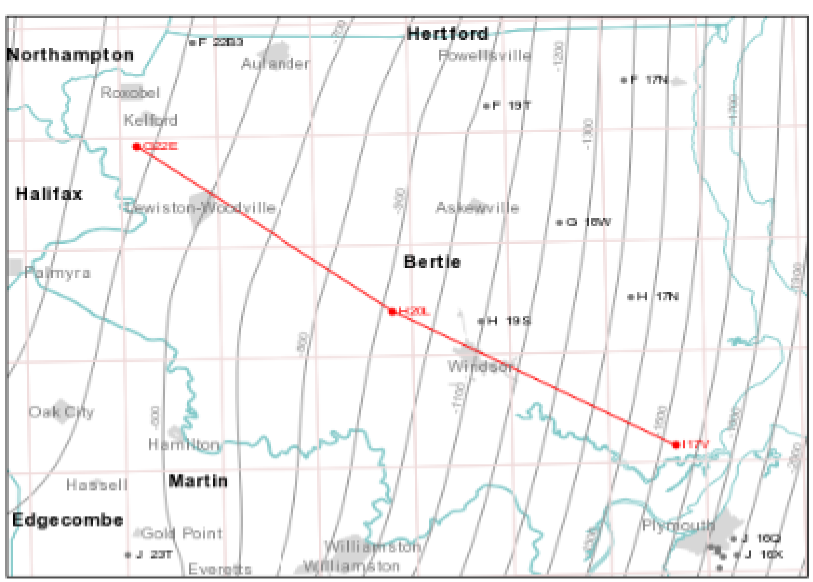
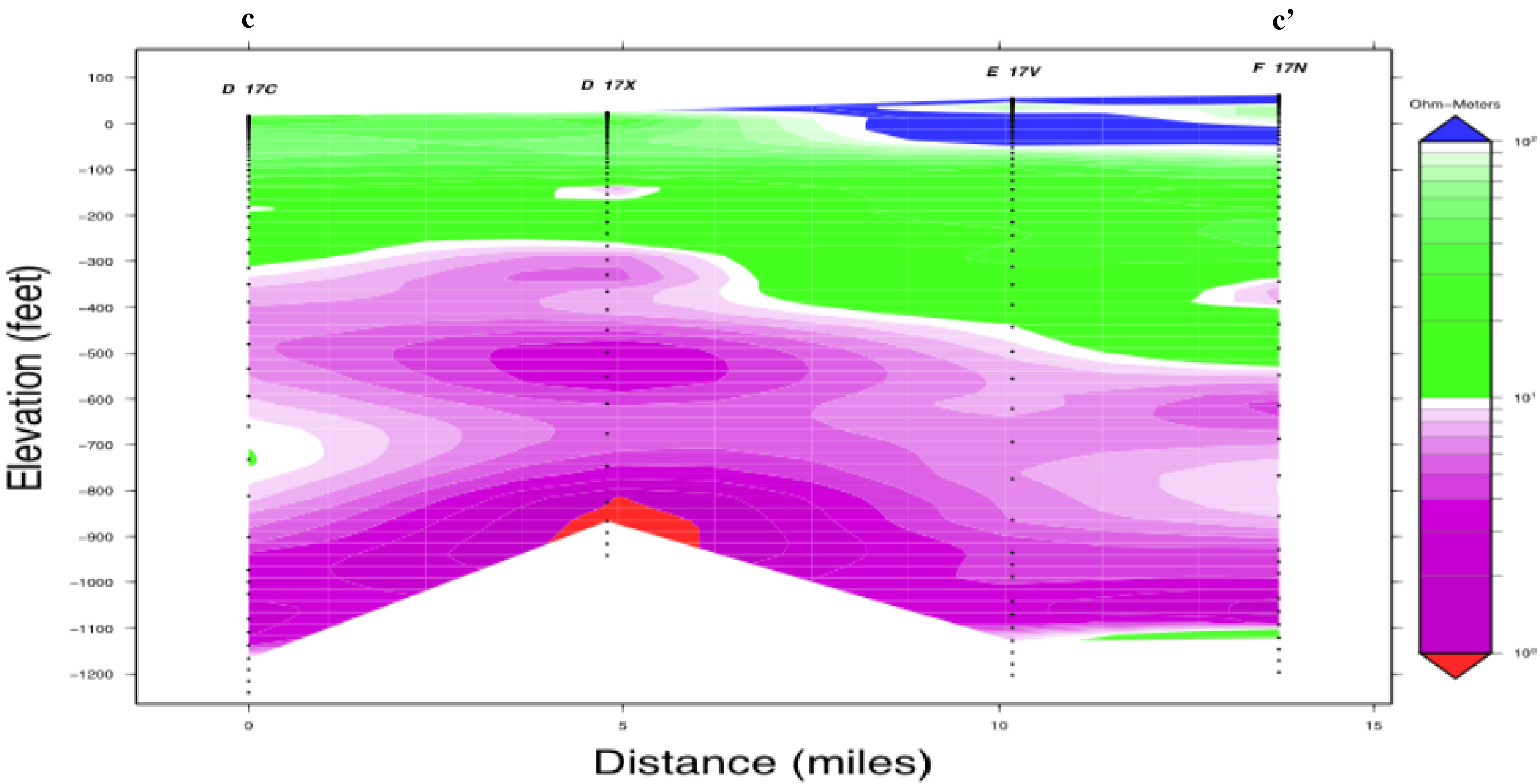


Figure 14

Northwest-Southeast Tdem Resistivity Profile b-b’ through Bertie County North Carolina



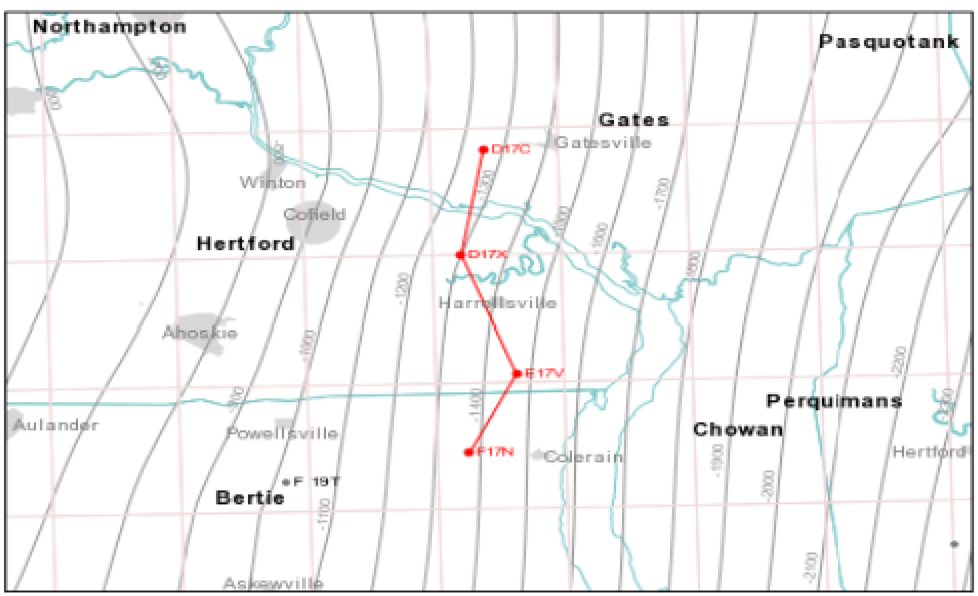


Figure 15

North to South Tdem Resistivity Profile c-c’ through Gates, Hertford, and Bertie Counties , North Carolina