

Prepared in cooperation with the Cape Fear Public Utility Authority

Hydrogeology, Hydraulic Characteristics, and Water-Quality Conditions in the Surficial, Castle Hayne, and Peedee Aquifers of the Greater New Hanover County Area, North Carolina, 2012–13



Scientific Investigations Report 2014–5169

Cover. U.S. Geological Survey hydrologist Laura N. Gurley documenting field activities prior to collecting a water-quality sample from a domestic well near the Intracoastal Waterway, Wilmington, North Carolina. (Photograph by Kristen Bukowski McSwain)

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By Kristen Bukowski McSwain, Laura N. Gurley, and Dominick J. Antolino

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Scientific Investigations Report 2014–5169

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

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Suggested citation:

McSwain, K.B., Gurley, L.N., and Antolino, D.J., 2014, Hydrogeology, hydraulic characteristics, and water-quality conditions in the surficial, Castle Hayne and Peedee aquifers of the greater New Hanover County area, North Carolina, 2012–13: U.S. Geological Survey Scientific Investigations Report 2014–5169, 52 p., <http://dx.doi.org/10.3133/sir20145169>.

ISSN 2328-0328 (online)

Acknowledgments

The authors thank the many homeowners who graciously allowed access to their wells for the purpose of measuring water levels and collecting water samples for this study. In addition, the authors thank the golf course superintendents who operate irrigation wells, large-water users who operate industrial-supply wells, and water purveyors who operate public-supply wells in Brunswick and New Hanover Counties for allowing access to their wells and records. Thanks also go to Nat Wilson with the North Carolina Department of Environment and Natural Resources Division of Water Resources for allowing the authors to access monitoring wells across southeastern North Carolina. The authors also thank Gary McSmith, John Malone, and Frank Styers of Cape Fear Public Utility Authority for their support of and assistance with this investigation.

Gratitude is extended to the following USGS personnel who assisted with this report through collection of field data and technical review: John Erbland, W. Fred Falls, Jason Fine, Edyth Hermosillo, Katharine Kolb, Eric Sadorf, Jason Sorenson, A. Gerald Strickland, and Chad Wagner.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m ²)
square foot (ft ²)	0.09290	square meter (m ²)
square inch (in ²)	6.452	square centimeter (cm ²)
square mile (mi ²)	2.590	square kilometer (km ²)
Volume		
gallon (gal)	3.785	liter (L)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
Flow rate		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
cubic foot per day (ft ³ /d)	0.02832	cubic meter per day (m ³ /d)

SI to Inch/Pound

Multiply	By	To obtain
Volume		
liter (L)	0.2642	gallon (gal)
cubic meter (m ³)	264.2	gallon (gal)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

Abbreviations

CFPUA	Cape Fear Public Utility Authority
DEMs	digital elevation models
DO	dissolved oxygen
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
GMWL	Global Meteoric Water Line
GWSI	Groundwater Site Inventory
Lidar	light detection and ranging
LMWL	Local Meteoric Water Line
MCL	maximum contaminant level
NC ACP	North Carolina Atlantic Coastal Plain
NCDENR	North Carolina Department of Environment and Natural Resources
NCDENR DWR	North Carolina Department of Environment and Natural Resources Division of Water Resources
NED	National Elevation Dataset
NLCD	National Land Cover Database
NWQL	National Water Quality Laboratory
PVC	polyvinyl chloride
QA/QC	quality assurance and quality control
RSIL	Reston Stable Isotope Laboratory
SDWS	secondary drinking water standards
USACOE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water

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Abstract

A major issue facing the greater New Hanover County, North Carolina, area is the increased demand for drinking water resources as a result of rapid growth. The principal sources of freshwater supply in the greater New Hanover County area are withdrawals of surface water from the Cape Fear River and groundwater from the underlying Castle Hayne and Peedee aquifers. Industrial, mining, irrigation, and aquaculture groundwater withdrawals increasingly compete with public-supply utilities for freshwater resources. Future population growth and economic expansion will require increased dependence on high-quality sources of fresh groundwater.

An evaluation of the hydrogeology and water-quality conditions in the surficial, Castle Hayne, and Peedee aquifers was conducted in New Hanover, eastern Brunswick, and southern Pender Counties, North Carolina. A hydrogeologic framework was delineated by using a description of the geologic and hydrogeologic units that compose aquifers and their confining units. Current and historic water-level, water-quality, and water-isotope data were used to approximate the present boundary between freshwater and brackish water in the study area.

Water-level data collected during August–September 2012 and March 2013 in the Castle Hayne aquifer show that recharge areas with the highest groundwater altitudes are located in central New Hanover County, and the lowest are located in a discharge area along the Atlantic Ocean. Between 1964 and 2012, groundwater levels in the Castle Hayne aquifer in central New Hanover County have rebounded by about 10 feet, but in the Pages Creek area groundwater levels declined in excess of 20 feet. In the Peedee aquifer, the August–September 2012 groundwater levels were affected by industrial withdrawals in north-central New Hanover County. Groundwater levels in the Peedee aquifer declined more than 20 feet between 1964 and 2012 in northeastern New Hanover County because of increased withdrawals. Vertical gradients calculated between

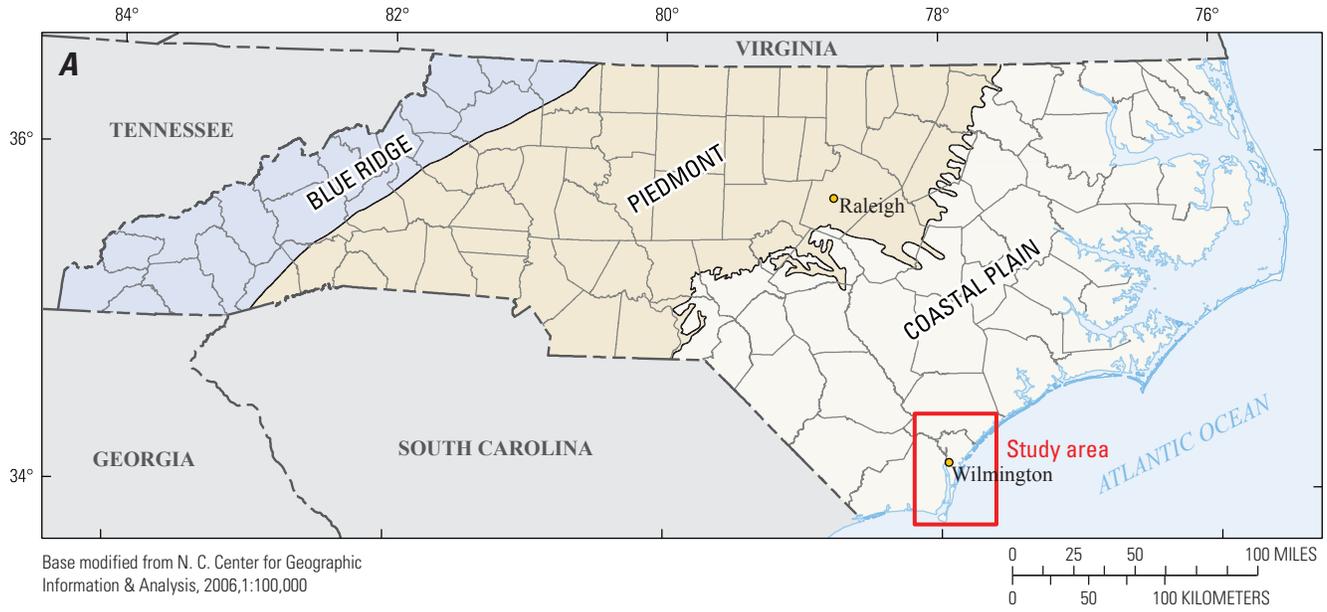
the Castle Hayne and Peedee aquifers at six well cluster sites were downward in August–September 2012 and March 2013 with the exception of one well pair that had a slight upward gradient in March 2013.

Major ion chemistry results from samples collected in August–September 2012 from 97 well sites suggest that seawater is mixing with groundwater in both the Castle Hayne and Peedee aquifers in several locations in Brunswick, New Hanover, and Pender Counties. The 250 milligram per liter line of equal chloride concentration has moved inland in both aquifers since 1965, with the area between Futch and Pages Creeks in northeastern New Hanover County experiencing the greatest increase. Groundwater from the surficial, Castle Hayne, and Peedee aquifers had a stable isotope of water composition similar to that of modern precipitation. A comparison of chloride concentration data collected from public-supply wells in the 1960s with that collected in 2012 shows marked increases in chloride concentrations in the Peedee aquifer near the town of Carolina Beach at the southern end of New Hanover County.

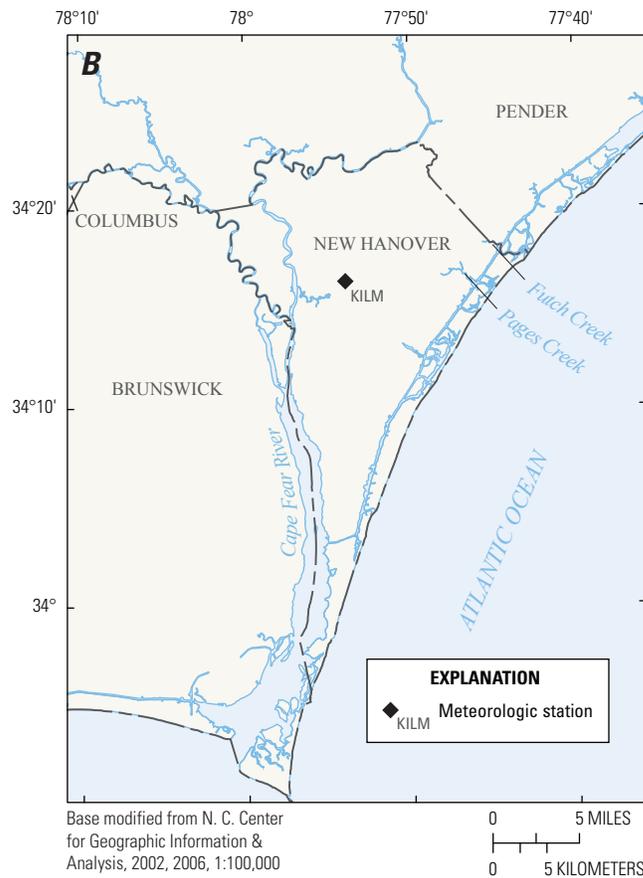
Introduction

New Hanover County is located on the southeastern coast of North Carolina in the Coastal Plain Physiographic Province and is surrounded on two sides by saline waters of the tidally affected Cape Fear River and the Atlantic Ocean (fig. 1). The county is one of the most populated areas along the North Carolina coastline, with a population of 202,667 in 2010 (U.S. Census Bureau, 2012). Population in the area grew steadily from 1970 (population 82, 996; U.S. Bureau of the Census, 1982) to 1990 (population 120,284; U.S. Census Bureau, 2002). However, growth in the area exploded with the completion of the Interstate 40 connector from Wilmington to Raleigh in 1990 (Wilmington Star News, 2013). This growth is expected to continue, with the population projected to increase by more than 38 percent in New Hanover County

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Base modified from N. C. Center for Geographic Information & Analysis, 2006, 1:100,000



Base modified from N. C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000

Figure 1. Location of the *A*, study area in the Coastal Plain Physiographic Province of North Carolina and *B*, area of maps in figures 2, 3, 5–10, 12–14, 19–22, and 25–30.

through 2030 (North Carolina Office of State Budget and Management, 2014). These population figures do not include the many seasonal tourists who visit the area's beaches and golf courses.

Future growth in the New Hanover County area will increase the demand for drinking water resources, one of the major issues facing the Coastal Plain area of North Carolina. Because of long-term over pumping, groundwater levels in the Cretaceous-aged Peedee, Black Creek, and Upper Cape Fear aquifers of the Central Coastal Plain of North Carolina in counties to the north of New Hanover County have declined substantially over the past 30 years (Lautier, 2001). To date, New Hanover County is not required to participate in the Central Coastal Plain Capacity Use Area water-withdrawal restrictions delineated under 15A North Carolina Administrative Code 2E .0501 (North Carolina Department of Environment and Natural Resources, 2013), because effects of over pumping and saltwater intrusion have not been noted in the Wilmington area.

The water-supply utilities in New Hanover County rely on a combination of surface water and groundwater to meet needs for potable water. However, industrial, mining, irrigation, and aquaculture groundwater withdrawals increasingly compete with public-supply utilities for freshwater resources. Proposed deepening of the shipping channel in Wilmington Harbor has the potential to alter nearby groundwater flow and potentially facilitate a direct pathway for saltwater intrusion into fresh groundwater. Future population growth and economic expansion in New Hanover County will require increased dependence on supplemental groundwater supplies.

In October 2011, the Cape Fear Public Utility Authority (CFPUA) and the U.S. Geological Survey (USGS) entered into a cooperative agreement to conduct a study of the groundwater resources of the surficial, Castle Hayne, and Peedee aquifers in the greater New Hanover County area to better understand how population growth in the Wilmington area has affected the quantity and quality of groundwater. It has been more than 40 years since the last comprehensive study of groundwater conditions in New Hanover County was conducted (Bain, 1970). Results from the current investigation will provide water-resource planners with an improved database and better understanding of water-quality conditions to manage and sustain drinking water resources in this densely populated coastal area.

Purpose and Scope

This report describes the results of an investigation of the hydrogeology and water quality of the surficial, Castle Hayne, and Peedee aquifers in the New Hanover County area, including southern Pender and eastern Brunswick Counties, North Carolina. The hydrogeology is described by the delineation of a hydrogeologic framework that is based on the analysis and interpretation of lithologic data, geophysical logs, groundwater levels, and water-quality and stable-isotope data.

Historic regional study information on the surficial, Castle Hayne, and Peedee aquifers was compiled and integrated with new water-level and water-quality data collected for this study.

Description of the Study Area

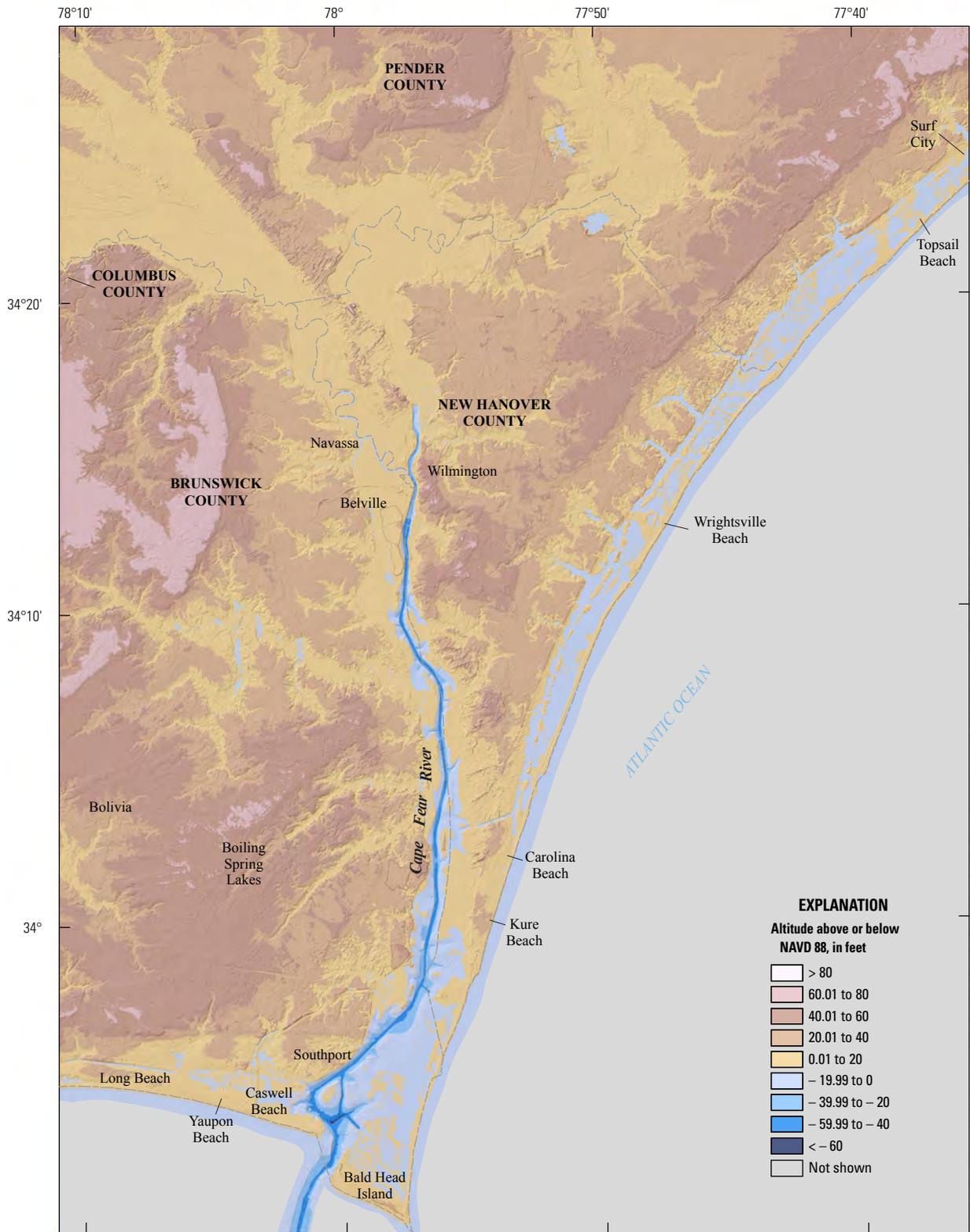
Brunswick, New Hanover, and Pender Counties are located in southeastern North Carolina within the Coastal Plain Physiographic Province (fig. 1). The Cape Fear River forms the county boundary between most of Brunswick County and New Hanover County, and the Northeast Cape Fear River separates most of Pender County from New Hanover County. New Hanover and Pender Counties are bounded to the east by the Atlantic Ocean. The Cape Fear River and major coastal streams are occasionally brackish because of estuarine water that is pushed upstream by storms, winds, and tides. The study area encompasses 1,488 square miles (mi²) of which 626 mi² are surface water (fig. 1).

The topography of the study area is relatively flat. The topographic high occurs in north-central Brunswick County at an altitude of 99 feet (ft) above the North American Vertical Datum of 1988 (NAVD 88) (fig. 2). Areas of Brunswick, New Hanover, and Pender Counties are characterized by karst topography, containing numerous sinkholes and depressional wetlands. These depressional wetlands contain water seasonally, but most were dry during the summer of 2012 when samples were collected for this study. Although no active sinkholes were noted during the course of this 2-year study, several sizeable sinkholes within the study area have affected area residents in the recent past (Wilmington Star News, 2001 and 2002). Many additional examples of relic sinkhole features can be easily identified across Brunswick, Pender, and New Hanover Counties.

The Cape Fear River is dredged by the U.S. Army Corps of Engineers (USACE) in order to maintain the shipping channel at a navigable depth of 44 ft. The river is dredged on a 2-year maintenance cycle, depending on the availability of Congressional funding. In between dredging cycles, the USACE regularly publishes updated hydrographic survey maps of the Cape Fear River (U.S. Army Corps of Engineers, 2012). Digital hydrographic bathymetry survey data collected by the USACE from January 2012 to February 2012 were tide adjusted and integrated with the digital topographic elevation model to form a seamless digital elevation surface (fig. 2). This elevation surface was also used in the construction of geologic sections.

In the greater New Hanover County area, the climate is subtropical with hot, rainy summers, punctuated by tropical storms and hurricanes, and relatively mild winters. The average annual rainfall measured at the New Hanover County Airport (station KILM) was 55.2 inches (in.) during the period January 1949 to December 2012, and ranged from a minimum of about 33 in. in 2007 to a maximum of about 72 in. in 1999 (State Climate Office of North Carolina, 2013; fig. 1B). In general, November is the driest month of the year and July

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Base modified from N.C. Center for Geographic Information & Analysis, 2006, 1:100,000
Elevation modified from U. S. Geological Survey

0 5 MILES
0 5 KILOMETERS

Figure 2. Topography of Brunswick, New Hanover, and Pender Counties and bathymetry of the Cape Fear River, North Carolina.

is the wettest. Mean monthly air temperatures range from 7.7 degrees Celsius (°C) in January to 26.7 °C in July (State Climate Office of North Carolina, 2013). Tropical storms regularly affect the greater New Hanover County area from June to November, though a direct impact from a hurricane has not occurred since Hurricane Charley made landfall near the Wilmington area in August 2004.

Land Use and Land Cover in the Study Area

Land use affects the quantity and quality of available freshwater. The recharge, discharge, and water quality of the surficial aquifer have been altered by urbanization; development of residential communities with septic systems; increased impervious surface area through building parking lots and roadways; industrialization of service stations, landfills, and quarries; and fertilization of lawns, golf courses, and agricultural crops. Current land use in the study area was evaluated using the 2006 National Land Cover Database (NLCD) maps (Fry and others, 2011) (fig. 3). More than 70 percent of land use for each county in the study area can be characterized using three categories (excluding open water). Brunswick County contains the highest percentage of forested area in the study area at 30 percent, 28 percent wetlands, and 15 percent scrub and grasslands. New Hanover County has the highest percentage of urban land use (36 percent), 23 percent wetlands, and 15 percent forests. Pender County has the highest percentage of wetlands at 42 percent, 25 percent forests, and 16 percent scrub and grasslands. Agricultural and barren land categories together make up less than 10 percent for all three counties.

About 25 percent of the wetlands in the study area are tidally influenced saltwater wetlands. The major saltwater wetlands are located in tidal marshes between the mainland area of New Hanover and Pender Counties and their barrier islands, as well as on both banks of the Cape Fear River, extending westward into Brunswick County. Groundwater in the surficial aquifer of the saltwater wetlands is too salty to be drinkable. Large areas of freshwater wetlands, such as marshes and swamps that are wet most of the year, are located throughout central Pender and Brunswick Counties, as well as northern New Hanover County.

The principal sources of freshwater supply in New Hanover, Brunswick, and Pender Counties are withdrawals of surface water from the Cape Fear River and groundwater from the underlying Castle Hayne and Peedee aquifers. The largest potable water suppliers in the study area—Brunswick County Utilities, Pender County Utilities, and CFPWA—withdraw water from the Cape Fear River to process into drinking water and distribute throughout most of Brunswick, Pender, and New Hanover Counties. Relatively small groundwater plants operated by Brunswick County Utilities and CFPWA pump water from the Castle Hayne and Peedee aquifers to augment supply in areas not serviced by surface-water

distribution systems or during times of peak water use. The barrier island communities of Topsail Beach, Wrightsville Beach, Carolina Beach, Kure Beach, and Bald Head Island depend on groundwater as a source of drinking water and also pump water from the Castle Hayne or Peedee aquifer. Several small local water suppliers pump groundwater wells to distribute water to subdivisions. In 2005, public-supply groundwater use was 3.90 million gallons per day (Mgal/d) for Brunswick County, 8.01 Mgal/d for New Hanover County, and 1.45 Mgal/d for Pender County. Self-supplied groundwater use in 2005 for Brunswick, New Hanover, and Pender Counties was 0.79, 1.15, and 2.32 Mgal/d, respectively (U.S. Geological Survey, 2008).

Previous Investigations

Many studies have been conducted on the geology, hydrology, and water quality of the surficial, Castle Hayne, and Peedee aquifers in the greater Wilmington area over the last 50 years. Gellici and Lautier (2010) defined the hydrogeologic framework of aquifers and confining units that make up the Atlantic Coastal Plain of North and South Carolina. Units were described by geometry, lithology and texture, hydrologic properties, and geophysical-log response.

An evaluation of the hydrogeology of the southeastern coastal plain of North Carolina was conducted by Lautier (2006), including Pender, Brunswick, and New Hanover Counties. The report includes 21 hydrogeologic cross sections of the coastal plain sediments from the surface to the Paleozoic-age basement rock and summarizes groundwater conditions for all monitored aquifers.

Harden and others (2003) conducted a study to evaluate the hydrogeologic framework, ground-water flow system, and quality of water in Brunswick County, North Carolina. The surficial, Castle Hayne, and Peedee aquifers were investigated.

Woods and others (2000) used natural geochemical tracers, including stable isotopes of oxygen, to study ground-water movement in the Castle Hayne aquifer in the coastal plain of North Carolina, including sampling sites in Brunswick and Pender Counties. They measured stable oxygen isotope values in the recharge area that were similar to values of Holocene-age meteoric water; however, near the coast, values increased by about 2 per mil (‰).

A groundwater study was conducted by Lautier (1998) to determine if deepening the shipping channel in Wilmington Harbor would have detrimental effects on the underlying aquifer system. Groundwater models showed that the proposed channel deepening would not adversely alter water-level gradients to induce saltwater intrusion from the Cape Fear River.

Winner and Coble (1996) delineated 10 aquifers and 9 confining units to create a hydrogeologic framework for the North Carolina Coastal Plain. Their report included 18 interconnected hydrogeologic sections as well as information about the occurrence of saltwater.

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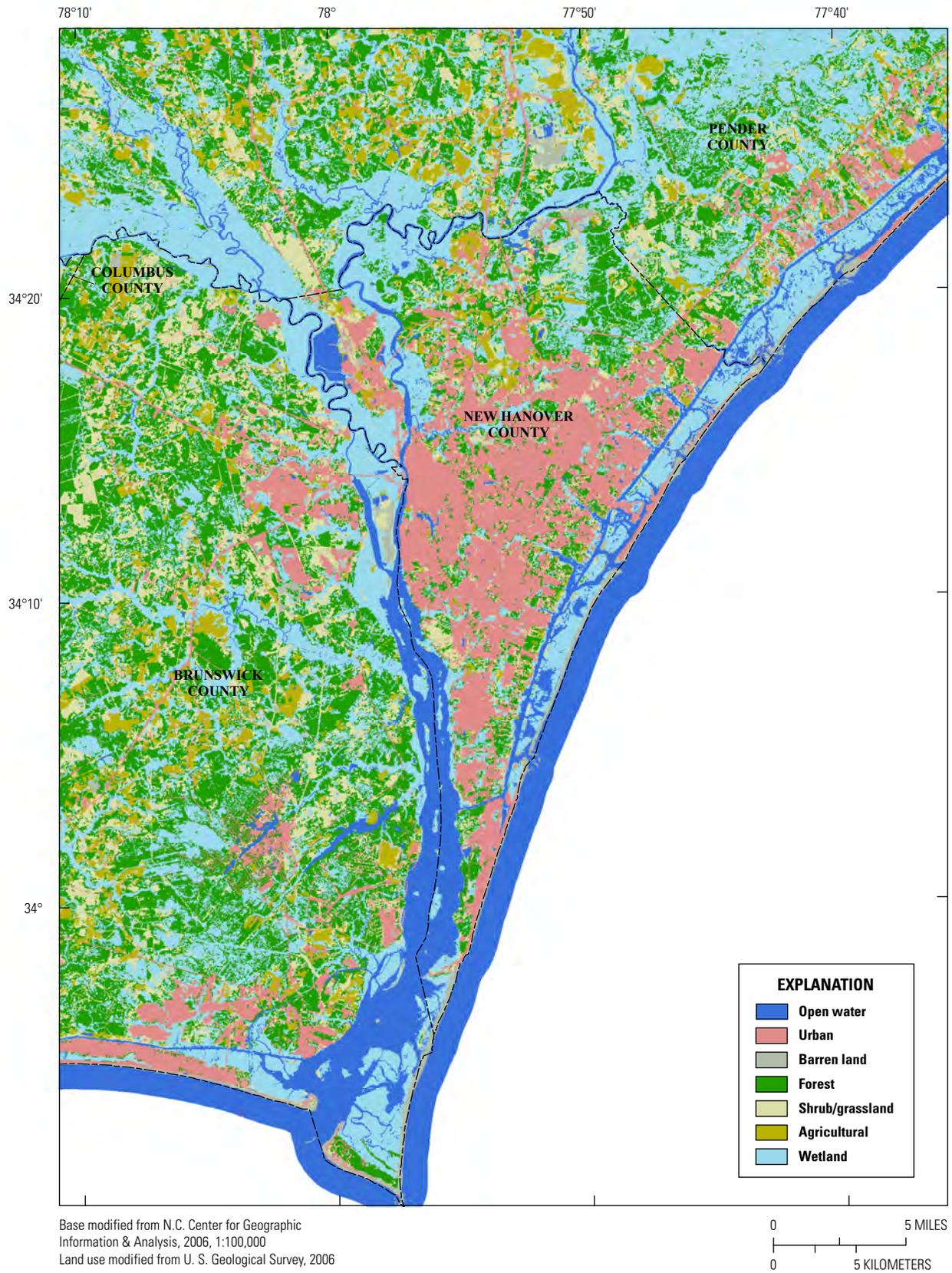


Figure 3. Land use and land cover in Brunswick, New Hanover, and Pender Counties, North Carolina.

A reconnaissance study in Brunswick and New Hanover Counties, North Carolina, was conducted by Zarra (1991) to identify and delineate Cenozoic-age formations and informal stratigraphic units. Eight geologic units were described. Four structure contour maps, three isopach maps, and six geologic sections were constructed to describe the subsurface stratigraphy.

Bailey (1984) determined that the surficial and Castle Hayne aquifers were the primary aquifers used for water supply (in 1984) in Brunswick, New Hanover, and Southern Pender Counties. Reported well yields in the surficial aquifer typically were less than 10 gallons per minute (gal/min), and water quality often was affected by high iron concentrations and acidity. Use of the Castle Hayne aquifer for water supply could be limited by water with a chloride concentration exceeding 250 mg/L, but well yields could exceed 300 gal/min.

Bain (1970) conducted the first comprehensive assessment of New Hanover County's groundwater resources. A hydrogeologic framework was constructed, delineating the surficial, Castle Hayne, and Peedee aquifers. Groundwater availability was noted to vary from one part of the county to another, but at that time the quantity of groundwater being withdrawn was a small part of the available supply. Water quality in all three aquifers was found to be acceptable throughout much of the county but was susceptible to salt-water intrusion near the Atlantic Ocean and Cape Fear River.

A reconnaissance of groundwater resources in the New Bern and Wilmington area was conducted by LeGrand (1960). The Castle Hayne aquifer was identified by LeGrand as an underutilized source of groundwater supply for Pender and New Hanover Counties.

Methods of Investigation

This section provides a discussion of the methods used to delineate the hydrogeologic framework within eastern Brunswick, southern Pender, and New Hanover Counties. Methods used to measure groundwater levels, collect groundwater samples, and analyze geochemical data are also discussed.

Well Numbering System

Wells inventoried by the USGS were assigned unique 15-digit site identification numbers on the basis of their geographic location. The first 13 digits of the well site identification number represent the latitude and longitude of the well and are followed by a 2-digit sequence number to differentiate between wells that are clustered together.

In addition to site identification numbers, wells were assigned station names. For this study, the first two letters of the station name represent the county where the well is located (NH, PE, or BR for New Hanover, Pender, or Brunswick

County, respectively). The 2-letter county abbreviation is followed by a hyphen and a 3-digit county sequence number. The final part of the station name includes the name of a nearby municipal location and the name of the aquifer in which the well is completed.

Well Data and Well Construction

Wells and borings inventoried for this study were used for water-quality, water-level, and (or) hydrostratigraphic framework analysis. Data from more than 240 wells located in New Hanover, eastern Brunswick, and southern Pender Counties were inventoried for this study, including domestic, public water supply, industrial, other large water users, and monitoring wells. Paper and electronic well records were obtained from the USGS National Water Information System, North Carolina Department of Environment and Natural Resources Division of Water Resources (NCDENR DWR), County Environmental Health Departments, well owners, and well tag labels. Well construction, owner, and location data were compiled. Latitude and longitude data were measured in the field, reported, and (or) estimated using Google Earth™. All data collected as part of this study were reviewed, and new data were uploaded into the USGS Groundwater Site Inventory (GWSI) database.

Inventoried wells were completed in either the surficial, Castle Hayne, Peedee, or Black Creek aquifers. Construction dates for each well ranged from 1967 to 2013. Domestic wells were predominantly cased with polyvinyl chloride (PVC) casing and ranged in diameter from 1.25 to 6 in. depending on the age and use of the well. Smaller wells generally were installed for lawn irrigation and larger wells for domestic supply. These domestic irrigation and supply wells were commonly equipped with a jet pump rather than a submersible pump, because the water level typically is close to land surface. Wells of large water users, such as golf courses, residential subdivisions, and industries, were cased with either PVC or steel and ranged in diameter from 4 to 14 in. Monitoring wells were constructed with PVC or steel casing ranging in diameter from 2 to 14 in. Most wells were constructed such that they were screened in only one aquifer; however, a few of the domestic-supply wells inventoried in New Hanover County installed in the early 1990s were screened in both the Castle Hayne and the Peedee aquifer. Water samples collected from wells screened in both the Castle Hayne and Peedee aquifer were chemically similar to water samples collected from wells screened in only the Peedee aquifer; therefore, results of dissolved iron, chloride, and stable isotopes of oxygen analyses for water samples collected from the Castle Hayne/Peedee aquifer were grouped together with Peedee aquifer samples. Similarly, water-level measurements collected at wells screened in both the Castle Hayne and Peedee aquifers were grouped with water-level measurements collected at wells screened in unconfined areas of the Peedee aquifer.

Measurement of Groundwater Levels

Water-level measurements were conducted in 71 wells during August and September 2012 and 69 wells during March 2013 in order to observe seasonal changes within the surficial, Castle Hayne, and Peedee aquifers throughout the study area. Water levels were measured during the summer season in August and September of 2012 when the aquifers were more likely to be stressed, and in March 2013 when the aquifers likely would have seen some degree of precipitation recharge during the wet season. Measurements were made using a chalked graduated steel tape, electric water-level tape, or an acoustic-sounding meter. Both the steel tape and electric tape methods yield a data accuracy within 0.01 ft and are consistent with techniques described in Cunningham and Schalk (2011). The acoustic-sounding meter method yields data that are accurate to the nearest 1 ft and was only employed when other more accurate methods were not feasible.

Water-level measurements at each site were made from a determined measuring point below, at, or above land surface. Water levels were entered into the GWSI database and were reported as feet below land surface. The water-level measurements were also related to land-surface altitude measurements, most of which were obtained from the National Elevation Dataset (NED). The NED is based on source data from several local digital elevation models (DEMs) with an overall absolute vertical accuracy expressed as the root mean square error of 8.00 ft (2.44 meters) (Gesch, 2007). The underlying local light detection and ranging (lidar) data for the State of North Carolina has a vertical accuracy that is within 0.82 ft.

Water-Quality Sampling, Quality Assurance, and Quality Control

Water-quality samples were collected at 97 well sites and 4 surface-water sites in August and September 2012. Sampling methods followed those outlined in the USGS National Field Manual (U.S. Geological Survey, 2006). Samples from the monitoring wells were collected using a submersible pump after at least three casing volumes were purged or water-quality field properties (temperature, pH, specific conductance, and dissolved oxygen) had stabilized. For residential wells where either an in situ submersible or centrifugal jet pump was being operated on a regular basis, samples were collected after water-quality field properties had stabilized. Industrial and municipal wells were sampled in a similar manner, as large volume in situ turbine pumps were frequently in operation. In some instances, a double-ball bailer was used as a thief sampler to collect samples within the screened interval of the well, as it was at BR-012, NH-872, NH-874, NH-875, NH-881, and NH-882.

Cations and Anions

Water samples were analyzed for major ions, iron, and bromide at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, using methods outlined in Fishman (1993). Five field blanks and 13 sample replicates were also collected throughout the sampling process to address quality assurance and quality control (QA/QC). The blanks and replicates provide information regarding the accuracy and precision of the water-quality data presented in this report. The QA/QC samples were collected in accordance with policies and procedures documented in the USGS Quality Assurance Plan for Water Resources Activities in North Carolina (U.S. Geological Survey, 2010). The plan defines policy statements that describe responsibilities for project planning and implementation, equipment calibration and maintenance, data collection, data processing and storage, data analysis and interpretation, synthesis, report preparation and processing, and training.

Results for the 13 major-ion replicates collected generally signified good analytical precision with most replicates having less than a 10 percent difference with the original sample. Notable exceptions include one sample where a dissolved iron concentration difference of 110 micrograms per liter ($\mu\text{g/L}$) was observed and another sample containing a sulfate concentration difference of 4.1 milligrams per liter (mg/L). Five blank samples were collected with results generally below reporting limits for all samples, except for 0.04 and 0.075 mg/L of calcium detected in two blank samples and 7.7 $\mu\text{g/L}$ of dissolved iron detected in another blank sample.

Stable Isotopes of Water

Samples for stable isotopes of oxygen and hydrogen ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) were analyzed by the USGS Reston Stable Isotope Laboratory (RSIL) in Reston, Virginia, following methods outlined in Révész and Coplen (2008a, 2008b). Results are reported with an analytical error (2σ) of $\pm 0.2\text{‰}$ for ^{18}O and $\pm 2.0\text{‰}$ for ^2H . Isotope data are presented in delta (δ) notation as the ratio of the heavy to the light isotope, normalized to a standard,

$$\delta_{\text{sample}} = 1,000 * [(R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}}]$$

where R is the ratio of the heavy to the light isotope in the sample. The result is conventionally expressed as per mil (parts per thousand) deviations from the international isotopic standard for hydrogen and oxygen known as the Vienna Standard Mean Ocean Water (VSMOW). The use of delta (δ) notation compensates for the difficulties that arise in using direct ratios due to the disproportion of natural abundance for each of the water isotopes. Results for 27 stable isotope replicates collected generally signified good analytical precision with most replicates having less than a 10 percent difference with the original sample.

The variations within isotopic ratios for hydrogen and oxygen are a result of physicochemical processes within the hydrologic cycle. For example, water molecules composed of lighter isotopes (^1H and ^{16}O) will preferentially evaporate, leaving behind water that is relatively more enriched in the heavier isotopes (^2H and ^{18}O). The isotope ^2H is called deuterium and generally is represented by the symbol D. Craig (1961) showed that there is a linear relation between δD and $\delta^{18}\text{O}$ in precipitation samples that have not undergone excessive evaporation and that were collected from a worldwide network of stations. This relation can be expressed as a linear equation

$$\delta\text{D} = 8 * \delta^{18}\text{O} + 10 \quad (1)$$

known as the Global Meteoric Water Line (GMWL). Similarly, a Local Meteoric Water Line (LMWL) can also be determined on the basis of isotopic analyses of local precipitation. A LMWL of

$$\delta\text{D} = 5.54 * \delta^{18}\text{O} + 2.02 \quad (2)$$

was determined by linear regression ($R^2 = 0.909$), using precipitation data collected from the USGS rain gage located along the Cape Fear River near Tarheel, North Carolina (USGS station 345006078493145) (U.S. Geological Survey, 2013).

The stable isotope composition of water samples can be compared to these meteoric water lines to infer the origin of the water. Samples that have been influenced by evaporation will be isotopically heavier (more positive) than the local precipitation and, therefore, will plot along a line below the meteoric water line. A regression line can be constructed from δD and $\delta^{18}\text{O}$ data in water samples that have undergone evaporative processes (also known as an evaporation line), having a slope that is less than that of the LMWL. The point where the evaporation line intersects the LMWL infers the original isotopic composition of the local source precipitation for the given water samples.

Statistical Analysis of Water-Quality Data

The water-quality data were summarized using Piper (trilinear) diagrams and boxplots. Charge-balance errors calculated for the major cation and anion data were found to have less than a 10 percent difference, which was determined acceptable for statistical evaluation (U.S. Geological Survey, 1992). Piper diagrams are trilinear plots used to visually describe and compare the major ion composition of multiple samples of water on one graph. Ternary diagrams for both cations and anions are projected onto a diamond-shaped plot where samples can be divided into hydrochemical facies, or groups of samples, with similar chemical characteristics

as a result of similar hydrogeochemical processes (Piper, 1953). Using this approach, distinct source waters and the mixing relations that exist between them can be identified, as well as any water-rock interactions that may occur along the groundwater flow path. Boxplots also provide a way to visually compare datasets by displaying the statistical spread of the data (Sincich, 1993).

Hydrogeology of the Study Area

Coastal Plain sediments of Cretaceous to Quaternary age underlie the study area. The sediments consist of alternating units of sand, clay, silt, limestone, and sandstone that thicken and dip toward the east-southeast. The sand, limestone, and sandstone formations compose the aquifers, and the silt and clay layers form the confining units that separate the aquifers. Only sediments of upper Cretaceous age and younger were investigated as part of this study. These units include, in ascending order, the Peedee Formation, the Beaufort Formation, the Castle Hayne Formation, the River Bend Formation, the undifferentiated deposits of the Pleistocene and Pliocene Epochs, and the surficial sand deposits. Together, these units make up the surficial, Castle Hayne, and Peedee aquifers. A generalized hydrostratigraphic sequence and description of the sedimentary units in the study area are provided in figure 4.

The hydrostratigraphy of New Hanover, Brunswick, and Pender Counties has been documented previously by Bain (1970), Zarra (1991), Lautier (1998), Harden and others (2003), and Lautier (2006). Data from these reports were relied upon heavily and augmented with new data obtained during this study to build a comprehensive hydrostratigraphic framework for the surficial, Castle Hayne, and Peedee aquifers in New Hanover, eastern Brunswick, and southern Pender Counties. Reported data, driller's logs, and geophysical logs for 146 sites in the study area were analyzed (fig. 5; appendix 1). The resultant framework model, including structure contours (figs. 6–10), selected cross sections (figs. 11A–I), and characteristics of each cross section are discussed.

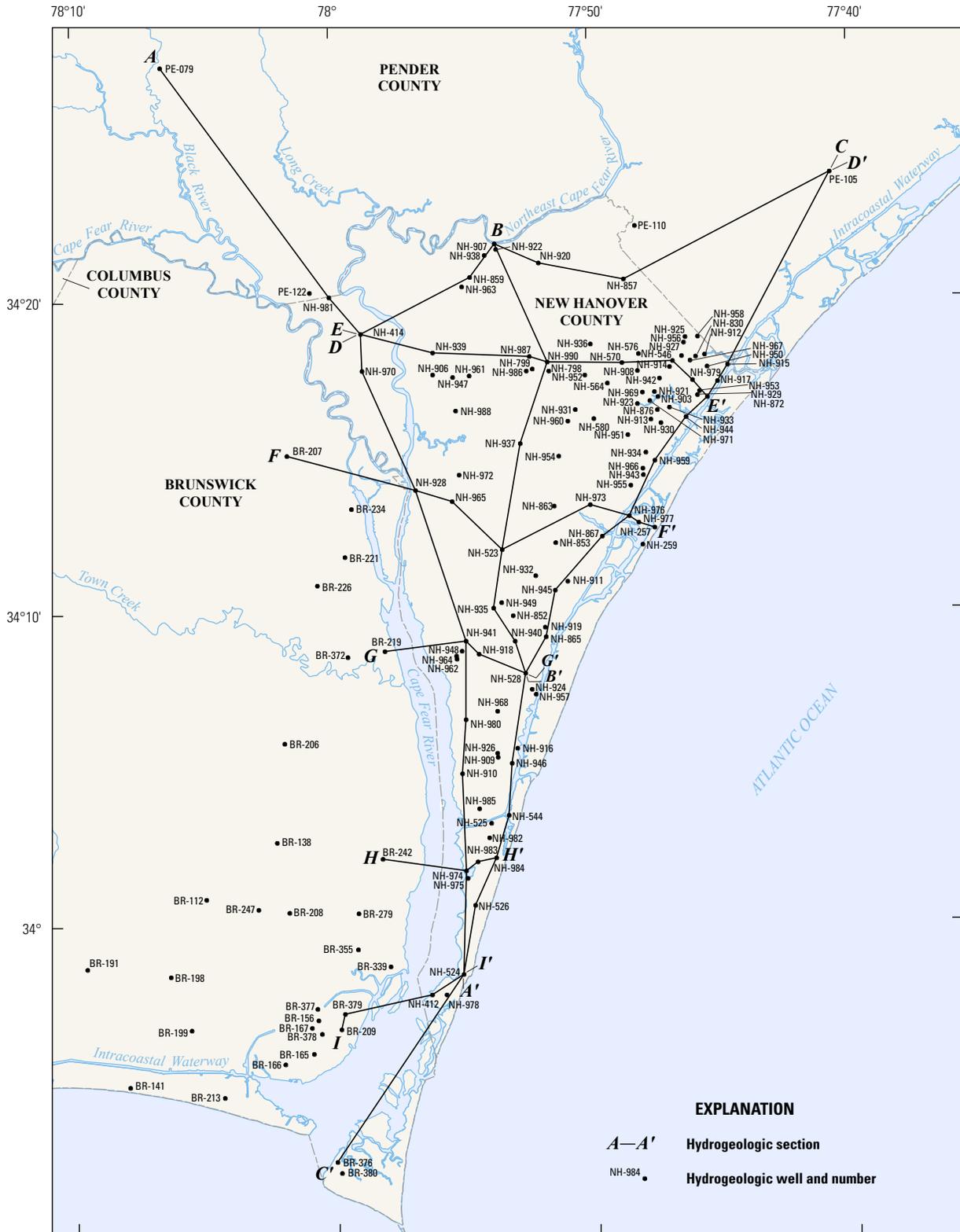
SYSTEM	SERIES	GEOLOGIC UNITS	HYDROGEOLOGIC UNITS	DESCRIPTION
Quaternary	Holocene	Surficial sand deposits	Surficial aquifer	light gray to light yellow sand, silt, and clay
	Pleistocene	Undifferentiated Pleistocene and Pliocene deposits		
Tertiary	Pliocene		River Bend Formation ¹	Castle Hayne confining unit
	Oligocene	Castle Hayne Formation ²		Castle Hayne aquifer
	Eocene		Beaufort Formation ³	Peedee confining unit
	Paleocene	Peedee Formation		Peedee aquifer
Cretaceous	Upper Cretaceous	Black Creek Formation	Black Creek confining unit	sandy clay, silty clay, and clay

¹ Exists only in southern New Hanover County (Zarra, 1991).

² Unit is discontinuous in study area.

³ Exists only in southeastern Brunswick and southern New Hanover Counties (Zarra, 1991).

Figure 4. Generalized relation between geologic and hydrogeologic units in the Brunswick, New Hanover, and Pender County, North Carolina, area. Only units discussed in this report are presented, although deeper units are present. Modified from Lautier (1998) and Harden and others (2003).



Base modified from N.C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000



Figure 5. Locations of wells used to describe the hydrogeologic framework of the study area and lines of cross section in Brunswick, New Hanover, and Pender Counties, North Carolina. Lines of sections are shown in figures 11A–I.

Surficial Aquifer

The surficial aquifer is the uppermost hydrostratigraphic unit, underlying the entire study area. For this study, the following geologic units constitute the surficial aquifer: Holocene-age surficial sand deposits and undifferentiated Pleistocene and Pliocene deposits. The surficial aquifer is unconfined and consists of interbedded light gray to light yellow sand, silts, and clay that vary in thickness (Zarra, 1991). The Quaternary- to late Tertiary-age sediments of the surficial aquifer overlie the Castle Hayne Formation in the eastern part of the study area and the Peedee Formation in the western part of the study area.

The surficial aquifer contains freshwater everywhere, with the exception of areas that are immediately adjacent to brackish water near the estuaries, ocean, or Intracoastal Waterway. Beneath the barrier islands and near the beaches, the surficial aquifer may form a thin lens of freshwater that floats on top of brackish water. The water table in the surficial aquifer generally follows topographic highs and lows, and recharge occurs by rainfall (Bain, 1970). The surficial aquifer serves as a recharge source for the aquifer that lies beneath it.

Castle Hayne Confining Unit and Aquifer

The Castle Hayne confining unit generally separates the underlying Castle Hayne aquifer from the surficial aquifer in eastern New Hanover, southeastern Brunswick, and southeastern Pender Counties. On the basis of available data, however, the Castle Hayne confining unit does not continuously overlie the Castle Hayne aquifer in New Hanover and Brunswick Counties (fig. 6). Where it was observed, the confining unit is composed of silt, clay, and sandy-clay beds present in the undifferentiated Pleistocene and Pliocene deposits, upper part of the River Bend Formation, and in some places, the uppermost part of the Castle Hayne Formation (Lautier, 2006).

The altitude of the top of the Castle Hayne confining unit dips steeply to the east-southeast in southern New Hanover and southeastern Brunswick Counties, ranging from greater than 10 ft above NAVD 88 to less than 110 ft below NAVD 88 in this part of the study area (fig. 6). The dip is less steep in northeastern New Hanover and southern Pender Counties where the altitude of the top of the confining unit ranges from 20 ft above NAVD 88 to 20 ft below NAVD 88 (fig. 6). The thickness of the Castle Hayne confining unit ranges from 0 to 72 ft and generally thickens toward the southeast. The confining unit begins to thin and (or) disappear completely in some areas, which is likely the result of historical hydrologic erosion. This erosion could explain why the confining unit is missing beneath Pages Creek, located along the northeastern coastline of New Hanover County (fig. 11C).

The Castle Hayne aquifer is a highly permeable and productive freshwater aquifer in New Hanover County, consisting of a light-gray or white moldic, fossiliferous limestone (Bain, 1970; Zarra, 1991). The Castle Hayne

aquifer primarily includes the Eocene-age Castle Hayne Formation (fig. 4) throughout much of the study area, whereas in southeastern Brunswick and New Hanover Counties the aquifer may include parts of the Beaufort Formation and River Bend Formation (Zarra, 1991). The altitude of the top of the Castle Hayne aquifer dips to the east-southeast in southern New Hanover and southeastern Brunswick Counties, ranging from 10 to 130 ft below NAVD 88 (fig. 7). In northeastern New Hanover County, the altitude of the top of the Castle Hayne aquifer ranges from greater than NAVD 88 to less than 50 ft below NAVD 88 with two distinct depressions near the coastline (fig. 7). The Castle Hayne aquifer is discontinuous, forming a wedge that is as much as 90 ft thick in the eastern part of the study area and thinning out to the west (fig. 11F). Although the Castle Hayne aquifer is largely confined where present throughout the study area, the extent of the aquifer exceeds that of the Castle Hayne confining unit in the northwestern part of New Hanover County and is therefore unconfined where this occurs (figs. 6, 7, 11G, and 11H).

Peedee Confining Unit and Aquifer

The Peedee confining unit and aquifer are located beneath the Castle Hayne aquifer in the eastern part of the study area and beneath the surficial aquifer in the western part of the study area where the Castle Hayne aquifer does not exist. The sediments are Cretaceous in age and generally consist of Peedee Formation sediments that are gray, fine- to medium-grained sand interbedded with black clay (fig. 4). In southeastern Brunswick and New Hanover Counties, the Peedee aquifer may include a sandy moldic limestone unit grading downward into a calcareous sandstone (Zarra, 1991; Lautier, 2006). For this study, the Peedee confining unit was defined as the silt, clay, or sandy clay bed that is located near the top of the Peedee Formation.

The Peedee confining unit is laterally discontinuous in New Hanover and Brunswick Counties (fig. 8). The dip of the altitude of the top of the clay confining unit changes from east-southeast in central New Hanover and eastern Brunswick Counties to south-southeast in southeastern Brunswick and southern New Hanover Counties (fig. 8). Thickness of the Peedee confining unit ranges from 0 to 89 ft and is thickest in northeastern New Hanover County (fig. 11A–C).

The Peedee aquifer consists of gray or light brown sandstone (Zarra, 1991) and contains freshwater only in its uppermost sands (Bain, 1970). The altitude of the top of the Peedee aquifer dips east-southeast, ranging from more than 10 ft below NAVD 88 in northwestern New Hanover County to less than 180 ft below NAVD 88 in southeastern New Hanover County (fig. 9). The thickness of the Peedee aquifer ranges from 194 to 431 ft throughout the study area, generally thickening to the west (fig. 11D–I). Recharge occurs in areas where the aquifer is unconfined and, to a lesser extent, from groundwater moving downward from the units above.

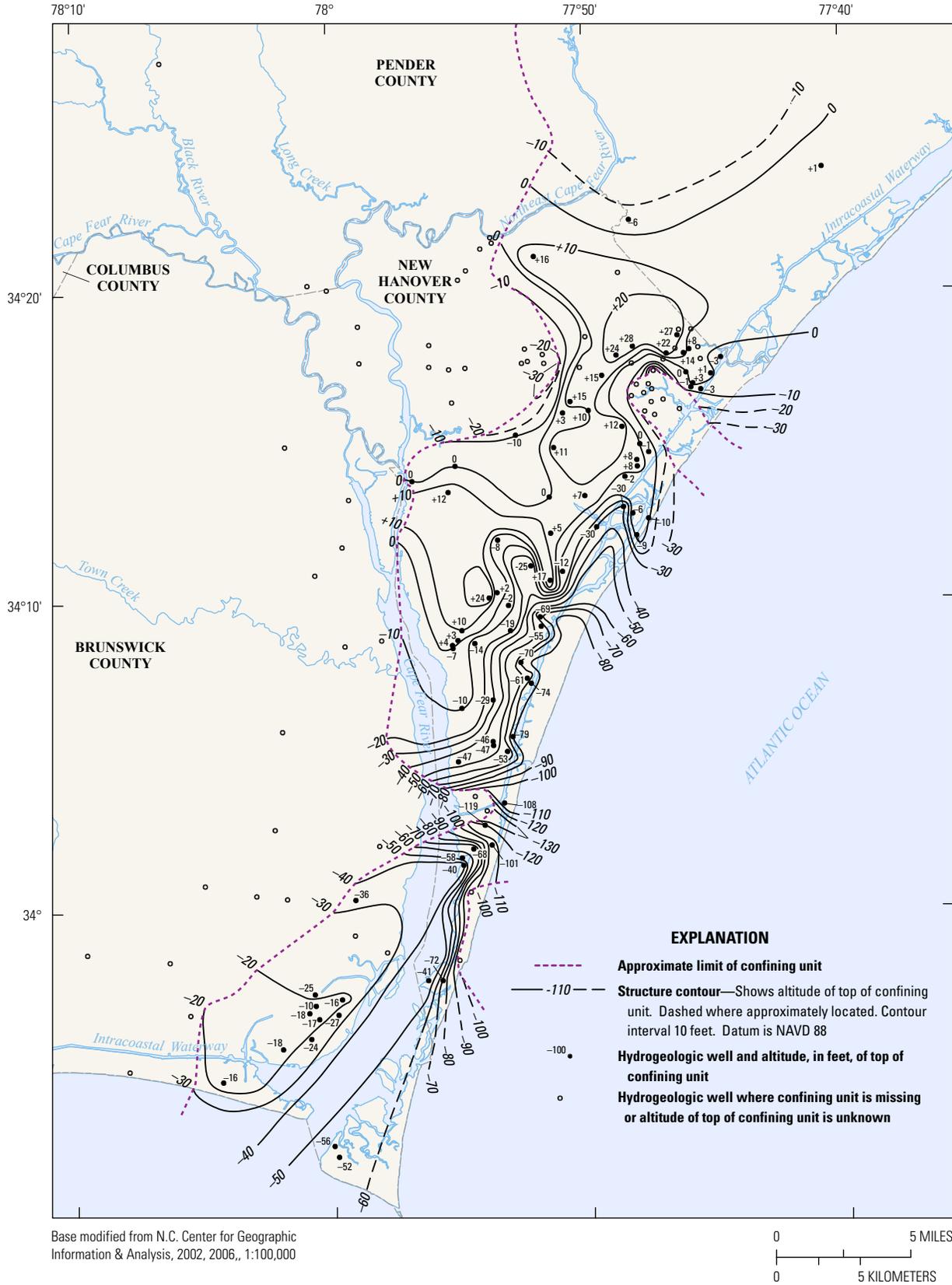


Figure 6. Altitude of the top of the Castle Hayne confining unit in the greater New Hanover County area, North Carolina.

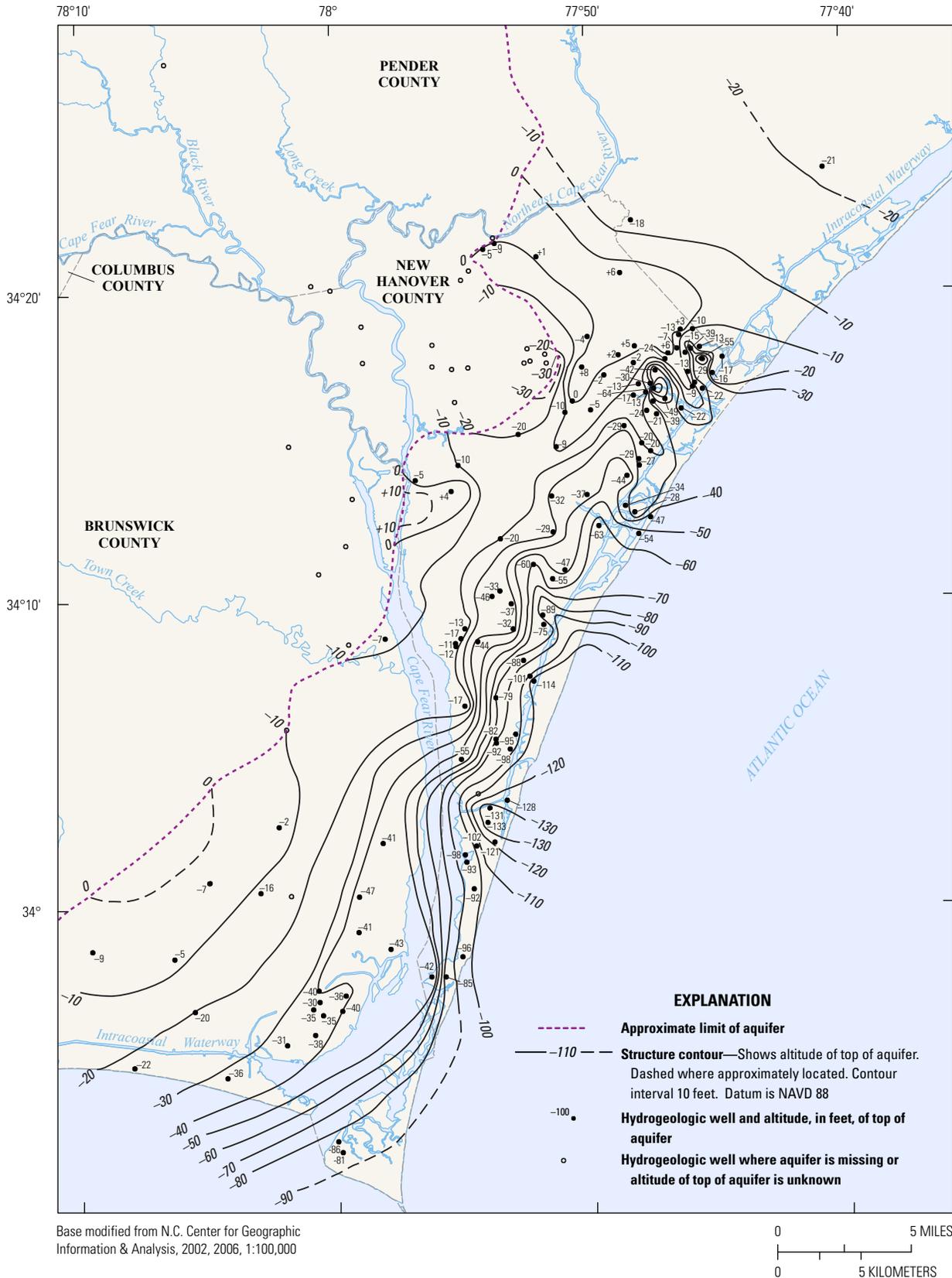


Figure 7. Altitude of the top of the Castle Hayne aquifer in the greater New Hanover County area, North Carolina.

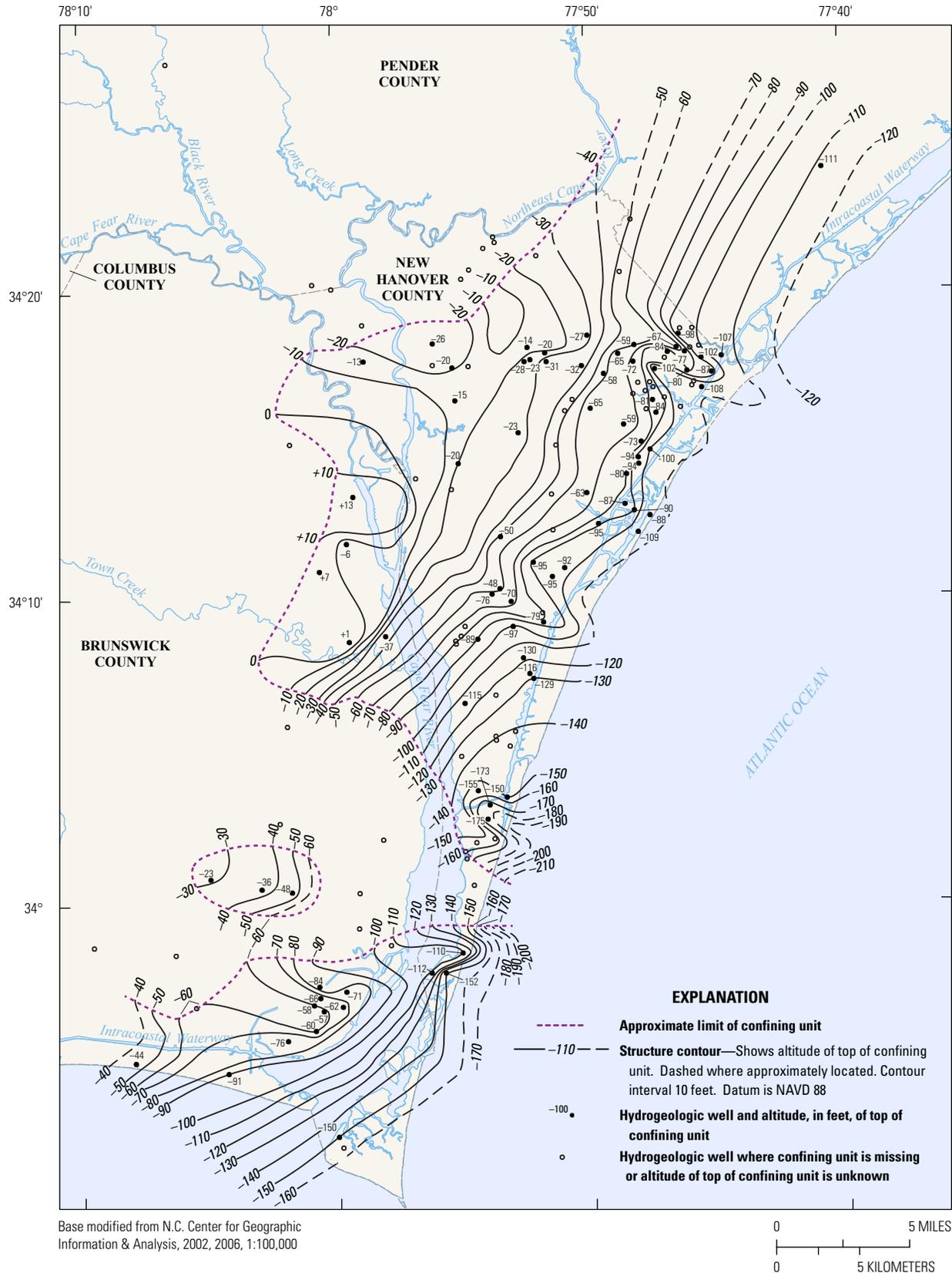


Figure 8. Altitude of the top of the Peedee confining unit in the greater New Hanover County area, North Carolina.

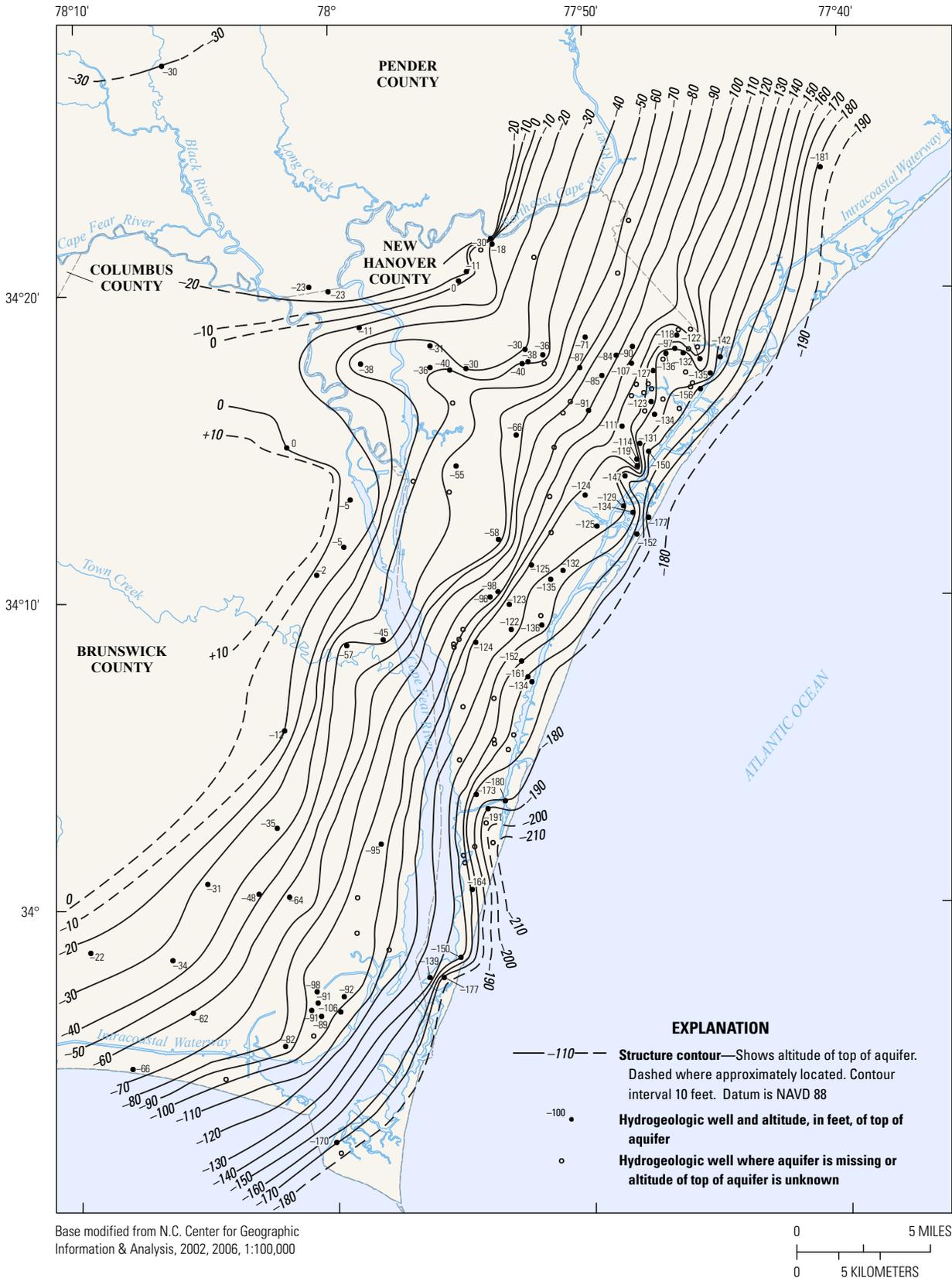


Figure 9. Altitude of the top of the Peedee aquifer in the greater New Hanover County area, North Carolina.

Black Creek Confining Unit

The Black Creek confining unit underlies the entire study area, and although data used in this study are limited, regional studies have shown that the confining unit is laterally continuous (fig. 10) (Winner and Coble; 1996; Lautier, 2006). The Black Creek confining unit consists of sandy clay, silty clay, and clay beds of the upper Black Creek Formation and lower Peedee Formation (fig. 4). The altitude of the top of the Black Creek confining unit dips east-southeast and ranges from about 225 ft below NAVD 88 in western Pender County to more than 550 ft below NAVD 88 in southeastern Brunswick County (fig. 11A–C).

Hydraulic Characteristics of the Study Area

Groundwater recharge occurs by rainfall over the land surface. Giese and others (1997) estimated recharge to the surficial aquifer in the study area to range from 12 to 16 inches per year. Recharge to the Castle Hayne and Peedee aquifers is enhanced where these aquifer are unconfined. Some recharge also occurs by downward-moving water passing through the Castle Hayne and Peedee confining units. The vertical exchange of water is also enhanced in areas where sinkholes or depressional wetlands (suggestive of relic sinkholes) are present. Dissolution of limestone present in the Castle Hayne Formation can allow surficial materials to collapse into voids and cavities, creating a direct surface connection to the Castle Hayne aquifer.

Groundwater Levels

Groundwater flow in the study area was evaluated by constructing potentiometric-surface maps from water levels measured at 80 wells screened in the Castle Hayne and Peedee aquifers (fig. 12). Groundwater flows laterally downgradient from the recharge areas where groundwater levels are highest to discharge areas where water levels are lower in a direction

perpendicular to the potentiometric contours. The potentiometric surfaces discussed in this section are not true potentiometric surfaces by definition, but rather hybrid water-table/potentiometric-surface maps because they are complicated by the fact that both the Castle Hayne and Peedee aquifers have discontinuous or missing confining units in the northern and western extent of the study area. Because the majority of the aquifer where the water-level measurements were collected is confined, the maps will be referenced as potentiometric surfaces for this report.

The potentiometric-surface maps for the Castle Hayne aquifer were constructed using water-level data collected from 35 wells during August and September 2012 (fig. 13A) and from 36 wells during March 2013 (fig. 13B). Generally, the highest groundwater altitudes were measured in the central parts of New Hanover, Pender, and Brunswick Counties in both 2012 and 2013 sampling events, suggesting these areas are areas of recharge. The lowest groundwater altitudes in the Castle Hayne aquifer were measured in groundwater discharge areas along the Atlantic Ocean and Cape Fear River. These lowest groundwater altitudes were located in the northeast corner of New Hanover County and the southeast corner of Pender County. In August–September 2012 the lowest measured groundwater level was 6.65 ft below NAVD 88 (fig. 13A), and in March 2013 the lowest measured groundwater level was 8.10 ft below NAVD 88 (fig. 13B).

Potentiometric-surface maps for the Peedee aquifer were constructed using water-level data collected from 31 wells during August and September 2012 (fig. 14A) and from 26 wells during March 2013 (fig. 14B). The Peedee aquifer is unconfined throughout much of Brunswick, Pender, and the northwest corner of New Hanover County. The highest groundwater altitudes measured in the Peedee aquifer were located in northern Brunswick and central New Hanover Counties. The lowest groundwater altitudes were measured near the Northeast Cape Fear River, the Cape Fear River, and the Atlantic Ocean. In August–September 2012 the lowest measured groundwater level was 20.33 ft below NAVD 88 (fig. 14A), and in March 2013 the lowest measured groundwater level was 15.38 ft below NAVD 88 (fig. 14B). Groundwater levels in August–September 2012 were affected by industrial withdrawals in north-central New Hanover County.

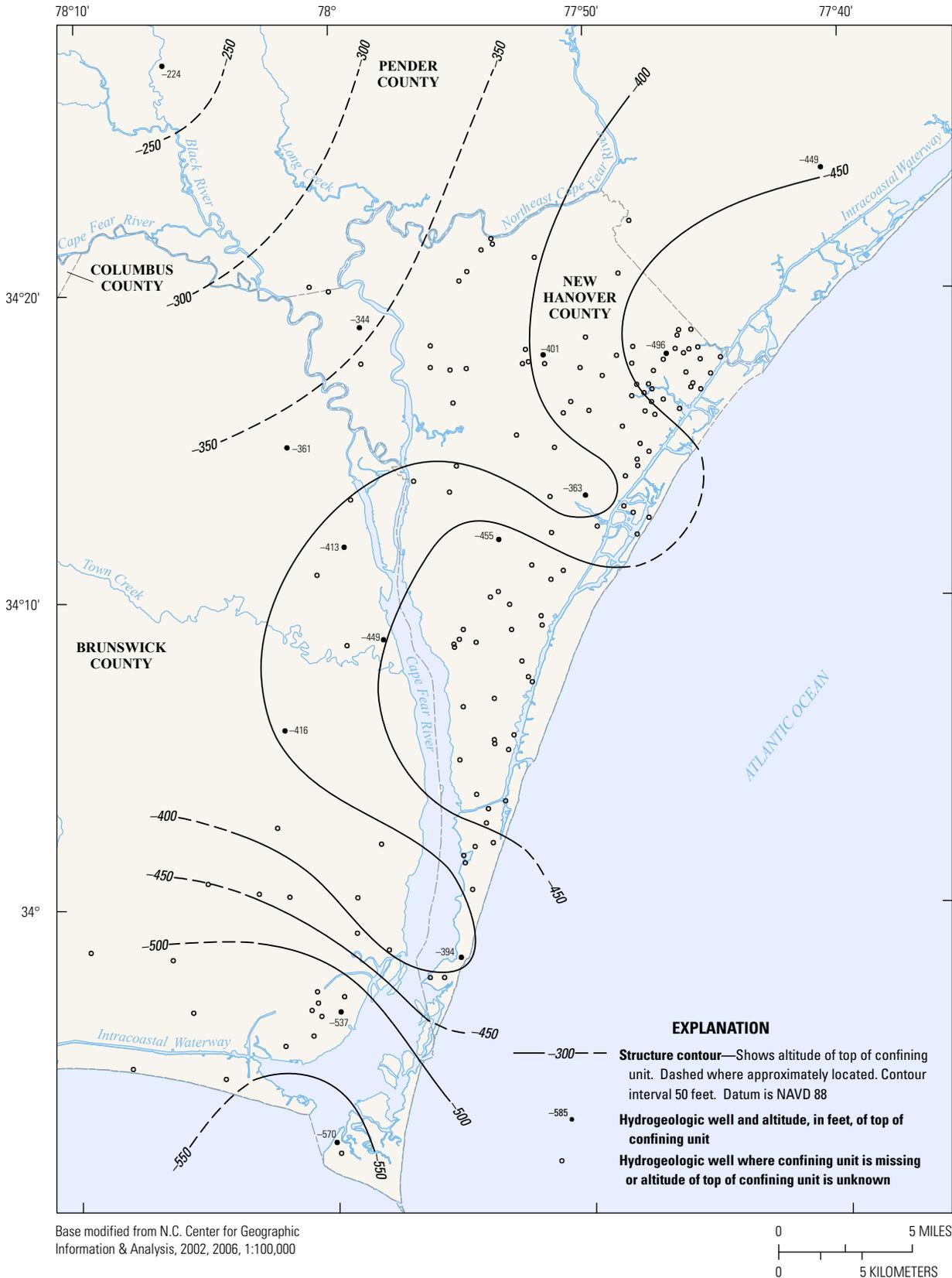


Figure 10. Altitude of the top of the Black Creek confining unit in the greater New Hanover County area, North Carolina.

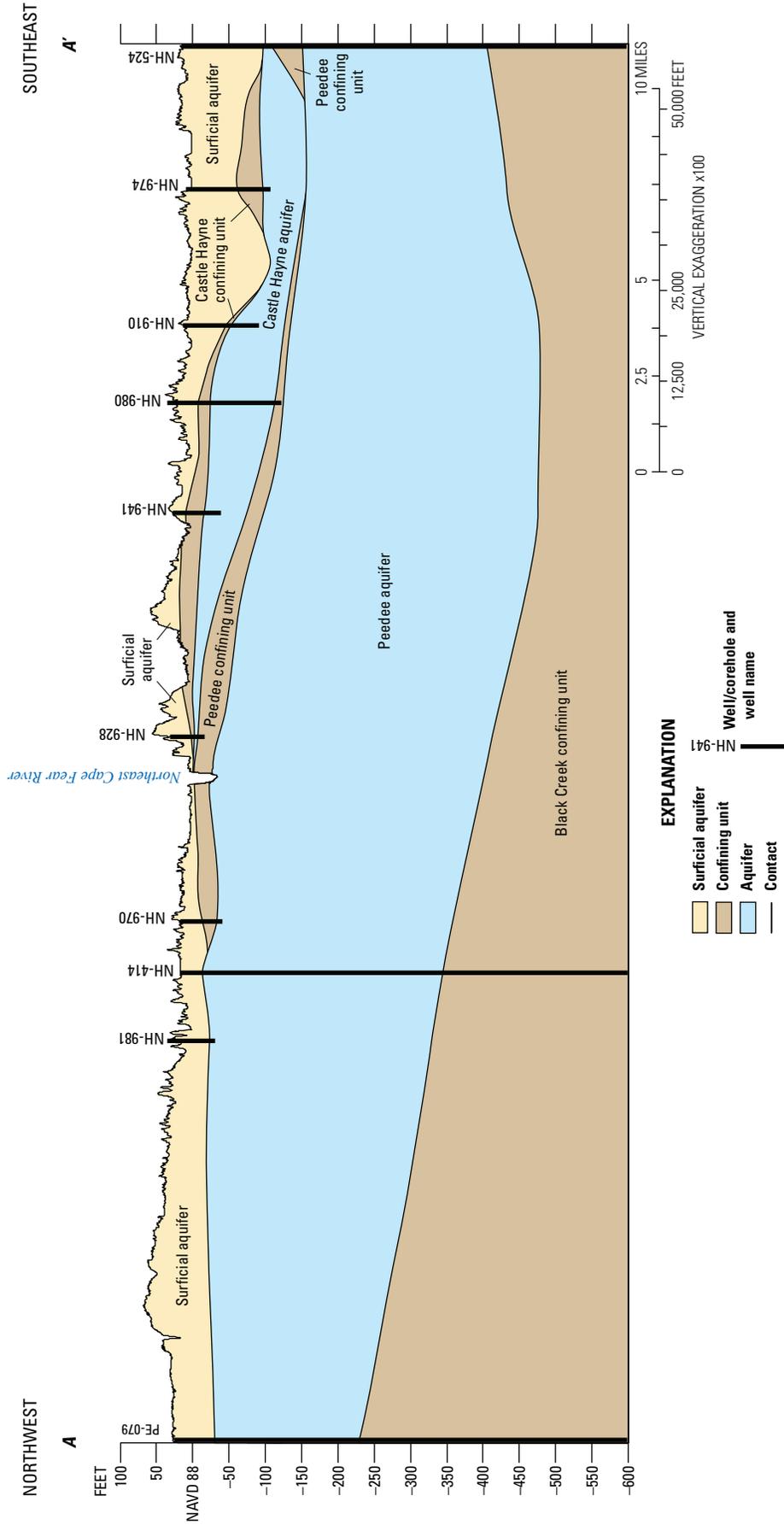


Figure 11A. Hydrogeologic cross section A-A' located in Pender and New Hanover Counties, North Carolina. Line of section is shown in figure 5.

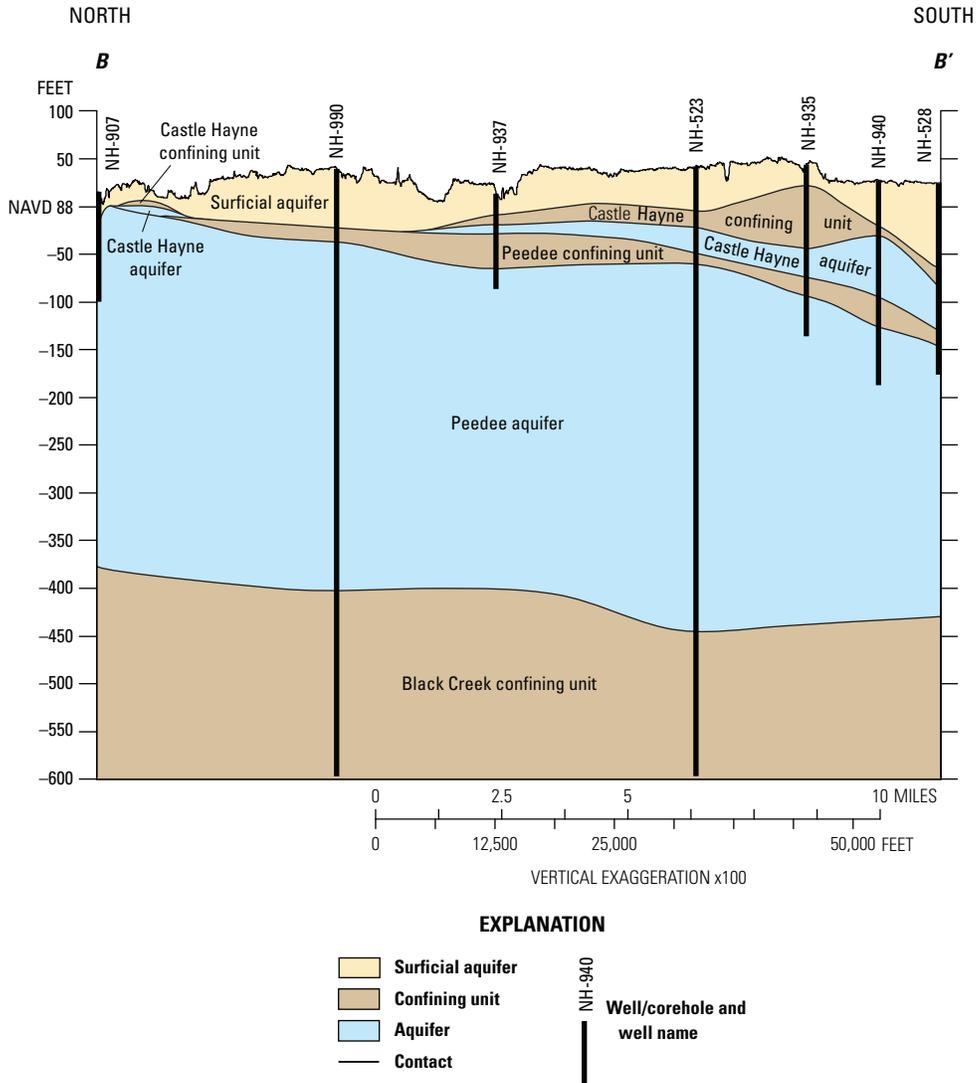


Figure 11B. Hydrogeologic cross section B–B' located in New Hanover County, North Carolina. Line of section is shown in figure 5.

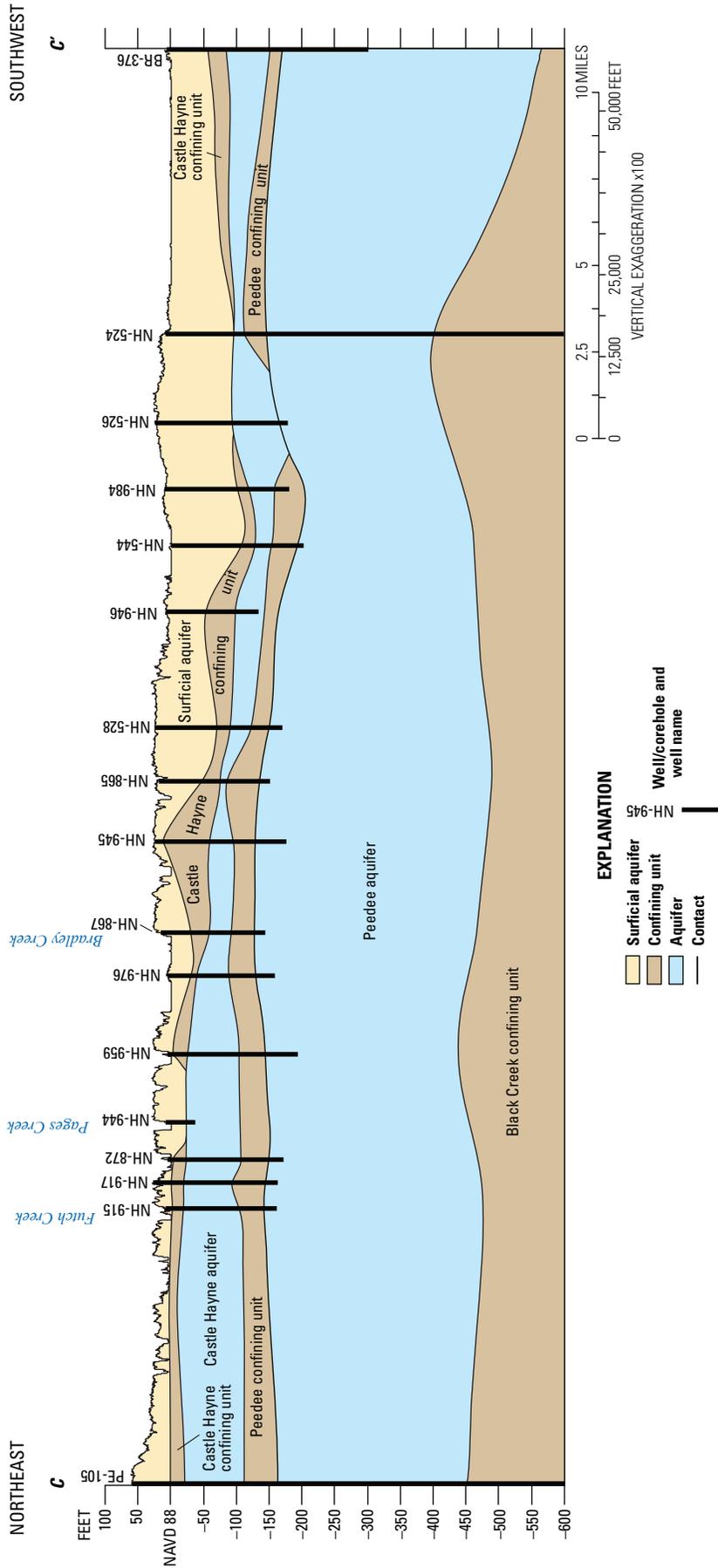


Figure 11C. Hydrogeologic cross section C–C’ located in Brunswick, Pender, and New Hanover Counties, North Carolina. Line of section is shown in figure 5.

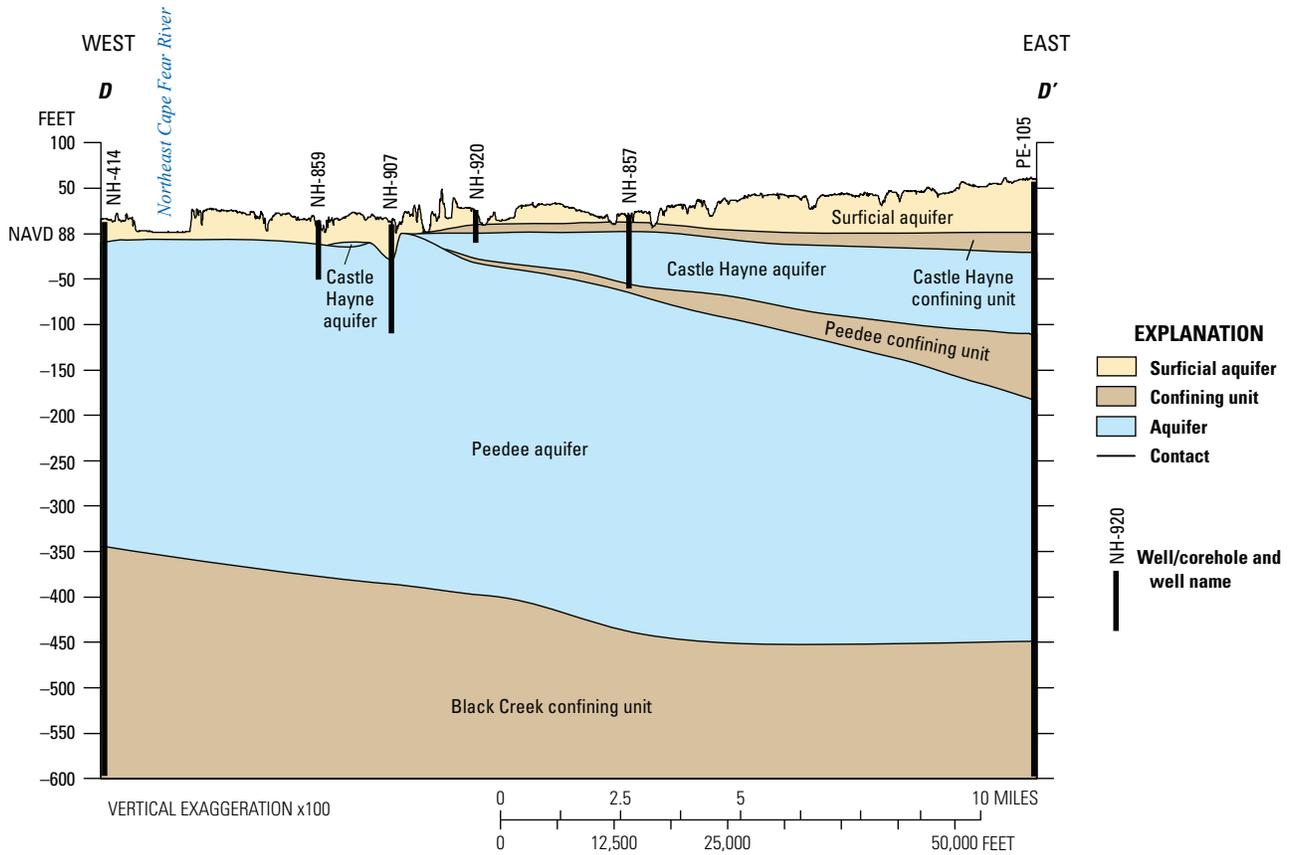


Figure 11D. Hydrogeologic cross section *D-D'* located in New Hanover and Pender Counties, North Carolina. Line of section is shown in figure 5.

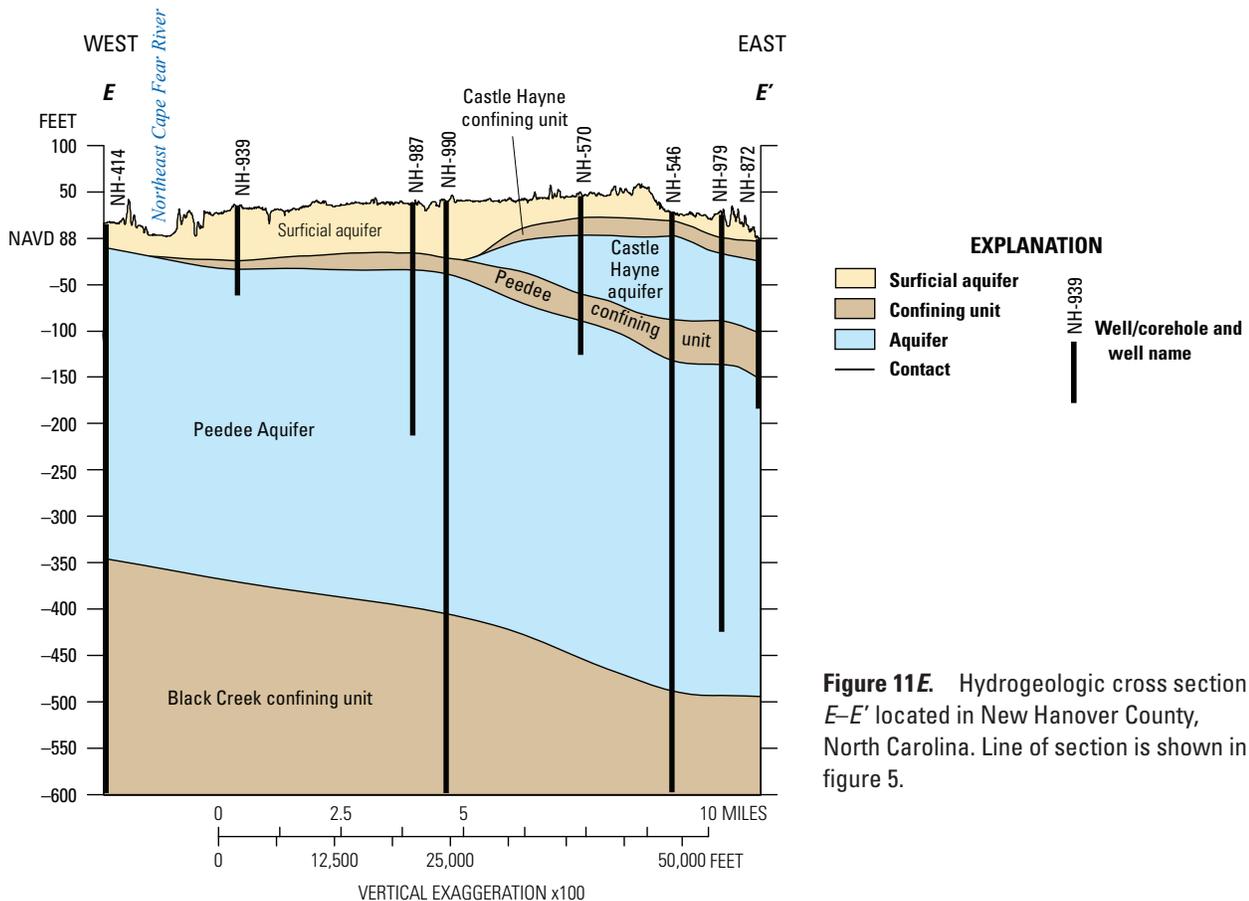


Figure 11E. Hydrogeologic cross section *E-E'* located in New Hanover County, North Carolina. Line of section is shown in figure 5.

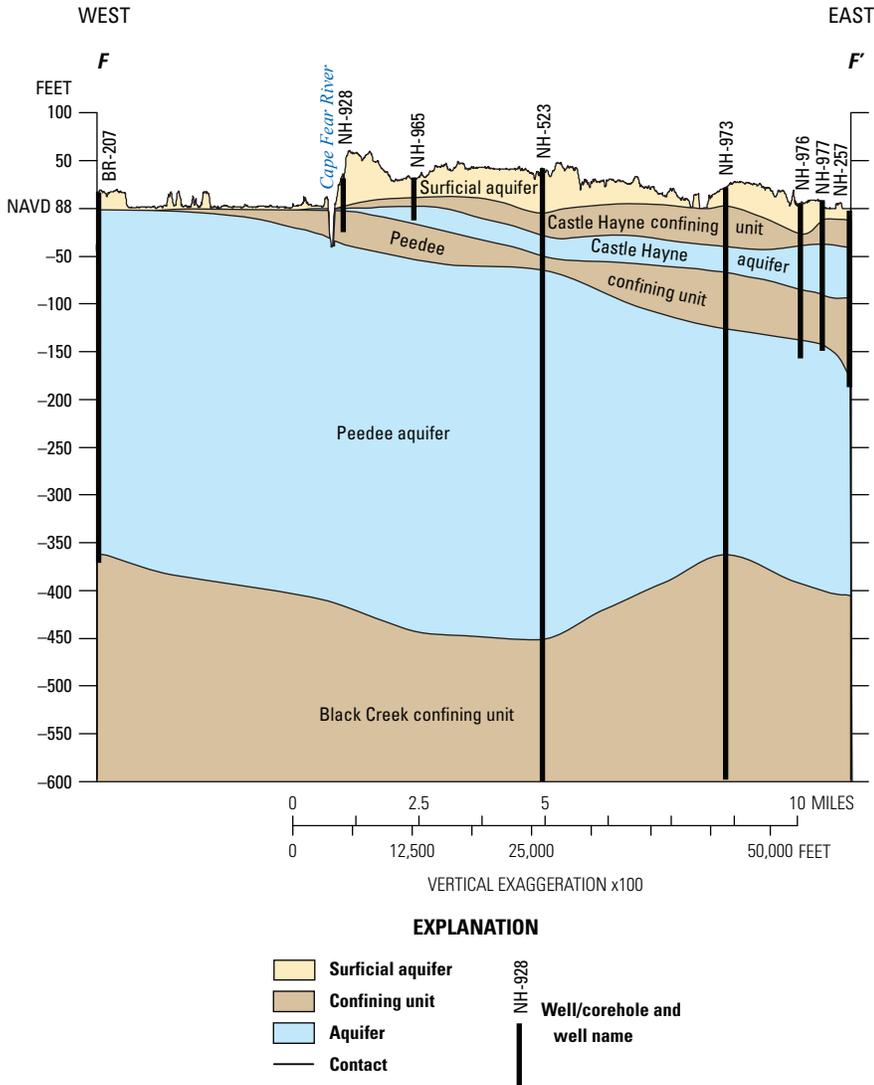


Figure 11F. Hydrogeologic cross section *F–F'* located in Brunswick and New Hanover Counties, North Carolina. Line of section is shown in figure 5.

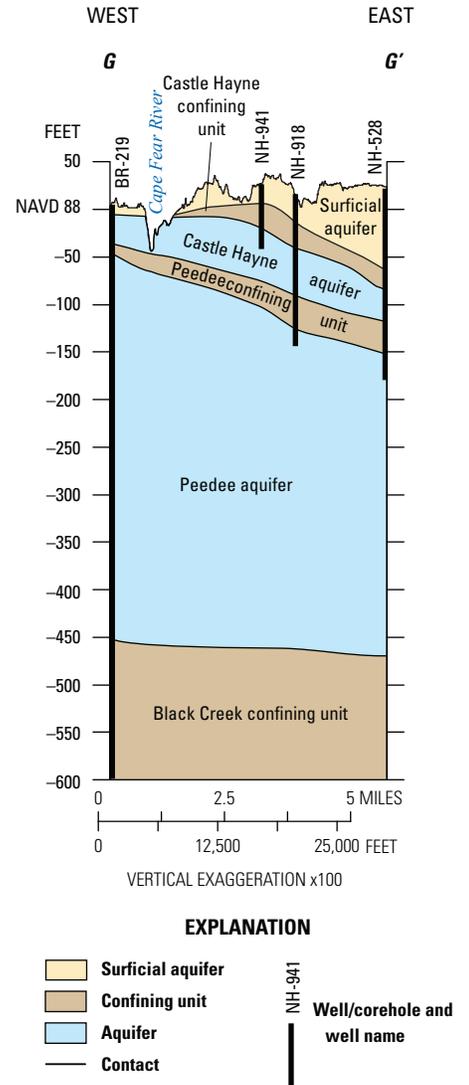
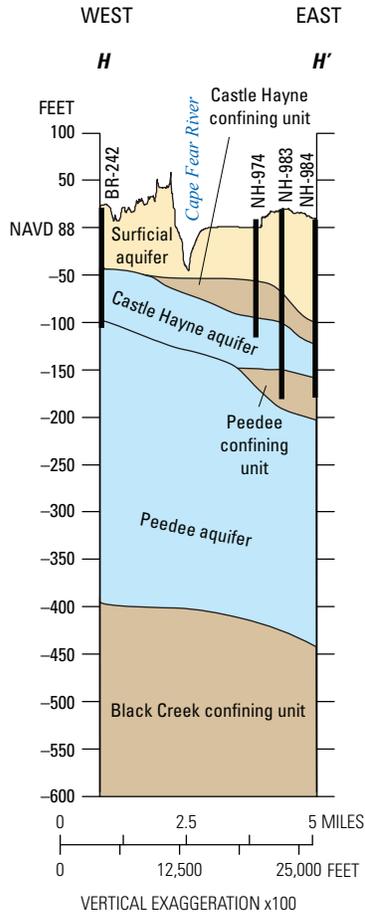


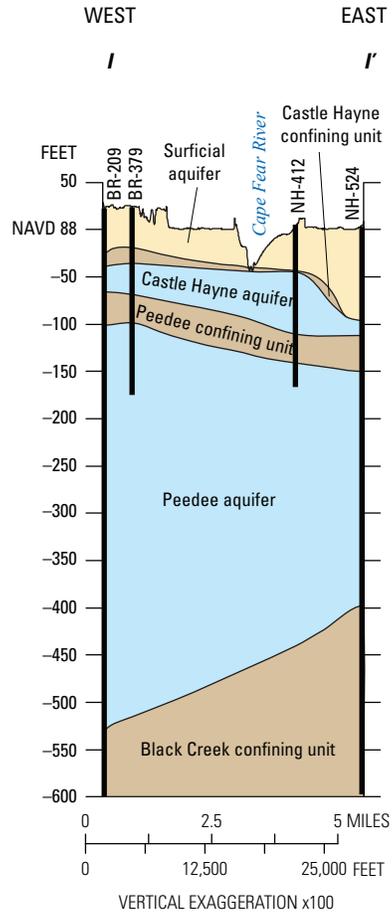
Figure 11G. Hydrogeologic cross section *G–G'* located in Brunswick and New Hanover Counties, North Carolina. Line of section is shown in figure 5.



EXPLANATION

- Surficial aquifer
- Confining unit
- Aquifer
- Contact
- Well/corehole and well name

Figure 11H. Hydrogeologic cross section H–H' located in Brunswick and New Hanover Counties, North Carolina. Line of section is shown in figure 5.



EXPLANATION

- Surficial aquifer
- Confining unit
- Aquifer
- Contact
- Well/corehole and well name

Figure 11I. Hydrogeologic cross section I–I' located in Brunswick and New Hanover Counties, North Carolina. Line of section is shown in figure 5.



Base modified from N.C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000

Figure 12. Site locations used for water-level measurements and water-quality sampling conducted in August–September 2012 and March 2013 in Brunswick, New Hanover, and Pender Counties, North Carolina. Where wells are clustered at one groundwater site, groundwater site symbolizes the well completed in the deepest aquifer.

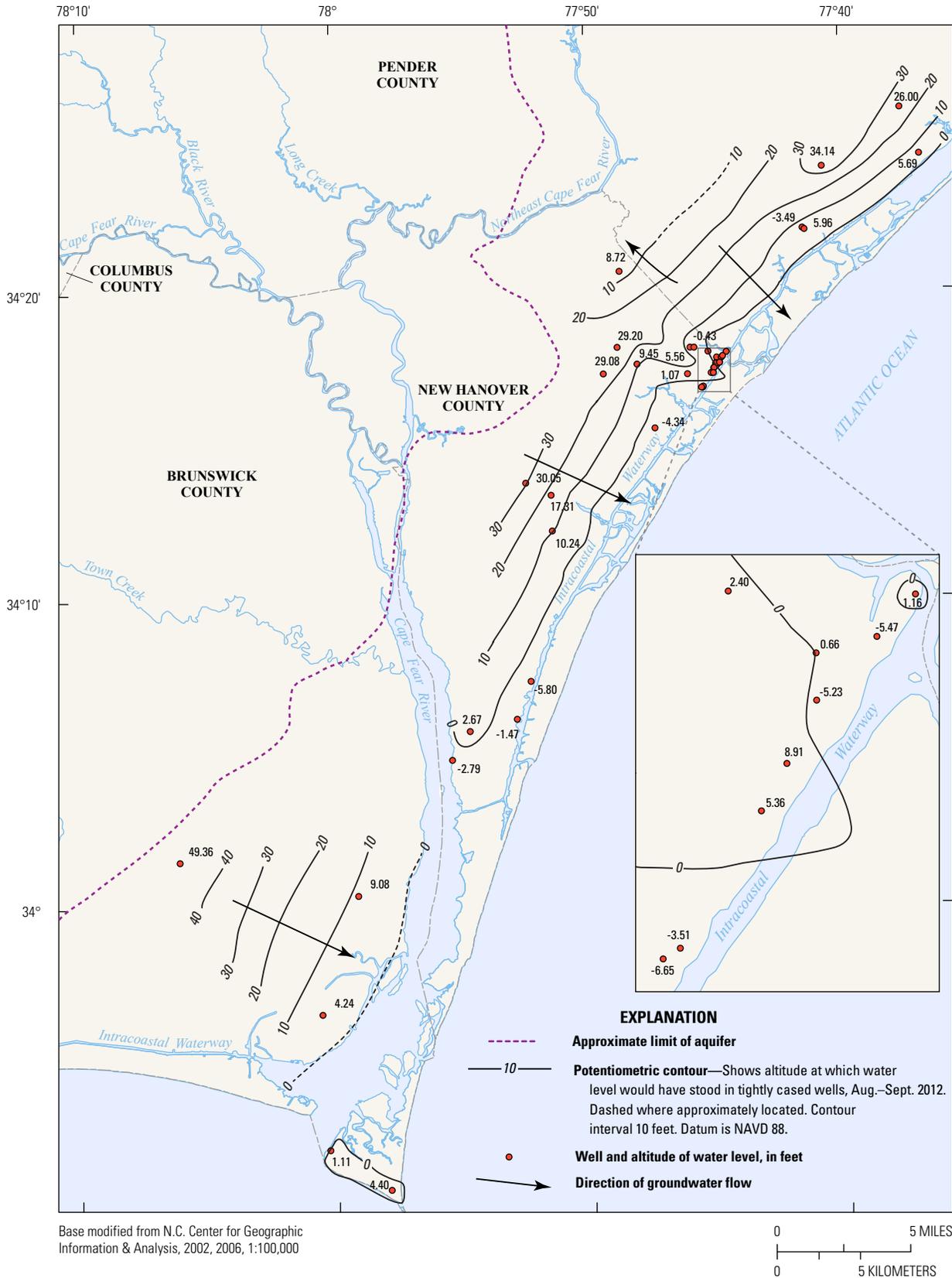


Figure 13A. Altitude of the potentiometric surface of the Castle Hayne aquifer measured in August–September 2012 in Brunswick, New Hanover, and Pender Counties, North Carolina.

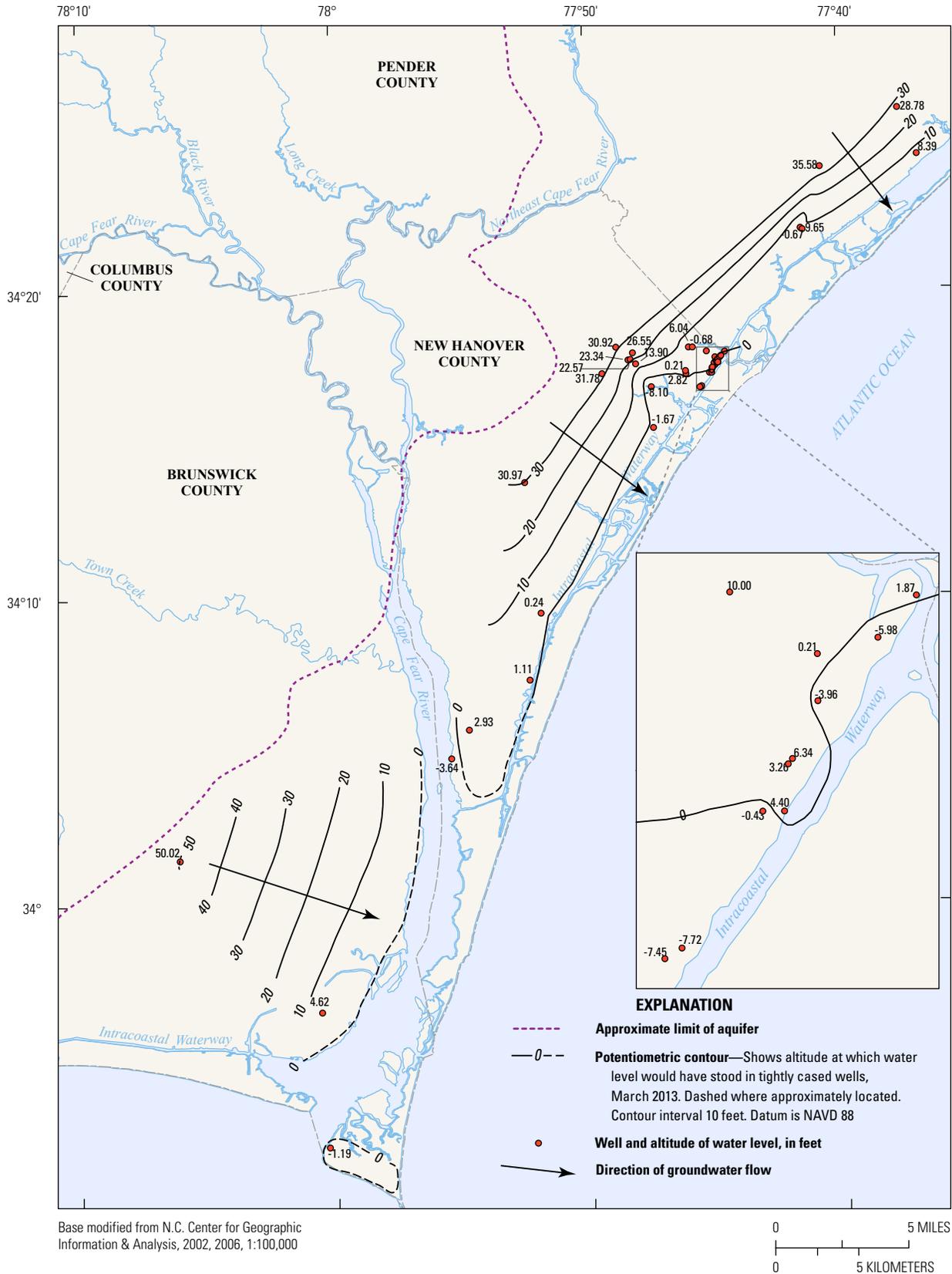


Figure 13B. Altitude of the potentiometric surface of the Castle Hayne aquifer measured in March 2013 in Brunswick, New Hanover, and Pender Counties, North Carolina.

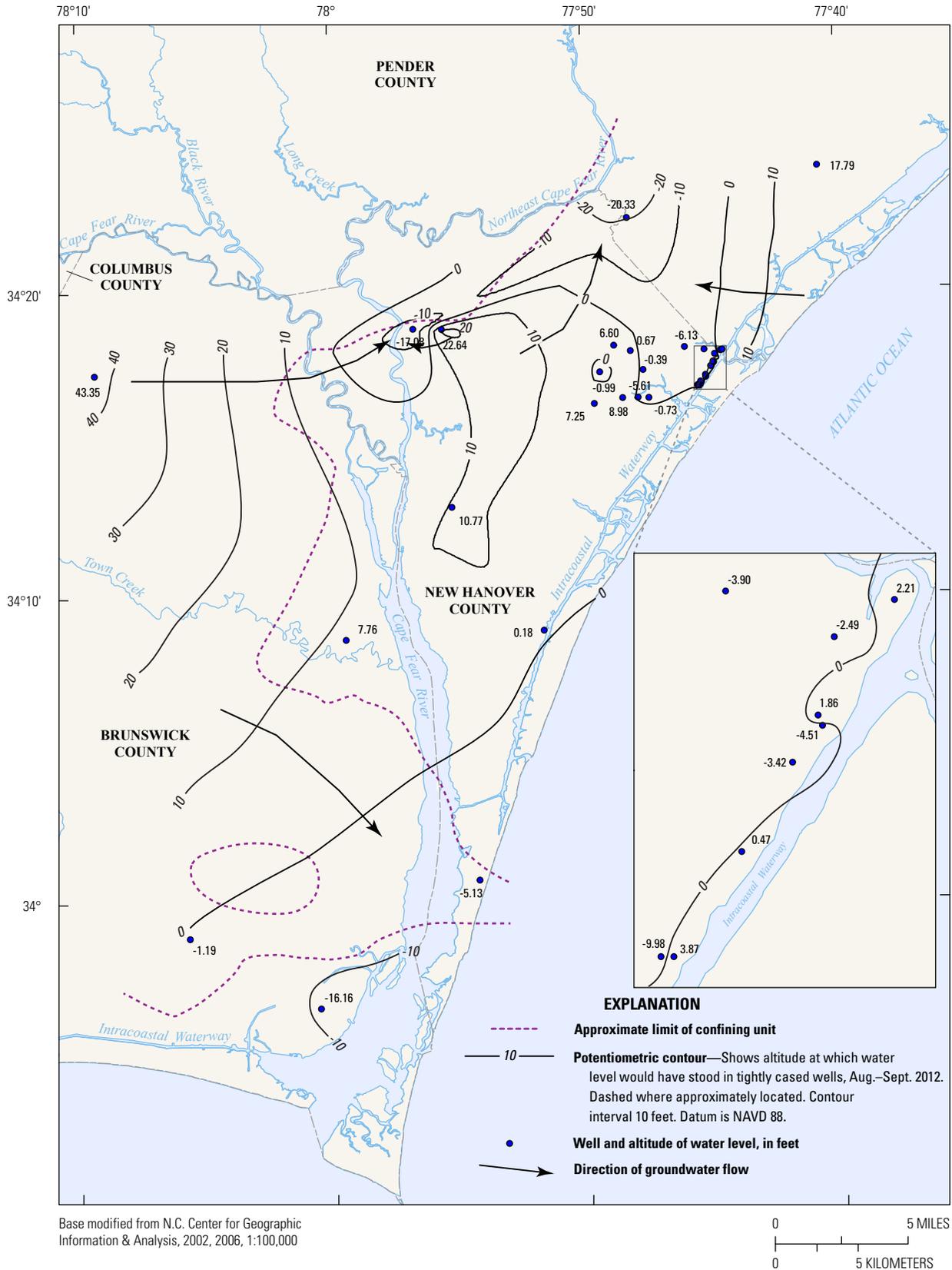


Figure 14A. Altitude of the potentiometric surface of the Peedee aquifer measured in August–September 2012 in Brunswick, New Hanover, and Pender Counties, North Carolina.

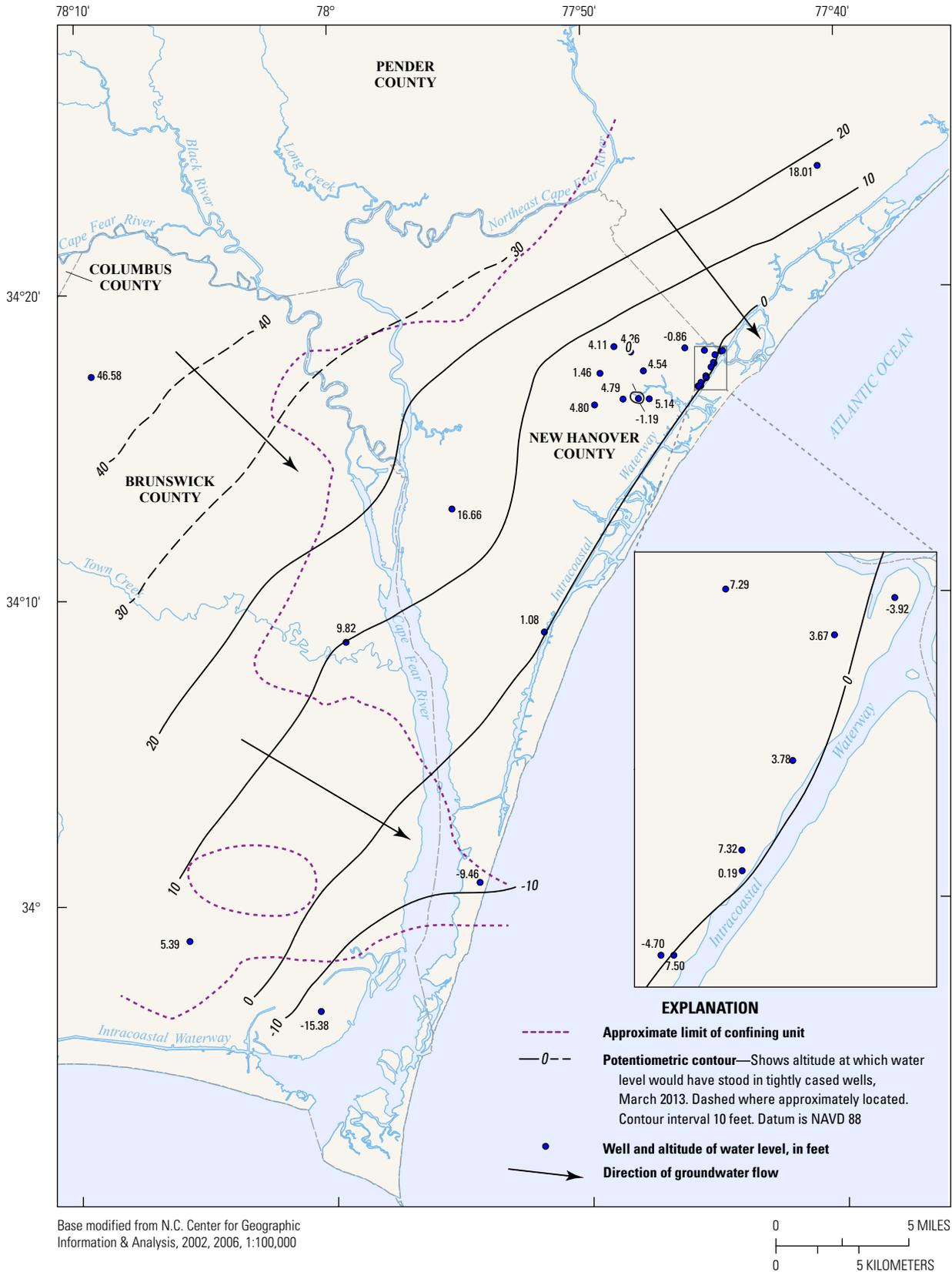


Figure 14B. Altitude of the potentiometric surface of the Peedee aquifer measured in March 2013 in Brunswick, New Hanover, and Pender Counties, North Carolina.

Vertical Hydraulic Gradients

Groundwater-level measurements at six well cluster sites were used to determine the vertical hydraulic gradient at several locations in the Castle Hayne and Peedee aquifers in late summer 2012 and early spring 2013. Four of the well clusters were located in northeastern New Hanover County, one in southeastern Pender County, and one in southeastern Brunswick County. The vertical gradient at each well cluster was calculated by dividing the difference in the groundwater level in the Peedee aquifer well and the Castle Hayne well by the difference between the centroid distance of the screened opening for each of the wells. The centroid of the opening in each well was calculated by adding the depth to the top of the screen and the depth to the bottom of the screen and dividing the results by two.

All six well clusters had a downward (negative) vertical gradient for the measured periods, with the exception of the NH-872/NH-873 well pair, which had a slight upward gradient in March 2013 (table 1). A water level for the Castle Hayne aquifer could not be measured in the NH-558 well during September 2012; therefore, a gradient could not be calculated for that period at the NH-574/NH-558 well cluster. The magnitude range of the calculated gradients varies by geographic location and is highest near areas with active groundwater withdrawals. Vertical gradients ranged from -0.351 to 0.020 foot per foot. A downward vertical gradient between the Castle Hayne and Peedee aquifers suggests that pressure in the Castle Hayne aquifer was high enough to prevent the upward seepage of groundwater from the Peedee aquifer into the Castle Hayne aquifer. In the area near well cluster NH-872/NH-873 (fig. 12), however, pressure in the Peedee aquifer was high enough to potentially seep upward into the Castle Hayne aquifer.

Water-Quality Conditions

Water-quality samples were collected at 97 well sites and 4 surface-water sites in August–September 2012 and analyzed to characterize the groundwater quality of the New Hanover County area (fig. 12). Of the 97 well sites, 7 were screened in the surficial aquifer, 42 in the Castle Hayne aquifer, 43 in the Peedee aquifer, and 5 were finished in multiple aquifers. Analytical results of groundwater samples were used to (1) statistically summarize water-quality characteristics, (2) determine the distribution of major ions, (3) map the concentration of dissolved iron and chloride, and (4) determine areas of active saltwater intrusion. Analytical results of groundwater samples were compared to State (North Carolina Department of Environment and Natural Resources, 2002) and Federal (U.S. Environmental Protection Agency, 2013) maximum contaminant levels (MCL) for drinking water to determine if sample constituents exceeded drinking water standard criteria. The analytical results were also compared to the U.S. Environmental Protection Agency (EPA) secondary

drinking water standards (SDWS). Results of all water-quality analyses are listed in appendix 2.

Results for physical properties measured during field water-quality sampling (temperature, pH, specific conductance, and dissolved oxygen concentration) are shown in boxplots for each aquifer (fig. 15). Temperature ranged from 17.4 to 27.5 °C in the Peedee aquifer, 17.3 to 23.0 °C in the Castle Hayne aquifer, 20.1 to 23.5 °C in the surficial aquifer, and 26.4 to 27.5 °C in the surface-water sites (fig. 15A).

Recorded values for pH ranged from 5.6 to 7.8 in the Peedee aquifer, 5.0 to 7.7 in the Castle Hayne aquifer, 4.5 to 7.4 in the surficial aquifer, and 5.6 to 7.9 in the surface-water sites (fig. 15B). The pH values of 8 samples were less than the lower limit of 6.5 as designated in the MCL and SDWS.

Specific conductance ranged from 106 to 3,420 microsiemens per centimeter ($\mu\text{S}/\text{cm}$) in the Peedee aquifer, 65 to 21,000 $\mu\text{S}/\text{cm}$ in the Castle Hayne aquifer, 90 to 800 $\mu\text{S}/\text{cm}$ in the surficial aquifer, and 50 to 53,600 $\mu\text{S}/\text{cm}$ in the surface-water sites (fig. 15C). The range in conductivity was largest in the surface-water samples, because the types of sample sites are different, ranging from freshwater ponds to seawater collected from the Intracoastal Waterway.

Dissolved oxygen (DO) concentrations ranged from 0.1 to 7.2 mg/L in the Peedee aquifer, 0.1 to 8.2 mg/L in the Castle Hayne aquifer, 0.1 to 6.8 mg/L in the surficial aquifer, and 2.73 to 7.4 mg/L for the surface-water sites (fig. 15D). The low median DO concentrations in the Peedee, Castle Hayne, and surficial aquifers were at or below 0.25 mg/L, suggesting that anoxic conditions were dominant.

Boxplots were also constructed for major cations (fig. 16), major anions, bromide, and iron (fig. 17). All plots use a logarithmic scale because sample results encompass multiple orders of magnitude for each dominant analyte. The smallest interquartile ranges were seen in the boxplots for calcium (fig. 16B) and bicarbonate (fig. 17A) in the Peedee and Castle Hayne aquifers. The concentrations of magnesium ranged from 0.568 to 468 mg/L in the groundwater samples and 1.2 to 1,340 mg/L in the surface-water samples (fig. 16C). Sodium concentrations for groundwater samples ranged from 3.73 to 3,710 mg/L (fig. 16D). Chloride concentrations for groundwater samples ranged from 4.99 to 7,350 mg/L, with most groundwater samples having concentrations less than 250 mg/L (fig. 17C). Surface-water sites had concentrations of chloride ranging from 10.6 mg/L in the Northeast Cape Fear River to 20,500 mg/L in the Intracoastal Waterway (fig. 17C). Bromide concentrations were highest in the Intracoastal Waterway at 60.7 mg/L, followed by 24.1 mg/L at the coastal well NH-842, which is open to the Castle Hayne aquifer (fig. 17D).

Because of oxidation-reduction (redox) reactions occurring under anaerobic conditions that can exist within the Castle Hayne and Peedee aquifer, microbial respiration was actively reducing sulfate into hydrogen sulfide gas, giving the groundwater a “rotten egg” odor when pumped for sampling. This redox reaction is a long-term continuous reaction that actively depletes the concentration of sulfate

Table 1. Calculated vertical head gradients at well-cluster sites for August–September 2012 and March 2013 in Brunswick, New Hanover, and Pender Counties, North Carolina.

[CH, Castle Hayne aquifer; PD, Peedee aquifer; ft, foot; NAVD 88, North American Vertical Datum of 1988; NM, not measured; —, data unavailable]

Well number	Aquifer	Land-surface		Opening		Centroid (feet below land surface)	Date of water level	Water-level elevation (feet above or below NAVD 88)	Date of water level	Water-level elevation (feet above or below NAVD 88)	Vertical gradient	
		altitude (feet NAVD 88)	Top (feet below land surface)	Bottom (feet below land surface)	land surface)						Fall 2012 (ft/ft)	Spring 2013 (ft/ft)
BR-082	CH	28.26	64	74	69	8/30/2012	4.24	4.62	3/14/2013	4.62	-0.262	-0.256
BR-081	PD	28.08	94	200	147	8/30/2012	-16.16	-15.38	3/14/2013	-15.38		
NH-548	CH	42.28	50	80	65	9/5/2012	29.08	31.78	3/19/2013	31.78	-0.348	-0.351
NH-564	PD	42.26	133	170	151.5	9/5/2012	-0.99	1.46	3/19/2013	1.46		
NH-556	CH	46.7	45	100	72.5	9/5/2012	29.2	30.92	3/19/2013	30.92	-0.271	-0.321
NH-572	PD	46.75	137	175	156	9/5/2012	6.6	4.11	3/19/2013	4.11		
NH-558	CH	48.17	49	95	72	NM	—	26.55	3/19/2013	26.55	—	-0.246
NH-574	PD	48.17	150	175	162.5	9/5/2012	0.67	4.26	3/19/2013	4.26		
NH-873	CH	6.22	29	39	34	9/7/2012	-6.65	-7.45	3/19/2013	-7.45	-0.024	0.020
NH-872	PD	6.22	165	180	172.5	9/7/2012	-9.98	-4.70	3/19/2013	-4.70		
PE-107	CH	57.35	80	160	120	9/5/2012	34.14	35.58	3/19/2013	35.58	-0.045	-0.049
PE-109	PD	57.35	477	487	482	9/5/2012	17.79	18.01	3/19/2013	18.01		

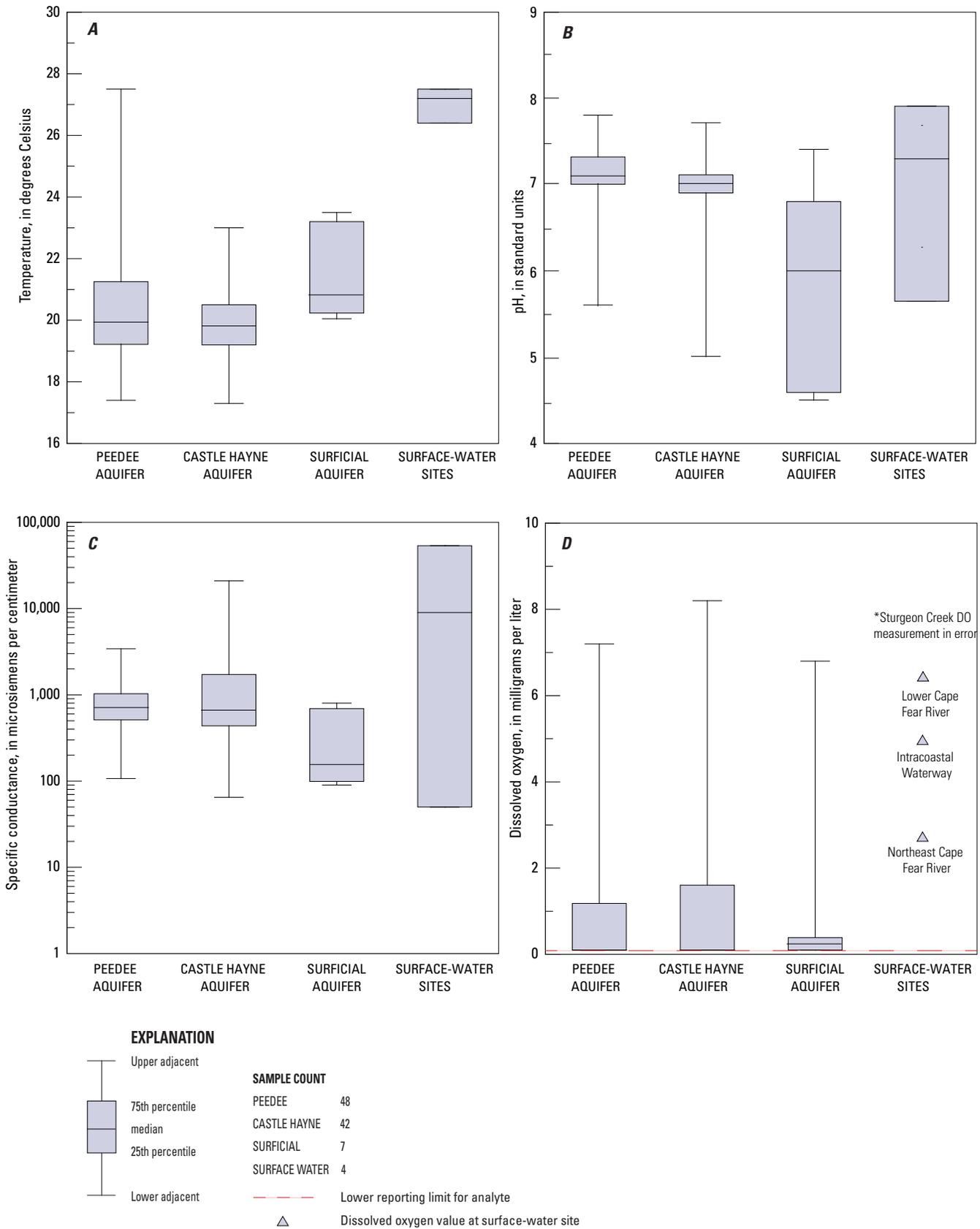


Figure 15. Boxplots showing range, median, and quartile statistical values for *A*, temperature, *B*, pH, *C*, specific conductance, and *D*, dissolved oxygen concentrations in the wells and surface-water sites recorded during the August–September 2012 sampling events in Brunswick, New Hanover, and Pender Counties, North Carolina.

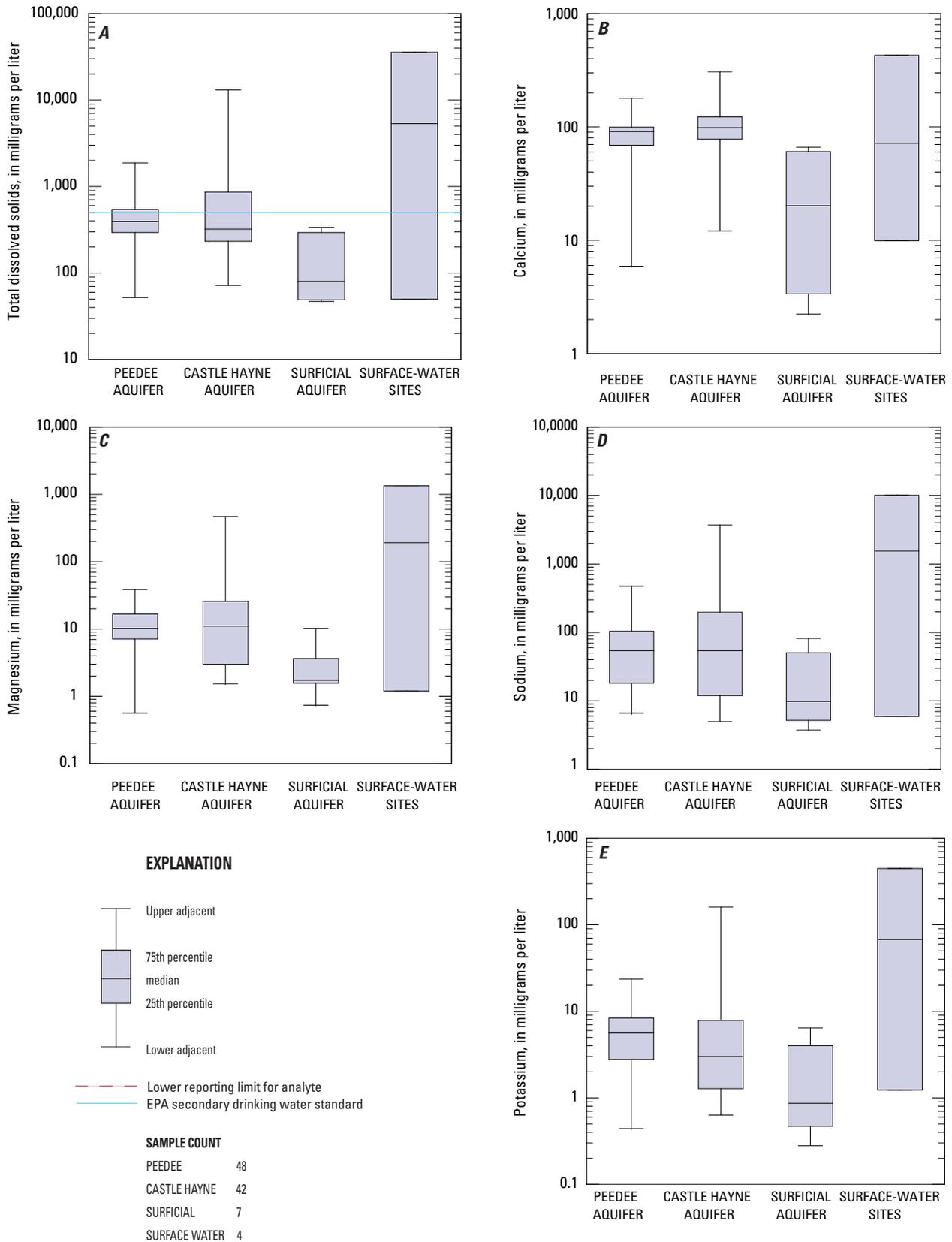


Figure 16. Boxplots showing range, median, and quartile statistical values for A, total dissolved solids, B, calcium, C, magnesium, D, sodium, and E, potassium in the wells and surface-water sites recorded during the August–September 2012 sampling events in Brunswick, New Hanover, and Pender Counties, North Carolina. The EPA secondary drinking water standards are guidelines for public water-supply managers and are provided here for reference only. The contaminants do not post a threat to human health at these levels.

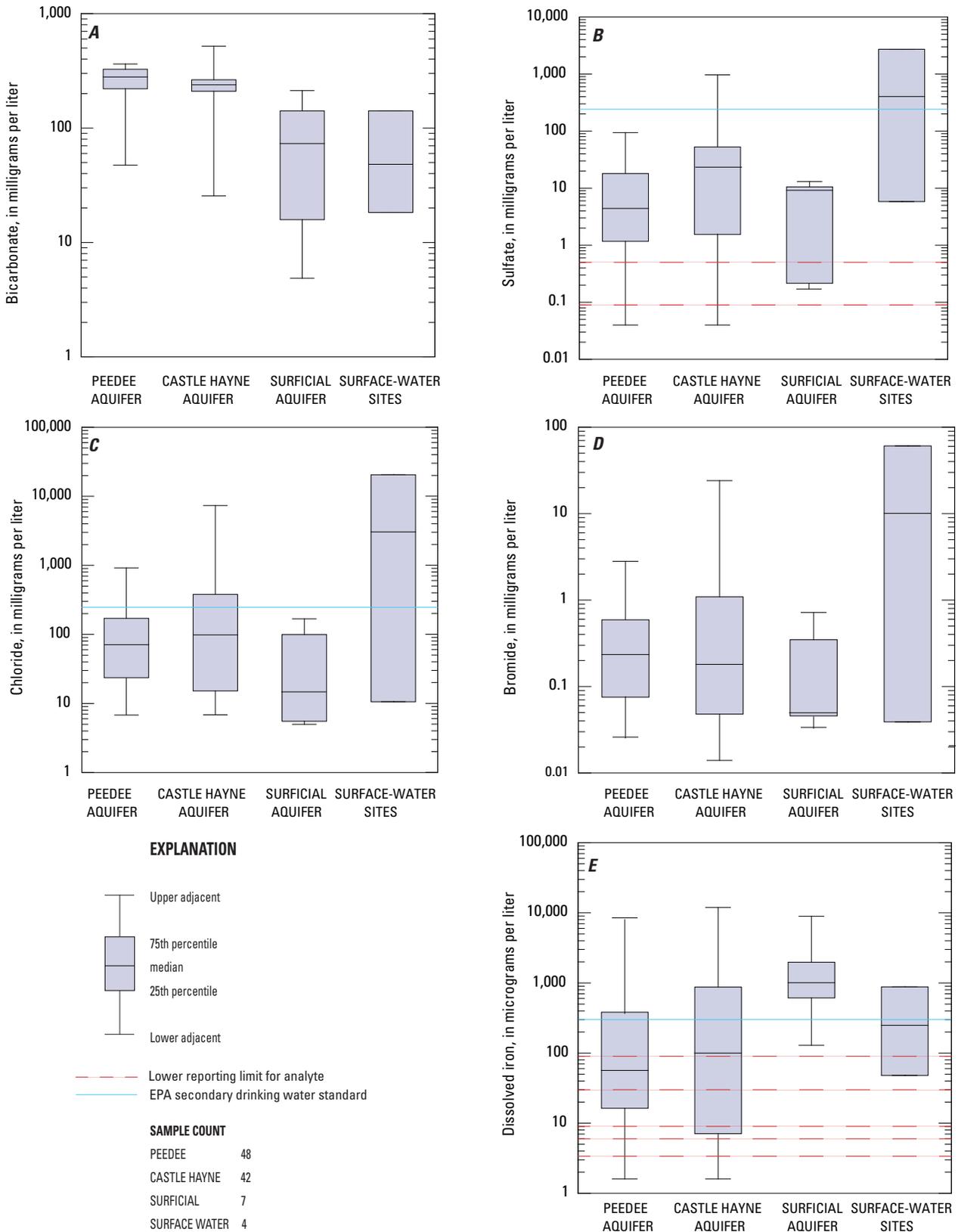


Figure 17. Boxplots showing range, median, and quartile statistical values for A, bicarbonate, B, sulfate, C, chloride, D, bromide, and E, dissolved iron in the wells and surface-water sites recorded during the August–September 2012 sampling events in Brunswick, New Hanover, and Pender Counties, North Carolina. The EPA secondary drinking water standards are guidelines for public water-supply managers and are provided here for reference only. The contaminants do not post a threat to human health at these levels.

in the aquifer over time. Measured sulfate concentrations in groundwater ranged from 0.04 to 965 mg/L, with the lowest median value of 4.56 mg/L found within the Peedee aquifer dataset (fig. 17B). Similar to sulfate, iron can also undergo a redox reaction in low dissolved oxygen environments, where insoluble ferric iron (Fe^{3+}) can be reduced to ferrous iron (Fe^{2+}) and thereby increase dissolved iron concentrations. Dissolved iron concentrations in the groundwater samples ranged across four orders of magnitude from 1.6 to 11,900 $\mu\text{g/L}$, with the highest levels in the Castle Hayne aquifer samples (fig. 17E).

The major ion chemistry of the sampled sites is displayed on a Piper diagram (fig. 18). The Piper diagram shows that calcium-bicarbonate type waters are roughly trending along a subhorizontal line toward waters that are dominated by sodium-chloride. Groundwater sampled from the Peedee and Castle Hayne aquifers generally plots near the calcium-bicarbonate end-member, while surface water sampled from the Intracoastal Waterway plots as the sodium-chloride end-member. This trend is typical of a coastal area underlain by a carbonate aquifer, where some degree of conservative seawater mixing occurs (Appelo and Postma, 2005; Sivan and others, 2005).

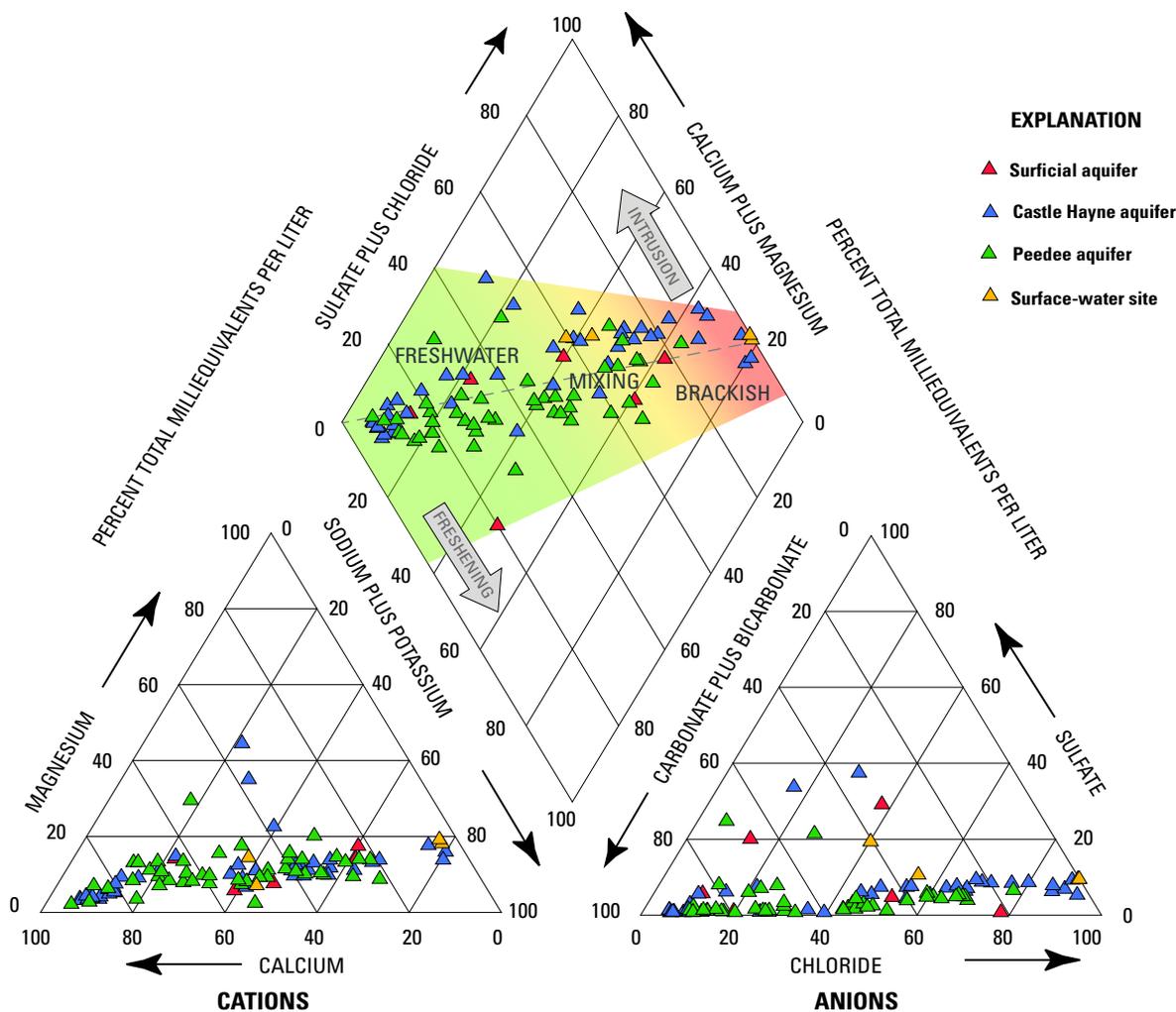


Figure 18. Water chemistry data for August–September 2012 displayed on a trilinear Piper diagram from water-quality samples collected at wells and surface-water sites in Brunswick, New Hanover, and Pender Counties, North Carolina.

The Piper diagram was also geochemically subdivided for freshwater to brackish water using grading criteria based on conservative groundwater-seawater mixing and ion-exchange reactions within the aquifer material (fig. 18). Freshwater was determined to include water samples that had chloride concentrations less than 250 mg/L, while brackish water samples had chloride concentrations that exceeded 1,000 mg/L. On the basis of these criteria, a majority (72 percent) of the samples were classified as freshwater, 7 percent as brackish, and 21 percent as a mixture of freshwater and brackish water. However, there is a marked difference in the distribution when subdivided by aquifer. Of the 42 groundwater samples collected from the Castle Hayne aquifer, 25 samples (60 percent) were classified as freshwater, and 5 samples (12 percent) were classified as brackish water. In contrast, of the 43 Peedee aquifer and 5 Castle Hayne/Peedee aquifer groundwater samples collected, 42 were classified as freshwater (88 percent), and no samples exceeded the 1,000 mg/L chloride threshold to be classified as brackish. One sample from well NH-850 showed a large component of brackish water mixing with groundwater and, with a chloride concentration of 919 mg/L, is near the classification threshold.

Contour maps were constructed to display the approximate distribution of dissolved iron concentrations in the Castle Hayne and Peedee aquifers (figs. 19 and 20, respectively), as dissolved iron is pervasive in both source-water aquifers, but its concentration varies considerably to include specific areas of high and low concentrations. The North Carolina MCL and EPA SDWS contaminant level for dissolved iron is 300 µg/L. Concentrations of dissolved iron that are greater than 300 µg/L can alter the aesthetics of the water by causing a metallic or bitter taste as well as staining clothes, washbasins, and other surfaces. High concentrations of dissolved iron (>3,600 µg/L) in the Castle Hayne aquifer are present in the northeast section of the study area and in Brunswick County, where the aquifer is near the land surface (fig. 19). Dissolved iron concentrations are lower (<470 µg/L) where the overlying confining unit is thick and the Castle Hayne aquifer is deeper within the subsurface near the southeastern coast of the study area. Similarly, dissolved iron concentrations in the Peedee aquifer are highest (>2,000 µg/L) in areas where the clay confining unit overlying the aquifer is intermittent to nonexistent, specifically in northwestern New Hanover County and large portions of Brunswick County (fig. 20). The presence of higher dissolved iron concentrations in groundwater near unconfined or intermittently confined areas may be attributed to the surficial aquifer where anaerobic conditions could enable the microbial reduction of ferric compounds within surficial deposits to infiltrate down into the lower aquifers. Tesoriero and others (2004) observed anaerobic conditions within the surficial aquifer of the Coastal Plain in North Carolina and concluded that areas with low topographic gradients, where horizontal flow dominates in poorly draining sediments, would provide adequate time for microbial oxidation of available organic matter to deplete oxygen levels.

The approximate distribution of the saltwater front in the Castle Hayne and Peedee aquifers was evaluated through the construction of chloride contour maps and then interpolating the position of the 250 mg/L line of equal chloride concentration (figs. 21 and 22, respectively). The freshwater/saltwater interface is defined in this report as the location of the 250 mg/L line of equal chloride concentration. Chloride concentrations greater than 250 mg/L cause the taste of water to become objectionable. Chloride concentrations in the Castle Hayne aquifer are elevated in two locations in the study area—along the Atlantic coast near the Pender/New Hanover County line and along the southern coast of Brunswick County at Bald Head Island (fig. 21). Despite these areas of concern, the large interior portions of the study area show low chloride concentrations in the Castle Hayne aquifer below 35 mg/L. Near the New Hanover/Pender County line, in the area between Futch and Pages Creeks, the 250 mg/L freshwater/saltwater interface contour extends about 1 mile inland from the Intracoastal Waterway. It is also in this area where the highest chloride concentration of 7,350 mg/L was measured at well NH-842 in the Castle Hayne aquifer. A seemingly anomalous chloride concentration of 305 mg/L was measured in well NH-870, located in north-central New Hanover County. Historic water-quality analyses reported for well NH-870 show that the chloride concentration has risen markedly since construction in 2010. Potential local sources for the elevated chloride concentration were not readily discernible at the time of this study.

In contrast, the Peedee aquifer exhibits a slightly increasing chloride gradient along the entire Atlantic coast. Chloride concentrations only exceed 250 mg/L in three areas: at one localized point in eastern Brunswick County near Town Creek, on the Intracoastal Waterway at the New Hanover/Pender County line, and on the Intracoastal Waterway in central New Hanover County (fig. 22). The highest chloride concentration in the Peedee aquifer was 919 mg/L, measured in well NH-850 located near the Intracoastal Waterway at the New Hanover/Pender County line between Futch and Pages Creeks. Chloride gradients for both the Castle Hayne and Peedee aquifers were also highest in that area.

In order to discern if the elevated chloride concentrations measured in the Castle Hayne and Peedee aquifers were caused by intrusion from modern seawater or from another chloride source, such as connate water, sewage effluent, or inorganic fertilizers, bromide and chloride were evaluated as conservative tracers. The concentrations of chloride and bromide are useful in salinity source studies because both ions act as conservative tracers in natural waters and both are present in appreciable amounts in seawater. In the case of seawater mixing, only dilution processes would have any effect on the source concentrations of chloride and bromide, while the proportion between the two ions would remain intact. Thus, observing a similar bromide-chloride relation between seawater and groundwater would denote that saltwater intrusion into the aquifer is the chloride source for groundwater-saltwater mixing. Equally, deviations from the bromide-chloride relation would indicate an alternate or additional source of chloride for groundwater.

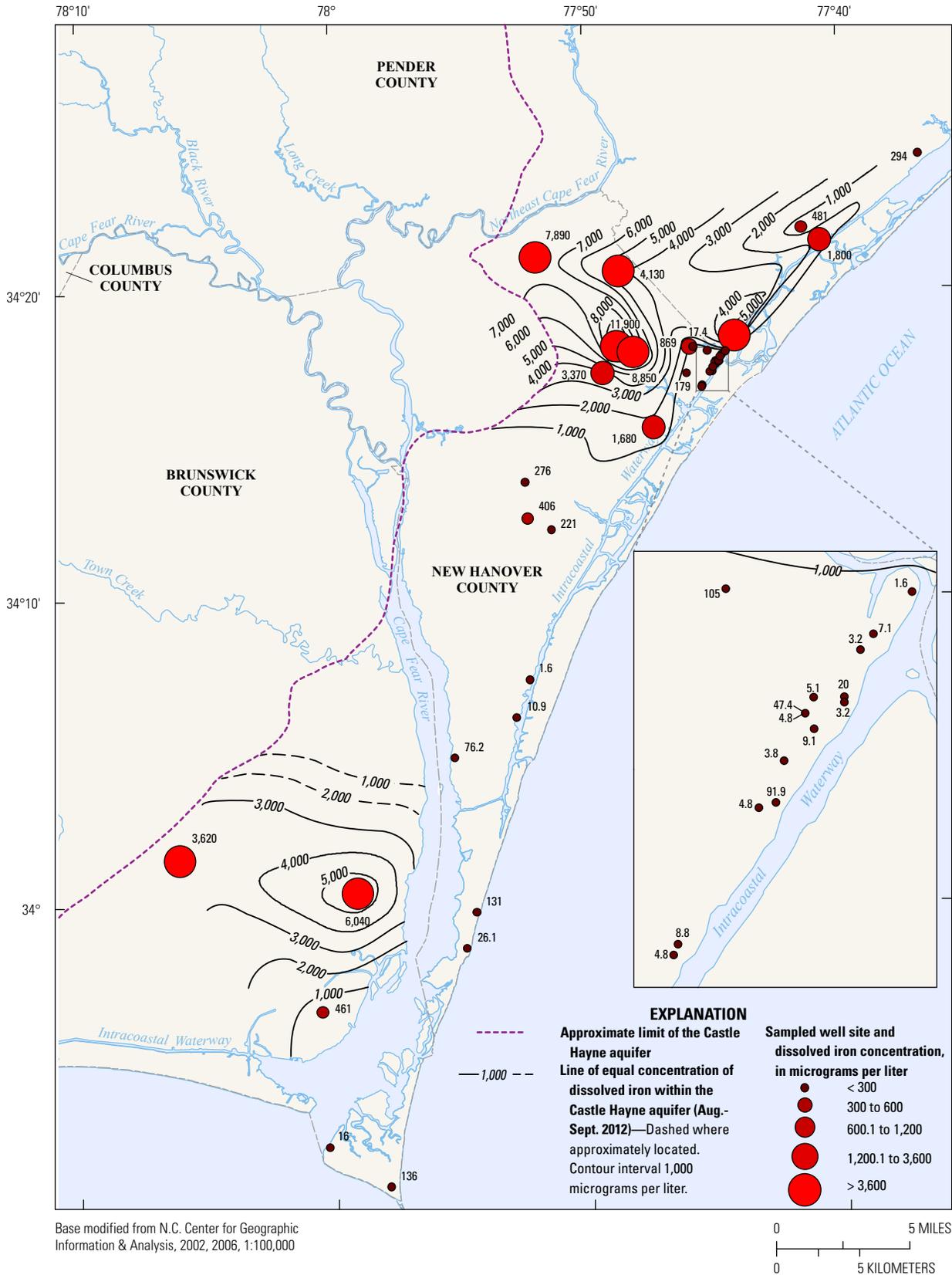
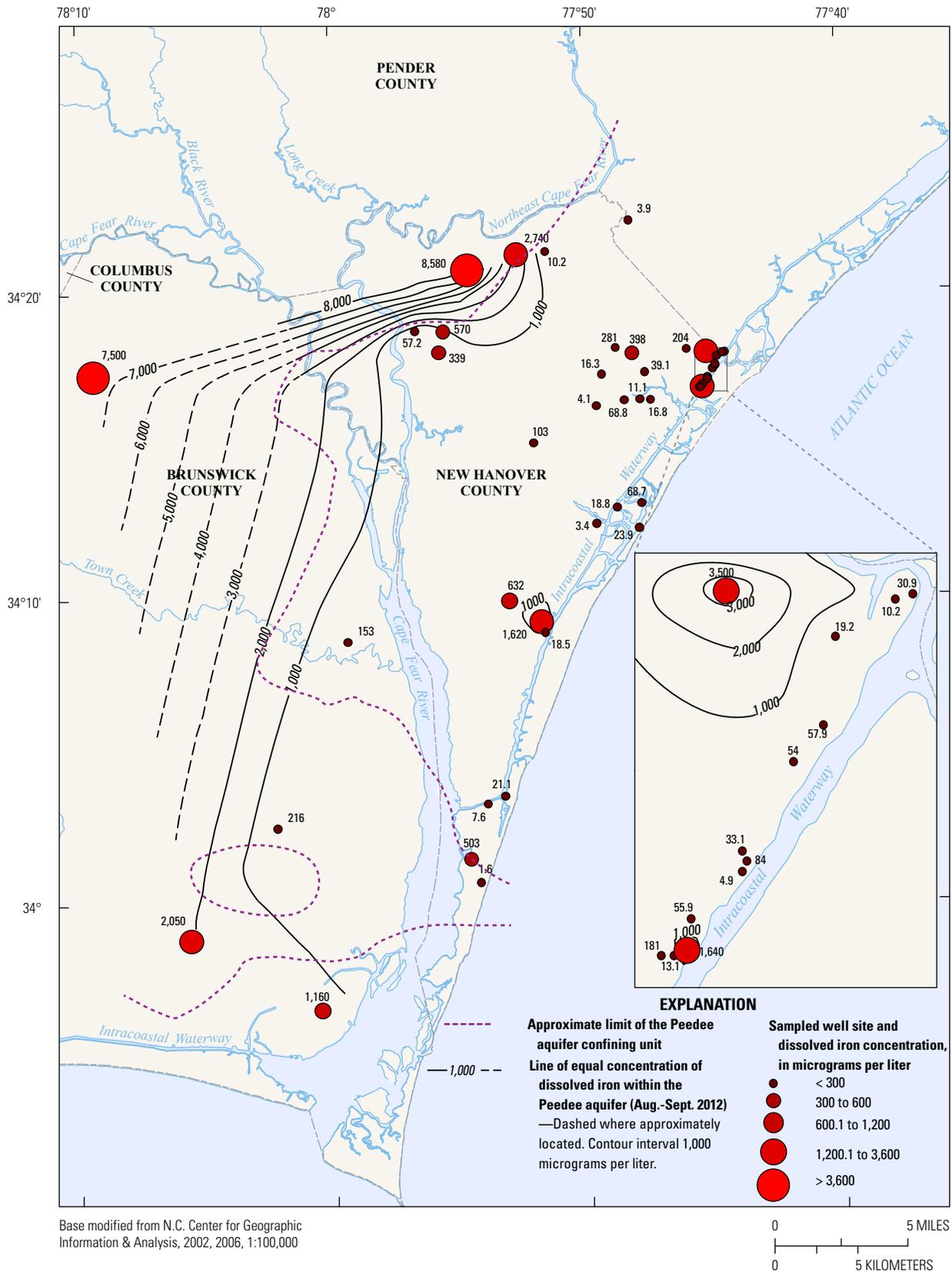


Figure 19. Location of wells sampled during August–September 2012 in the Castle Hayne aquifer with iron concentration values and approximate iron concentration contours in Brunswick, New Hanover, and Pender Counties, North Carolina.



Base modified from N.C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000

Figure 20. Location of wells sampled during August–September 2012 in the Peedee aquifer with iron concentration values and approximate iron concentration contours in Brunswick, New Hanover, and Pender Counties, North Carolina.

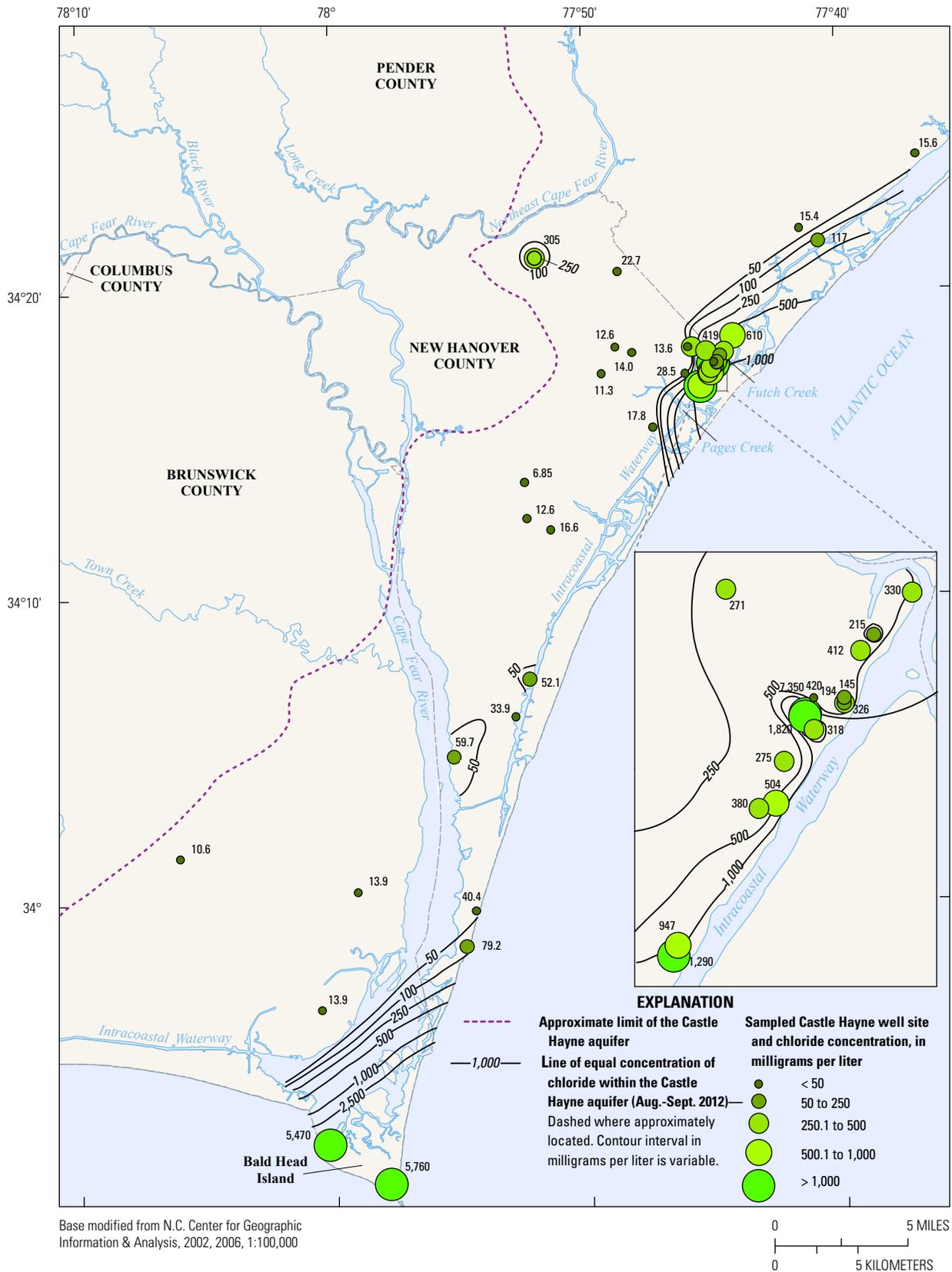
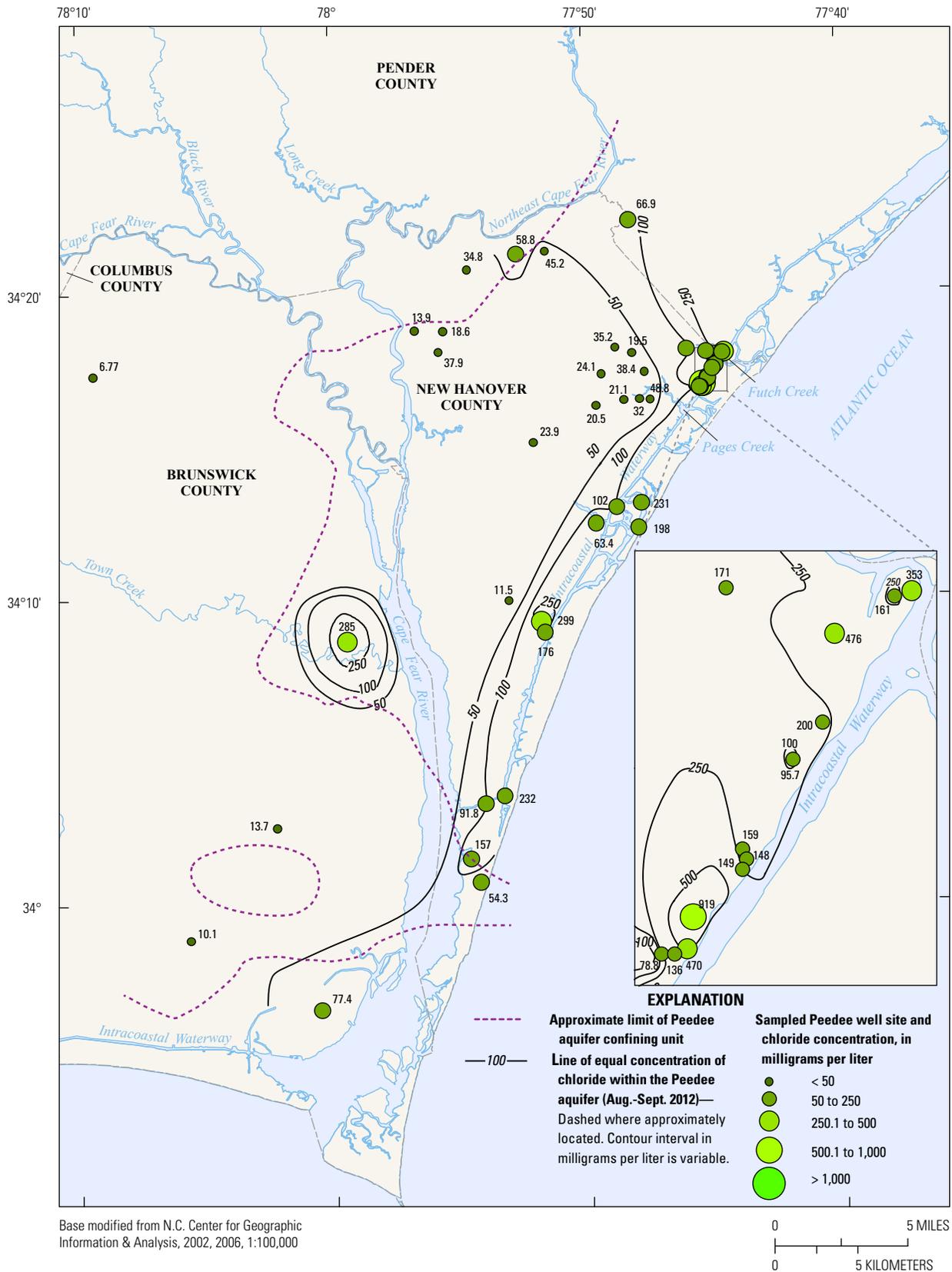


Figure 21. Location of wells sampled during August–September 2012 in the Castle Hayne aquifer with chloride concentration values and approximate chloride concentration contours in Brunswick, New Hanover, and Pender Counties, North Carolina.



Base modified from N.C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000

Figure 22. Location of wells sampled during August–September 2012 in the Peedee aquifer with chloride concentration values and approximate chloride concentration contours in Brunswick, New Hanover, and Pender Counties, North Carolina.

A plot of bromide and chloride concentrations measured at sites sampled during this study, by aquifer, is shown in figure 23. Using mean bromide and chloride concentrations for seawater (65 mg/L and 19,000 mg/L, respectively) from Hem (1985) and EPA SDWS for chloride (250 mg/L), figure 23 was subdivided into “freshwater,” “mixing,” and “seawater” areas. Almost 75 percent of the samples fell within the “freshwater” zone and about 25 percent of the samples would be considered to be influenced by seawater mixing. Most of the wells that showed evidence of saltwater intrusion were screened in the Castle Hayne aquifer near the coast. Most sampled sites exhibit a similar bromide-chloride relation as seawater based on the surface-water sample collected from the Intracoastal Waterway and most sites plot along a regression line with a coefficient of determination (R^2) value of 0.997. The relation seems to deteriorate when chloride concentrations are below 20 mg/L, which could be the result of less substantial sources of chloride (possibly in addition to seawater) either naturally occurring (wind-driven marine aerosols by way of rainfall recharge) or anthropogenic (leaking septic tanks, water-softener backwash brine, fertilizers, pesticides, and so forth) (Andreasen and Fleck, 1997). The bromide-chloride relationship for well NH-870 suggests that saltwater intrusion is not the source of the elevated groundwater chloride concentration (fig. 23).

Stable Isotopes of Water

Stable isotopes of many different elements are used in hydrology, although the most commonly used are hydrogen (H) and oxygen (O). The isotopic composition of water commonly varies between water sources, providing an indicator of source contribution from streamflow and groundwater recharge. Stable isotopes of water are particularly useful as natural groundwater tracers because they behave conservatively (chemically non-reactive) in aquifers at low temperatures, and fractionate (separate based on physical properties) in environments with less than 100 percent humidity. Physicochemical reactions and phase changes take place during processes such as evaporation and condensation, causing variations in stable isotope ratios. Groundwater typically is recharged directly by precipitation and retains the original isotopic signature of the climatic conditions present during the time of recharge. Surface water also originates as precipitation, but it undergoes evaporative isotopic enrichment by heavy isotopes (^2H and ^{18}O) as it moves downstream toward the ocean. If the isotopically enriched surface water later recharges a groundwater system, the groundwater will retain the enriched isotopic signature.

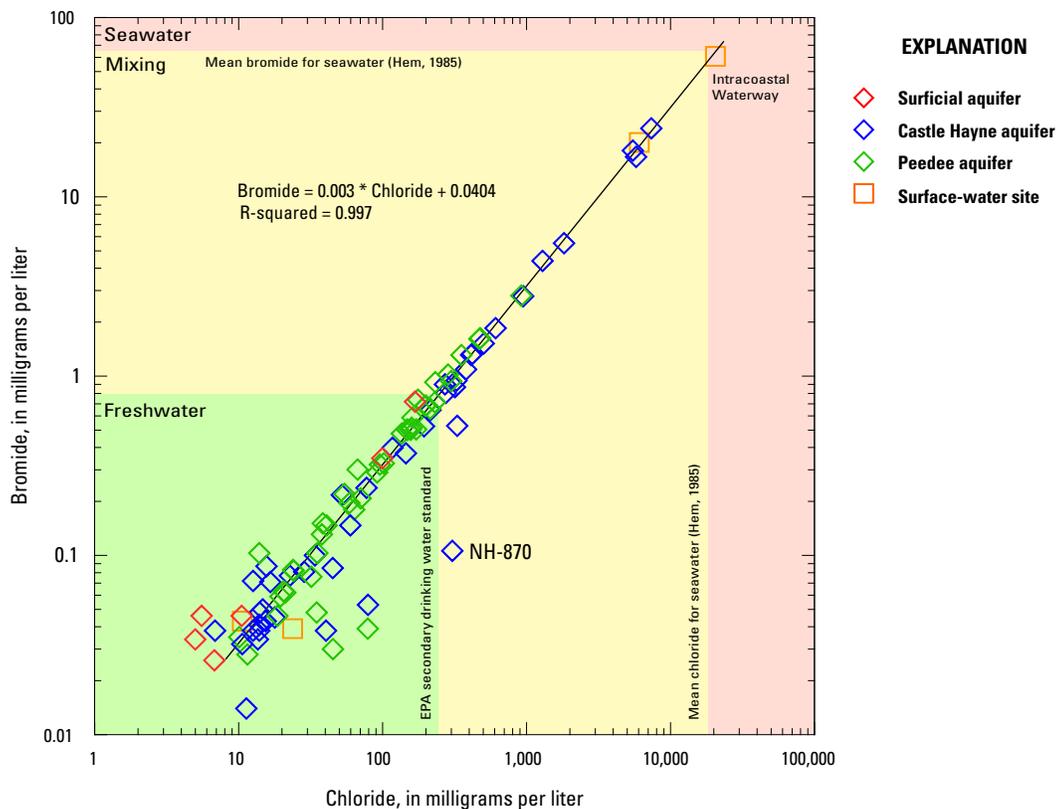


Figure 23. Bromide concentration plotted against chloride concentration for sites sampled during August–September 2012 in the surficial, Castle Hayne, and Peedee aquifers, as well as multiple surface-water sites in Brunswick, New Hanover, and Pender Counties, North Carolina.

Water isotope samples were collected from the 97 groundwater and 4 surface-water sites that were sampled for water quality in August–September 2012. The relation between the composition of δD and $\delta^{18}O$ in all water samples is plotted in figure 24. The δD and $\delta^{18}O$ results for groundwater in all three aquifers generally plotted along and in between the GMWL and the LMWL (fig. 24). This arrangement indicates that the groundwater is not very isotopically different from that of modern precipitation, signifying the recharge from rainfall has not undergone large amounts of evaporation before entering the aquifer.

However, the isotopic results for a few sampled wells plotted below the GMWL (fig. 24). Water that has undergone multiple cycles of evaporation would have an isotopic signature that is heavier (more positive) than modern precipitation, as would be expected from standing surface-water bodies open to evaporation near the coast. Groundwater samples that plot along this evaporation line (fig. 24) as well as samples from nearby surface-water sites suggest that there is some degree of groundwater-surface water mixing, notably seawater intrusion, within these areas. To a certain extent, δD and $\delta^{18}O$ values for groundwater found in the Peedee aquifer generally are slightly

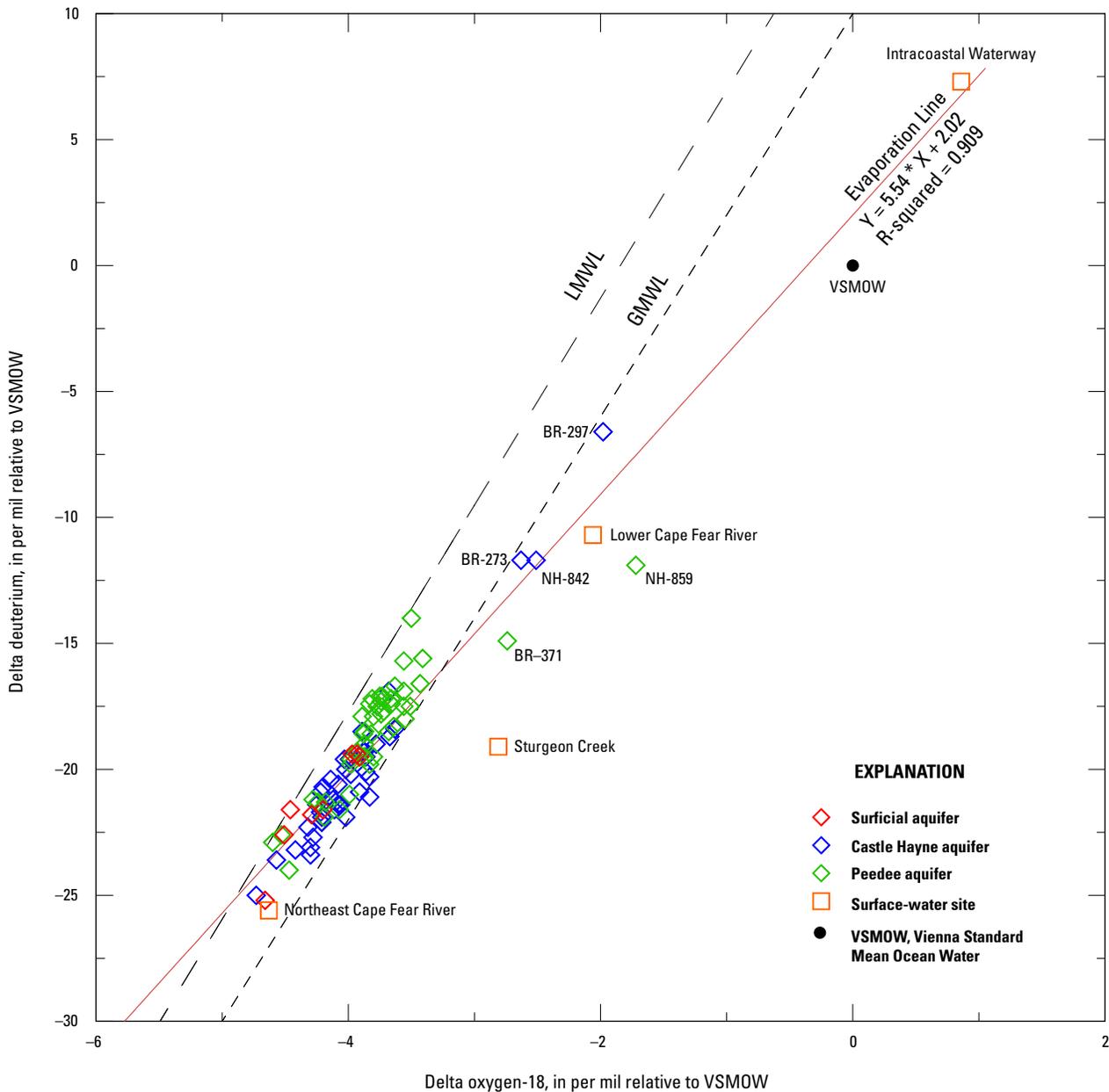


Figure 24. Relation between deuterium and oxygen-18 for wells sampled during August–September 2012 in the surficial, Castle Hayne, and Peedee aquifers, as well as multiple surface-water sites in Brunswick, New Hanover, and Pender Counties, North Carolina. Global Meteoric Water Line (GMWL) is based on Craig (1961); Local Meteoric Water Line (LMWL) is derived from precipitation data available in

more positive than those in the Castle Hayne and surficial aquifers. Because δD and $\delta^{18}O$ precipitation values are also indicative of air temperatures during condensation, this observed clustering may be the relic isotopic signature of pore water that dates to periods of warmer climate during the late Cretaceous age when the sediments were originally deposited.

Isotopic contour maps, or isoscapes, were constructed to predict the spatial distribution of $\delta^{18}O$ values in the groundwater on the basis of sample points within the Castle Hayne and Peedee aquifers across the study area (figs. 25 and 26, respectively). The $\delta^{18}O$ value distribution for both the Castle Hayne and Peedee aquifers generally reflects the location of recharge areas for each aquifer. Groundwater levels measured concurrently during water-quality sampling indicate areas of recharge for the Castle Hayne aquifer near the central and northeastern parts of the study area. The recharge areas coincide with the more negative values of $\delta^{18}O$ for the central (-4.57 per mil) and northeastern (-4.73 per mil) areas, which are comparable to the median isotopic value of -4.72 per mil (fig. 25) for local precipitation in the study area. Similarly, the more negative $\delta^{18}O$ values (near -4.50 per mil) found in the Peedee aquifer in northern New Hanover County, near where the overlying confining unit is missing, also suggests the influence of local recharge (fig. 26). The steepest isotope gradients in the Peedee aquifer involving one or two more positive values are those most likely to be affected by nearby surface-water bodies, because the overlying confining unit is not present.

Groundwater-Level Declines and Saltwater Intrusion

Quantifying saltwater intrusion movement is difficult without an extensive groundwater monitoring network. The North Carolina Department of Natural Resources and Community Development (now the NCDENR) installed many well nests across the coastal plain of North Carolina in the 1970s and 1980s to monitor ambient groundwater levels and quality in multiple aquifers. Although NCDENR installed a coastal well nest in southern Brunswick and Pender Counties, none were installed in New Hanover County. Therefore, only limited long-term ambient water-level and water-quality monitoring records are available for New Hanover County.

In the absence of long-term continuous groundwater-level and chloride records in New Hanover County, historic publications were data mined to help quantify the amount of groundwater-level and chloride concentration change that has occurred over time in the Castle Hayne and Peedee aquifers. Potentiometric surfaces were published by Bain (1970) for both the Castle Hayne and Peedee aquifers using groundwater-level data collected in October 1964. Chloride concentration maps also were published by Bain (1970) for the Castle Hayne and Peedee aquifers using water-quality data collected predominantly during the 1965 calendar year. These four Castle Hayne and Peedee aquifer potentiometric surface and chloride concentration maps were scanned, registered,

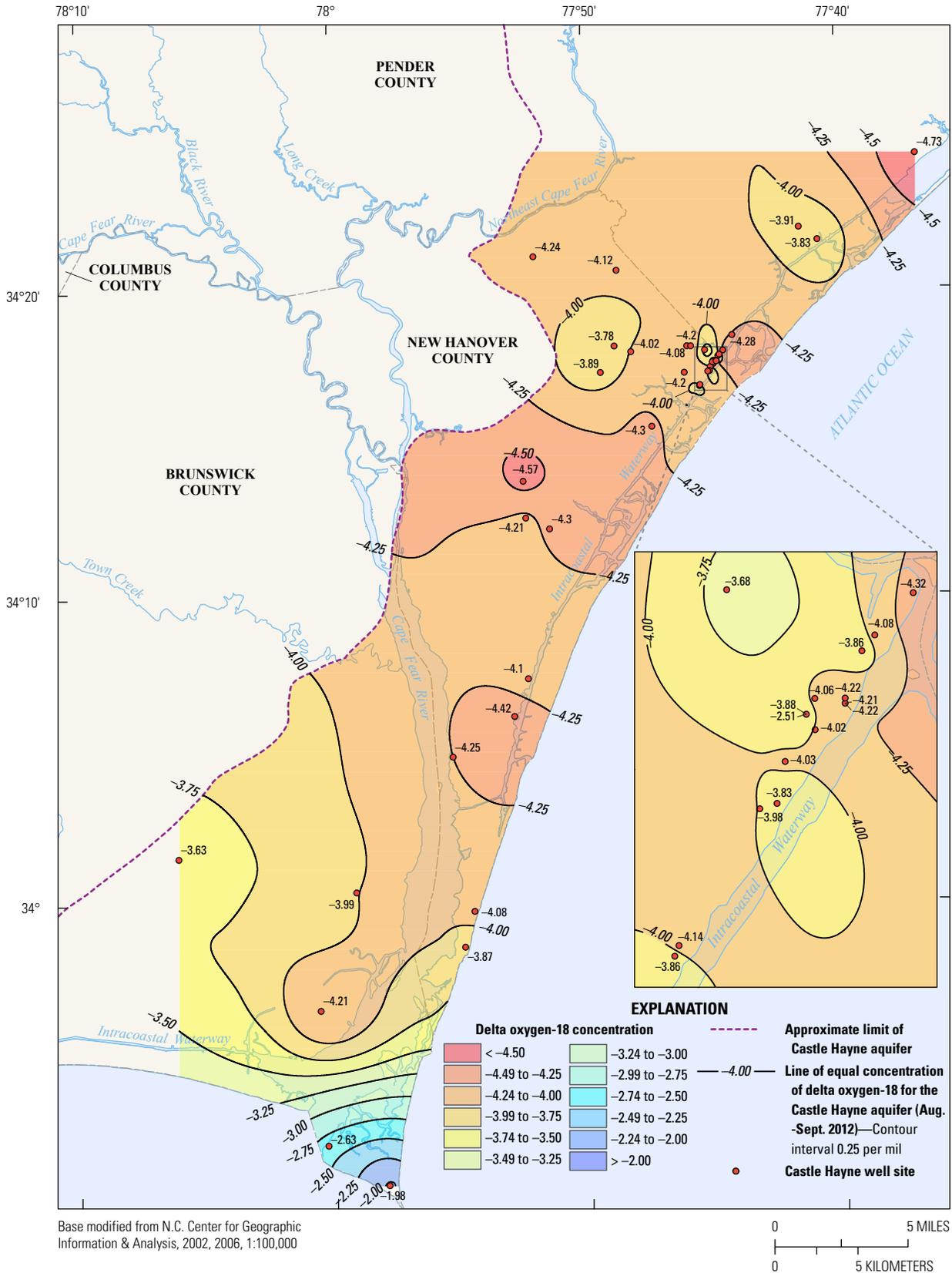
and georeferenced in a geographic information system (GIS), and a digital raster surface was created for each aquifer, using the contours. Additional raster surfaces were created in a GIS from the August–September 2012 potentiometric surfaces (figs. 13A and 14A) and chloride concentration maps (figs. 21 and 22). Water-level difference maps for the Castle Hayne and Peedee aquifers were created by subtracting the 1964 raster surfaces from the 2012 raster surfaces and contouring the resulting difference. Similarly, chloride concentration difference maps for the Castle Hayne and Peedee aquifers were created by subtracting the 1965 raster surfaces from the 2012 raster surfaces and contouring the resulting difference.

A groundwater change map from 1964 to 2012 for the Castle Hayne aquifer is shown in figure 27. Groundwater levels in the Castle Hayne aquifer have rebounded by about 10 ft over the last 48 years in the downtown Wilmington area, likely because this area is now fully served by public supply for domestic and irrigation usage (fig. 27). Rural areas of New Hanover County in 1964 are now suburban communities to the northeast, east, and south of Wilmington. Water-level declines in these areas reflect the increased stress that has been placed on the Castle Hayne aquifer with increased withdrawals over time. Groundwater-level declines in excess of 20 ft were calculated in an area west of Pages Creek in central New Hanover County. In both northern and southern New Hanover County, water-level declines of 10 ft were calculated over large areas.

A chloride concentration change map from 1965 to 2012 for the Castle Hayne aquifer is shown in figure 28. The northeast corner of New Hanover County has experienced the only large change in chloride concentration since 1965. Maps published in Bain (1970) display this area with chloride concentrations of about 100 mg/L. Nearly 50 years later, several domestic wells in the same area had chloride concentrations in excess of 1,000 mg/L (fig. 21), suggesting that active landward migration of the saltwater front is occurring within the Castle Hayne aquifer. A weak correlation also exists with the calculated water-level change for the Castle Hayne aquifer (fig. 27).

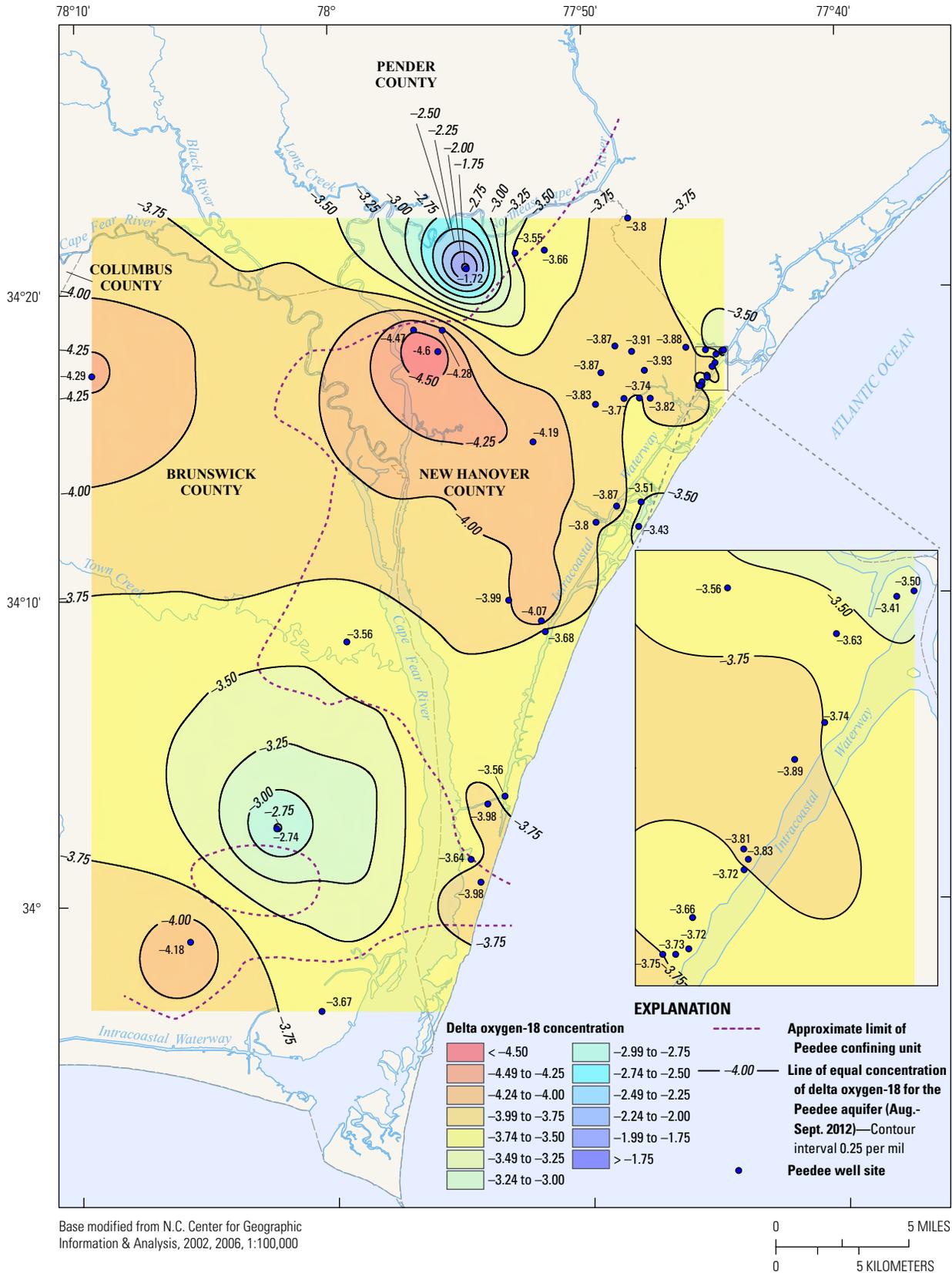
The difference in groundwater altitude from 1964 to 2012 for the Peedee aquifer is shown in figure 29. Because the Peedee aquifer has been used more extensively in 2012 than 50 years ago, one area of water-level increase was quantified in northwestern New Hanover County. Groundwater-level declines exceeding 20 ft were calculated in the northern and northeastern areas of New Hanover County. Both areas have been affected by industrial pumping for process supply and municipal water supply.

Figure 30 shows the difference in chloride concentration from 1965 to 2012 for the Peedee aquifer. Two coastal areas had changes in chloride concentration. The south-central area increased by about 100 mg/L, but the source of the increase is unknown. The largest increased change in chloride concentration (250 mg/L) occurred in northeastern New Hanover County in the same general area where chloride increases in the Castle Hayne aquifer were observed.



Base modified from N.C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000

Figure 25. Location of wells sampled during August–September 2012 in the Castle Hayne aquifer with delta oxygen-18 values and approximate delta oxygen-18 concentration contours in Brunswick, New Hanover, and Pender Counties, North Carolina.



Base modified from N.C. Center for Geographic Information & Analysis, 2002, 2006, 1:100,000

Figure 26. Location of wells sampled during August–September 2012 in the Peedee aquifer with delta oxygen-18 values and approximate delta oxygen-18 concentration contours in Brunswick, New Hanover, and Pender Counties, North Carolina.

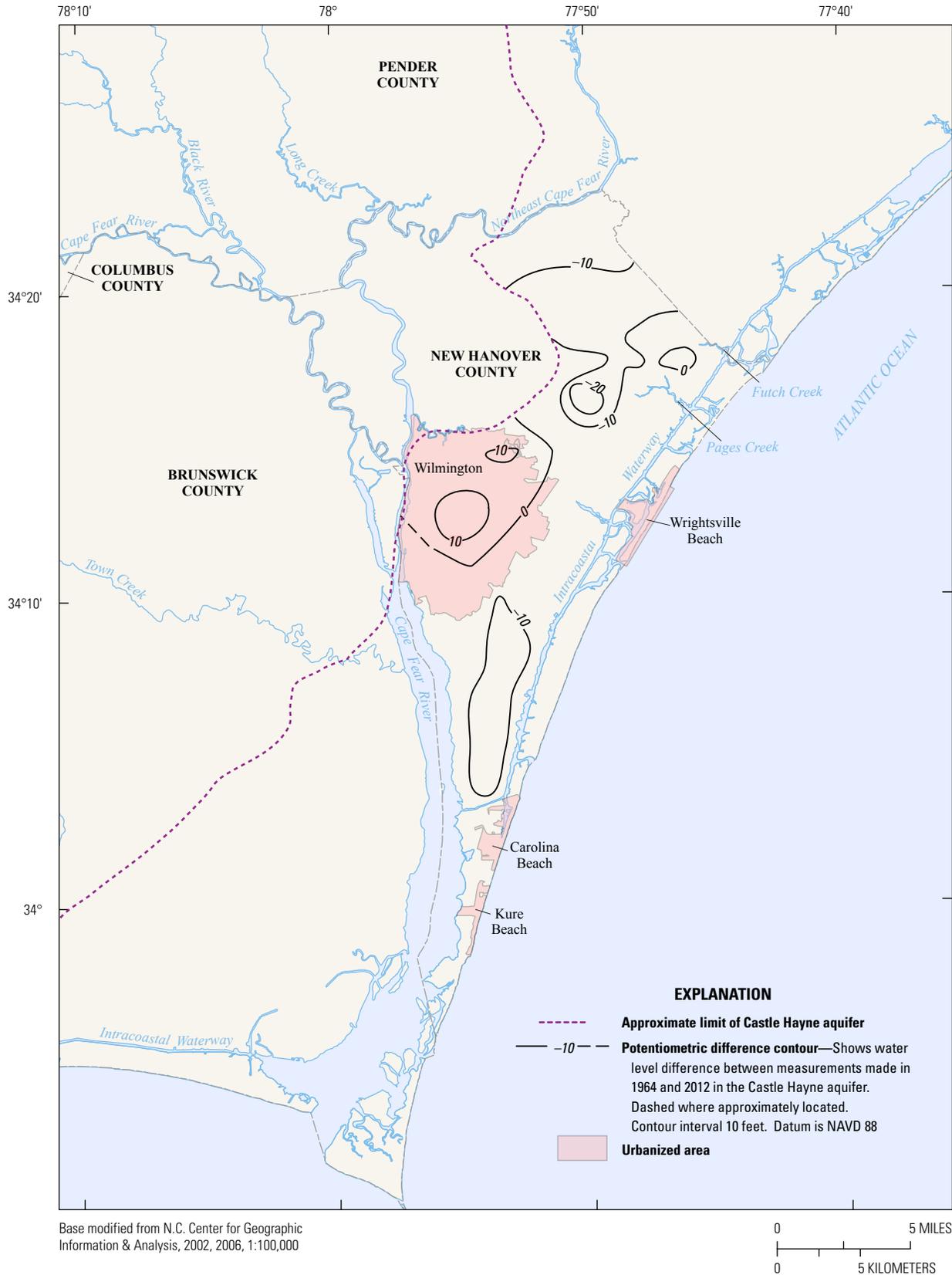


Figure 27. Potentiometric differences between water-level measurements made in 1964 and 2012 in the Castle Hayne aquifer in New Hanover County, North Carolina.



Figure 28. Chloride concentration differences between water-quality samples collected in 1965 and 2012 in the Castle Hayne aquifer in New Hanover County, North Carolina.

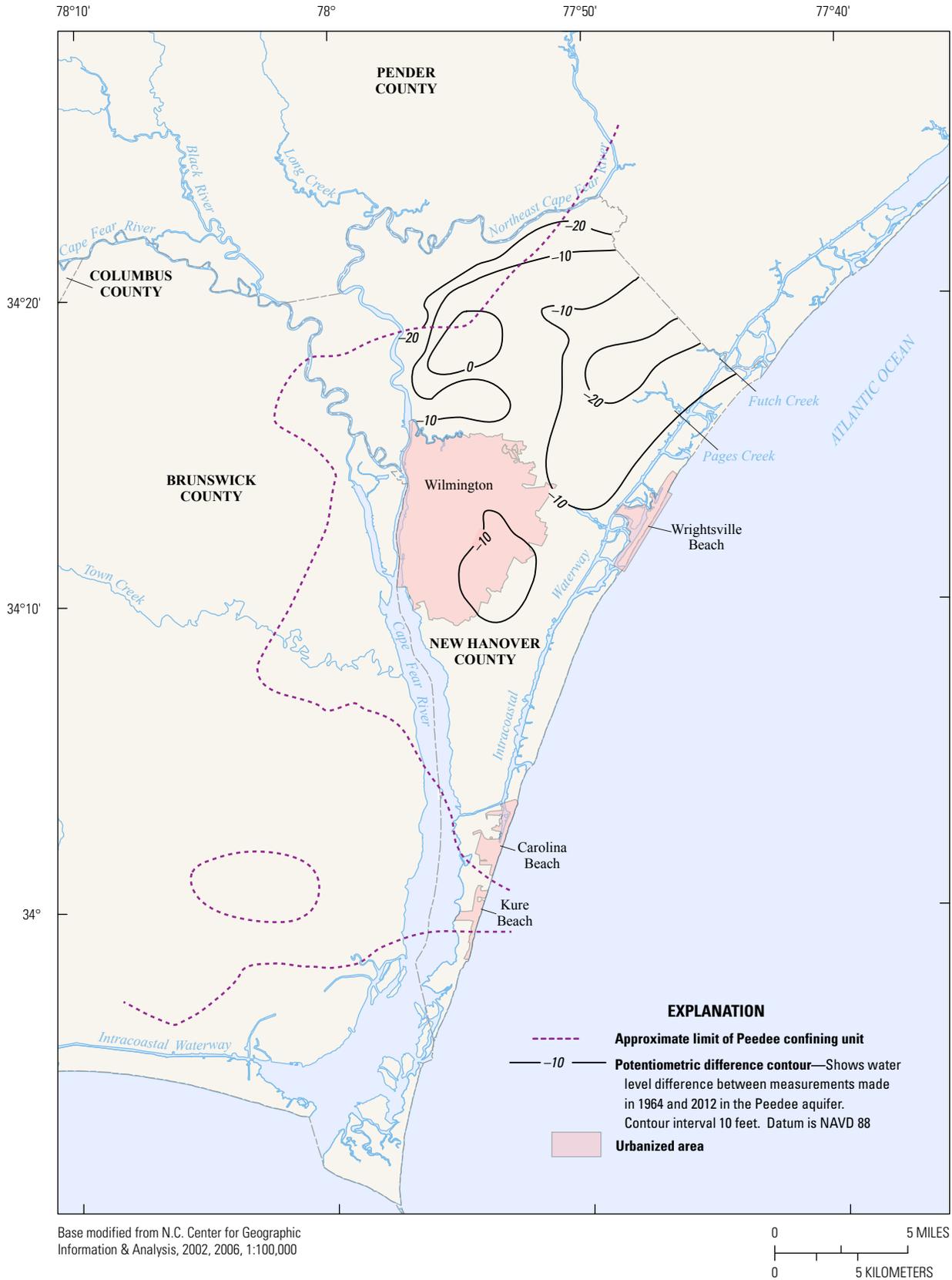


Figure 29. Potentiometric differences between water-level measurements made in 1964 and 2012 in the Peedee aquifer in New Hanover County, North Carolina.

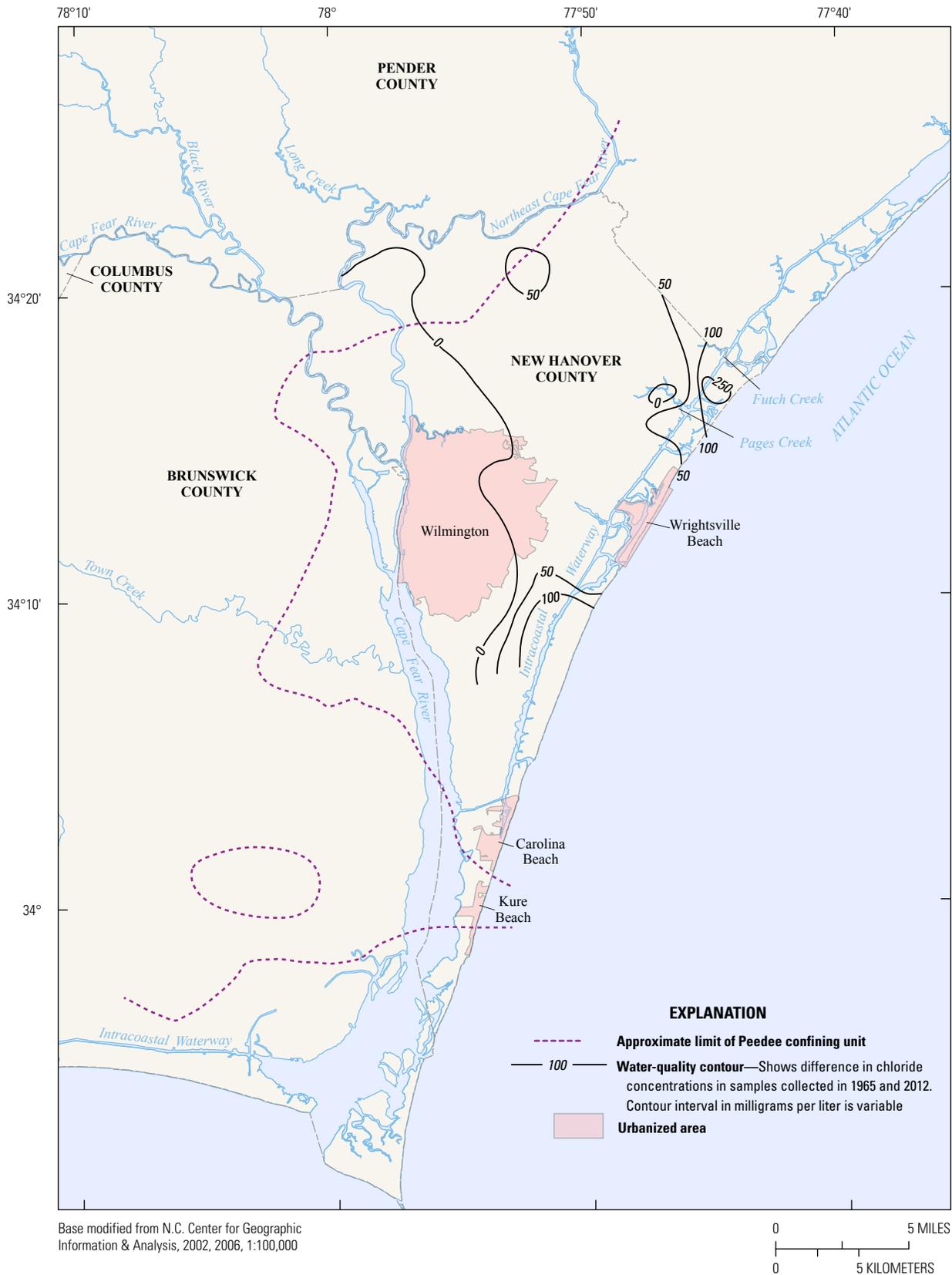


Figure 30. Chloride concentration differences between water-quality samples collected in 1965 and 2012 in the Peedee aquifer in New Hanover County, North Carolina.

Many small and large water users actively withdraw water from the Castle Hayne and Peedee aquifers in north-eastern New Hanover County. Seasonal irrigation withdrawals for homeowners and golf courses occur from both aquifers. A private water supplier located on one of the barrier islands just to the east of the Intracoastal Waterway withdraws water from the Peedee aquifer, and several municipal supply wells located a few miles inland withdraw water from both aquifers. Additionally, some communities do not have access to public water and those homeowners rely on domestic wells. During field reconnaissance for this study, it was discovered that about 3 percent of domestic wells in the area were screened in both the Castle Hayne and Peedee aquifers. Although this construction practice may have improved well productivity and mitigated aesthetic water-quality problems for the homeowner by blending water from both aquifers, the practice has also created a hydraulic conduit to connect the Castle Hayne and Peedee aquifers. Water-quality degradation is not isolated to one aquifer—over time, water quality in both aquifers degrades.

In studies conducted by the NCDENR DWR (Nat Wilson, written commun., July 20, 1999 and Northeast New Hanover Conservancy (Harris, 1998)), chloride concentrations measured in the Castle Hayne aquifer were described as generally low, averaging less than 300 mg/L (with a range of 20 to 800 mg/L) during a monitoring period from February 1995 to December 1997. Chloride concentrations in the Peedee aquifer during the same period averaged less than 500 mg/L (with a range of 64 to 750 mg/L).

Anecdotal evidence also suggests that saltwater intrusion in the Castle Hayne and Peedee aquifers in other parts of the study area may be occurring. Contemporaneous to the Bain (1970) study, the North Carolina Department of Water and Air Resources Water Pollution Control Division published a summary of the chemical and physical character of municipal water supplies in North Carolina for water samples collected from 1960 to 1965 (Phibbs, 1969). Chloride concentration values measured in groundwater production wells at that time were published for the barrier island towns of Wrightsville Beach, Carolina Beach, and Kure Beach in New Hanover County. Although the public-supply wells sampled in the early 1960s are not the exact same wells sampled for this study in 2012, some general comparisons can be made.

In the Wrightsville Beach area, seven supply wells were completed in the Peedee aquifer and were used for public supply. In 1965, these seven wells had chloride concentrations that ranged from 87 to 187 mg/L, with a median of 136 mg/L (Phibbs, 1969). The town of Wrightsville Beach continues to withdraw groundwater from the Peedee aquifer with measured chloride concentrations during this study averaging about 175 mg/L in three supply wells (fig. 22). The relatively unchanged chloride concentrations suggest that the location of the freshwater/saltwater interface in the Peedee aquifer has been relatively stable in the Wrightsville Beach area over the last 48 years.

The towns of Carolina Beach and Kure Beach on the southern end of New Hanover County also withdraw from the same source aquifers (Peedee and Castle Hayne, respectively) as they did in 1964. Chloride concentrations measured in five Carolina Beach supply wells in 1964 (Phibbs, 1969) ranged from 37 to 50 mg/L. Concentrations of chloride measured in groundwater from the Peedee aquifer were much more variable in the three supply wells measured in 2012, ranging from 91 to 220 mg/L (fig. 22). This increase in chloride concentration over the last 48 years suggests that the freshwater/saltwater interface in the Peedee aquifer has moved inland, likely because of decreased pressure in the aquifer. In contrast, chloride concentrations in the Castle Hayne aquifer in the Kure Beach area have not changed much since 1964. The chloride concentrations measured in the town of Kure Beach production wells ranged from 37 to 50 mg/L in 1964 (Phibbs, 1964), and in 2012 chloride concentrations ranged from 34 to 64 mg/L (fig. 21). This minimal change in chloride concentration over nearly 50 years suggests that the freshwater/saltwater interface in the Castle Hayne aquifer near Kure Beach is stable.

Conclusions

Three freshwater aquifers are located in the greater New Hanover County area, the surficial, Castle Hayne, and Peedee aquifers, although the surficial aquifer is not used for water supply. The Castle Hayne aquifer is discontinuous across the study area, and both the Castle Hayne and Peedee aquifers are unconfined in some areas, particularly to the northwest. Groundwater flow in the Peedee aquifer was affected seasonally by industrial pumping during the study period. The vertical gradient between the Castle Hayne and Peedee aquifers in eastern Brunswick, southeastern Pender, and northeastern New Hanover Counties was generally downward, with the exception of one coastal well cluster, which had a very slight upward gradient in March 2013. The groundwater from the surficial, Castle Hayne, and Peedee aquifers had a stable isotopic composition similar to that of modern precipitation.

Water-quality analyses suggest that groundwater in the Castle Hayne and Peedee aquifers may be affected by high iron concentrations, and is highest in areas where the confining unit is absent. Chloride concentrations were above the MCL of 250 mg/L in both the Castle Hayne and Peedee aquifers in northeastern New Hanover County and in the Castle Hayne aquifer at Bald Head Island in Brunswick County. In the Castle Hayne aquifer, the freshwater/saltwater interface is located about 1 mile inland between Futch and Pages Creeks in northeastern New Hanover County.

Calculated groundwater altitude change maps suggest that in the last 48 years, the Castle Hayne aquifer has rebounded by 10 ft in central New Hanover County, but declined by more than 20 ft toward the Atlantic coast. The groundwater altitude in the Peedee aquifer has also declined

by more than 20 ft since 1964. Chloride concentration difference maps also suggest that chloride concentrations have increased by more than 250 mg/L in the northeastern area of New Hanover County over the last 48 years. Because water levels in the Castle Hayne and Peedee aquifers have declined by more than 20 ft near the Atlantic coast in northeastern New Hanover County and the freshwater/saltwater interface is located inland, hydrologic and geochemical conditions appear to be favorable to induce further saltwater intrusion in northeastern New Hanover County if existing groundwater withdrawal practices continue in the area.

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Manuscript approved August 27, 2014

Prepared by the USGS Science Publishing Network
Raleigh Publishing Service Center

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