

Prepared in cooperation with the North Carolina Department of Environment  
and Natural Resources

## Baseline Well Inventory and Groundwater-Quality Data from a Potential Shale Gas Resource Area in Parts of Lee and Chatham Counties, North Carolina, October 2011–August 2012



Data Series 861

**Background Photograph:** Private well cover structure in Lee County, North Carolina, April 2012 (photograph by Douglas G. Smith, U.S. Geological Survey).

**Photograph on left:** Private well with concrete surface casing cover in Lee County, North Carolina, May 2012 (photograph by Douglas G. Smith, U.S. Geological Survey).

**Photograph on right:** Private wellhead construction in Lee County, North Carolina, showing surface casing and pump connections, well tag, and pressure tank, November 2011 (photograph by Mike Papay, Lee County, North Carolina, Public Health Department).

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**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:

Chapman, M.J., Gurley, L.N., and Fitzgerald, S.A., 2014, Baseline well inventory and groundwater-quality data from a potential shale gas resource area in parts of Lee and Chatham Counties, North Carolina, October 2011–August 2012: U.S. Geological Survey Data Series 861, 22 p., <http://dx.doi.org/10.3133/ds861>.

ISSN 2327-638X (online)



## Acknowledgments

The authors would like to thank all of the well and property owners who graciously allowed United States Geological Survey personnel access to their water-supply wells for the purpose of gathering field data and collecting groundwater-quality samples for this study. Much appreciation is extended to Susan Condlin, Lee County, North Carolina, Cooperative Extension Director, for hosting the public well owner meeting at the beginning of this study. Many thanks to the local well drillers, Worth Pickard and Russ Patterson, Patterson Exploration Services, for their discussions regarding well records and drilling experience in the study area. We appreciate cooperation and assistance from local County Health Department personnel including Terrell Jones, Roy Warren of the Lee County Public Health Department, Anne Lowry and Terri Ritter of the Chatham County Environmental Health Department. Special thanks to Mike Papay, formerly Lee County Public Health Department, who spent numerous hours searching through county well records. We greatly appreciated the cooperation of the Duke University Nicholas School of the Environment's Dr. Rob Jackson, Adrian Down, Alissa White, and the University of North Carolina at Chapel Hill Department of Geosciences, Katie Moore. Special thanks to Anne Chandler with the North Carolina Department of Environment and Natural Resources Division of Water Resources Laboratory for the support of analyses for selected organic compounds in well samples. The authors appreciate assistance from Lori Skidmore and Ray Milosh with the North Carolina Department of Environment and Natural Resources Division of Water Resources for field and sample preparation requirements for their internal laboratory.

Additional USGS North Carolina Water Science Center personnel who contributed to this study include Doug Smith, who inventoried wells in the field before sampling, and Erik Staub, Brad Huffman, and Dominick Antolino, who coordinated the field well sampling. Appreciation is extended to USGS colleague reviewers for this report Tim Kresse (Little Rock, AR) and Paul Heisig (Troy, NY).

Guidance and study approach discussions are appreciated from North Carolina Department of Environment and Natural Resources personnel Dr. Kenneth Taylor and Dr. Jeff Reid (Division of Energy, Mineral, and Land Resources, North Carolina Geological Survey) and Evan Kane and Rick Bolich (Division of Water Resources ). Funding for this study was provided by the North Carolina Department of Environment and Natural Resources, the USGS Cooperative Water Program in North Carolina, the USGS Water Mission Area Southeast Region, and the USGS Water Mission Area Office of Water Quality.

## Contents

Acknowledgments.....	iii
Abstract.....	1
Introduction.....	1
Purpose and Scope .....	1
Study Area.....	2
Geology.....	2
Aquifer System.....	2
Methods.....	6
Sampling and Quality Assurance/Quality Control .....	7
Data Summary .....	7
Water Well Data.....	7
Field Properties .....	7
Major Ions.....	10
Dissolved Metals.....	10
Exceedances .....	10
Methane .....	12
References Cited.....	18
Appendixes 1–4.....	21
Appendix 1.....	22
Appendix 2.....	22
Appendix 3.....	22
Appendix 4.....	22

## Figures

1. Map showing location of the Triassic Basins, urbanized areas, and the study area within the Piedmont Physiographic Province of North Carolina .....	3
2. Map showing topography of the study area showing colored shading of land-surface altitude depicting a trellised and rectangular drainage system, which suggests geologic controls .....	4
3. Map showing geology of the study area .....	5
4. Generalized geologic cross section showing Triassic-age deposits within the Sanford subbasin .....	6
5. Map showing locations of water supply wells and spring inventoried as part of this study including those where groundwater samples were collected .....	8
6. Map showing range of well depths inventoried across the study area.....	9
7. Graph showing well depth, casing depth, yield, and date of construction for wells inventoried in the study area .....	10
8. Map showing range of well yields inventoried across the study area .....	11
9. Graph showing field-measured properties of pH, dissolved oxygen, alkalinity, specific conductance, and temperature of well and spring water sampled in the study area .....	12
10. Map showing distribution of field pH values measured in well and spring water sampled in the study area .....	13

11. Map showing distribution of field specific conductance values measured in well and spring water sampled in the study area .....	14
12. Piper diagrams showing distribution of major ion geochemistry .....	15
13. Graph showing constituents exceeding at least one water-quality standard set by either the U.S. Environmental Protection Agency or the State of North Carolina .....	17
14. Graph showing range in detected dissolved methane gas analyses from well and spring samples in the study area .....	17

## Table

1. Number and percent of analyses exceeding at least one water-quality standard set by either United States Environmental Protection Agency or the State of North Carolina .....	12
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## Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:  
 $^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$ .

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:  
 $^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$ .

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here for instance, "North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, "North American Datum of 1983 (NAD 83).

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

## Abbreviations

BTEX	benzene, toluene, ethylbenzene, and xylene
C	carbon
CO <sub>2</sub>	carbon dioxide gas
D	deuterium
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
DRO	diesel-range organic compounds
GRO	gasoline-range organic compounds
GWSI	U.S. Geological Survey Groundwater Site-Inventory System
NAVD 88	North American Vertical Datum of 1988
NC DENR	North Carolina Department of Environment and Natural Resources
NWIS	U.S. Geological Survey National Water Information System
QA/QC	quality assurance and quality control
SVOCs	semivolatile organic compounds
USGS	U.S. Geological Survey
VOCs	volatile organic compounds



# Baseline Well Inventory and Groundwater-Quality Data from a Potential Shale Gas Resource Area in Parts of Lee and Chatham Counties, North Carolina, October 2011–August 2012

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## Abstract

Records were obtained for 305 wells and 1 spring in northwestern Lee and southeastern Chatham counties, North Carolina. Well depths ranged from 26 to 720 feet and yields ranged from 0.25 to 100 gallons per minute. A subset of 56 wells and 1 spring were sampled for baseline groundwater-quality constituents including the following: major ions; dissolved metals; nutrients; dissolved gases (including methane); volatile and semivolatile organic compounds; glycols; isotopes of strontium, radium, methane (if sufficient concentration), and water; and dissolved organic and inorganic carbon. Dissolved methane gas concentrations were low, ranging from less than 0.00007 (lowest reporting level) to 0.48 milligrams per liter. Concentrations of nitrate, boron, iron, manganese, sulfate, chloride, total dissolved solids, and measurements of pH exceeded federal and state drinking water standards in a few samples. Iron and manganese concentrations exceeded the secondary (aesthetic) drinking water standard in approximately 35 to 37 percent of the samples.

## Introduction

The U.S. Geological Survey (USGS) North Carolina Water Science Center conducted an inventory of well records in the Triassic Basins of Lee and Chatham Counties, North Carolina (fig. 1) and sampled selected water-supply wells and one spring to better delineate areas of groundwater use and to characterize groundwater quality prior to potential shale gas exploration in the State. Surface water supply for the study area also is available from the City of Sanford, in Lee County ([http://www.ncwater.org/Water\\_Supply\\_Planning/Local\\_Water\\_Supply\\_Plan/report.php?pwsid=03-53-010&year=2012](http://www.ncwater.org/Water_Supply_Planning/Local_Water_Supply_Plan/report.php?pwsid=03-53-010&year=2012)); accessed August 2014. The study period was from October 2011 through August 2012. Shale gas exploration has become economically viable in many areas of the United States (United States Energy Information Administration, 2013) as a result of improved directional drilling capabilities and high-volume hydraulic fracturing techniques. The quality of groundwater in drinking water aquifers near areas of shale gas drilling and production activities has been studied in several states including Pennsylvania (Osborn and

others, 2011; Breen and others, 2007), Arkansas (Kresse and others, 2012), and Wyoming (Wright and others, 2012). The compilation of baseline water well and groundwater-quality data in North Carolina makes possible future comparisons should drilling activities commence.

In June 2011, the North Carolina General Assembly passed House Bill 242 (<http://www.ncga.state.nc.us/Sessions/2011/Bills/House/PDF/H242v7.pdf>; accessed January 2014) directing the North Carolina Department of Environment and Natural Resources (NC DENR) to study issues related to potential shale gas exploration in the Triassic Basins of the State. A North Carolina Department of Environment and Natural Resources study report was released in April 2012 ([http://portal.ncdenr.org/c/document\\_library/get\\_file?uuid=9a3b1cc1-484f-4265-877e-4ae12af0f765&groupId=14](http://portal.ncdenr.org/c/document_library/get_file?uuid=9a3b1cc1-484f-4265-877e-4ae12af0f765&groupId=14); accessed January 2014) and addresses a wide variety of issues related to potential shale gas exploration in the State. More recently in July 2012, the North Carolina General Assembly ratified the “Clean Energy and Economic Security Act” (<http://www.ncleg.net/Sessions/2011/Bills/Senate/HTML/S820v6.html>; accessed January 2014), which directs NC DENR Division of Energy, Mineral, and Land Resources to assist the recently appointed NC Mining and Energy Commission in developing a modern regulatory program for the management of oil and gas exploration and development in the State, including the use of horizontal drilling and hydraulic fracturing (North Carolina Department of Environment and Natural Resources, 2014).

## Purpose and Scope

The purpose of this report is to present well inventory and groundwater-quality data collected during January through August 2012 in northwestern Lee County and extreme southeastern Chatham County, North Carolina (fig. 1). The study area was selected as a result of interest in exploration for shale gas resource extraction. Well inventory data were compiled to describe well construction characteristics, and the spatial distribution of active water-supply wells across the study area. From the 305 wells that were inventoried, a subset of 56 water-supply wells and 1 nearby spring were selected for sampling, based on available well construction data and access permissions. Analyses for collected groundwater-quality samples were tiered as a result of study funding limitations, with

the spatial groundwater-quality focus on major ion and dissolved gases (including methane) analyses for all 56 wells and the spring. As funding permitted, a subset of those selected wells (as many as 10 of the 56 wells) were sampled for additional analyses including dissolved metals; dissolved nutrients volatile and semivolatile organic compounds; glycols; isotopes of strontium, radium, methane (if sufficient concentration), and water; and dissolved organic and inorganic carbon.

## Study Area

The study area (fig. 1) was a previously delineated area having the most potential to develop shale gas based on available core and test drilling data and associated oil and gas “shows”, (an indication of oil or gas noted while drilling a borehole or well), within the Sanford subbasin within the Deep River Basin of the Triassic Basin area of North Carolina (fig. 1), as described by Reid and others (2011 and 2010). The total area defined by this boundary is about 79 square miles (fig. 1) which includes the northwestern quarter of Lee County and extreme southeastern Chatham County along the Deep River. Data from the 2010 U.S. Census indicates that 14,903 people live in the study area (<http://www.census.gov/geo/reference/ua/urban-rural-2010.html>; accessed January 2014) in northwestern Lee County and southeastern Chatham County, North Carolina.

Reinemund (1955) describes the topography of the Triassic rocks of the Deep River Basin as “lowland” because the geologic formations at land surface are more easily eroded than the surrounding crystalline rocks within the Piedmont Physiographic Province or nearby sand and gravel deposits in the Coastal Plain physiographic province. The Triassic Lowland in the Sanford subbasin generally is dissected, and generally has a trellised/rectangular drainage pattern, indicating geologic structural control. Land surface altitudes range from 205 to 493 feet (ft) (above NAVD 88; fig. 2).

## Geology

The study area is located in the Deep River Basin of the Triassic Basin area in North Carolina, is within the Piedmont Physiographic Province of the eastern United States, and is part of a group of extensional basins that formed during the Mesozoic Era (Milici and others, 2012). Geologic deposits within the Deep River Basin [regionally located within the Triassic Basin in North Carolina (fig. 1)] include the following sedimentary rock types: sandstone, conglomerate, shale, siltstone, claystone, coal, and small amounts of limestone and chert (Reinemund, 1955). These deposits also have been intruded by mafic diabase dikes and sills during the later Jurassic period [North Carolina Geological Survey, 1985 (fig. 3)]. Geologic formations mapped by Reinemund (1955) at the land surface in the Sanford subbasin include the Sanford Formation, the Cumnock Formation, and the Pekin Formation (fig. 3). These sedimentary rocks of the Deep River Basin were deposited as layers during early Mesozoic Era rifting of supercontinent Pangea and the opening of the Atlantic Ocean.

During rifting, the basin filled with clastic sediments, including alluvial fan, deltaic, lacustrine, and swamp deposits. The Deep River Basin is bordered to the east by a west-dipping, high angle, normal fault (Jonesboro Fault) (fig. 4). Intra-basinal faults also are mapped throughout the basin (fig. 3) (Reinemund, 1955; Reid and Taylor, 2011).

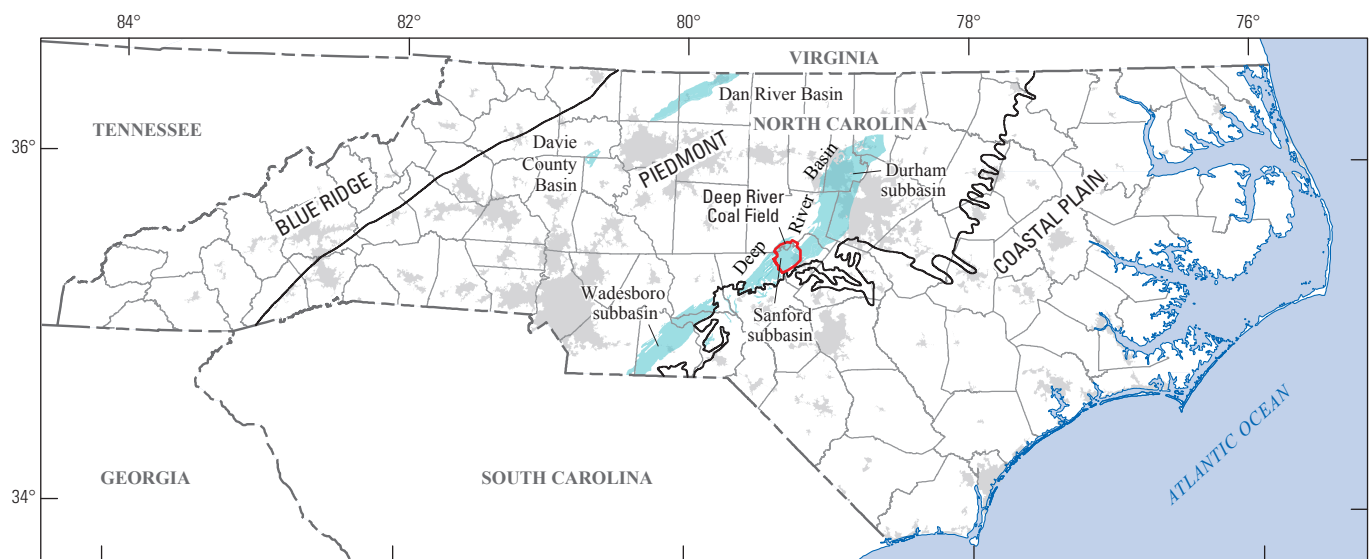
The natural gas resource reservoir rock in the study area is an organic-rich black shale (lacustrine gray and black fine-grained clastic rocks, fig. 4) within the Cumnock Formation (figs. 3 and 4) in the study area in Lee and Chatham Counties. The Cumnock Formation is described as dominantly a black and dark gray shale with associated gray sandstone and coal, approximately 230 to 250 meters thick (about 750 to 820 ft) (Reid and Taylor, 2011). The Cumnock Formation outcrops in the northern part of the study area (fig. 3) and dips beneath the Sanford formation to the south/southeast (fig. 4). Historic coal mining in the area was conducted during the Revolutionary War period in the late 1700s through the post-World War II Era. Small strip mining operations also were operated in the area again during the 1980s for a short time. Methane is known to be associated with these black shale/coal sequences as evidenced by the historic mine explosions at the Cumnock Mine (1895 and 1900) and Carolina Mine (1929) in study area (Reinemund, 1955).

Eight oil and gas test wells have been drilled in the study area since 1974 (Reid and others, 2010). Reid and Milici (2008) describe organic geochemical data, including oil and gas shows from test wells drilled in the study area. Milici and others (2012) provided an estimate of undiscovered oil and gas resources of the eastern U.S. East Coast Mesozoic basins (Milici and others, 2012, fig. 1). The assessment for the Deep River Basin included a mean estimate of 1,660 billion cubic feet of gas and 83 million barrels of natural gas liquids.

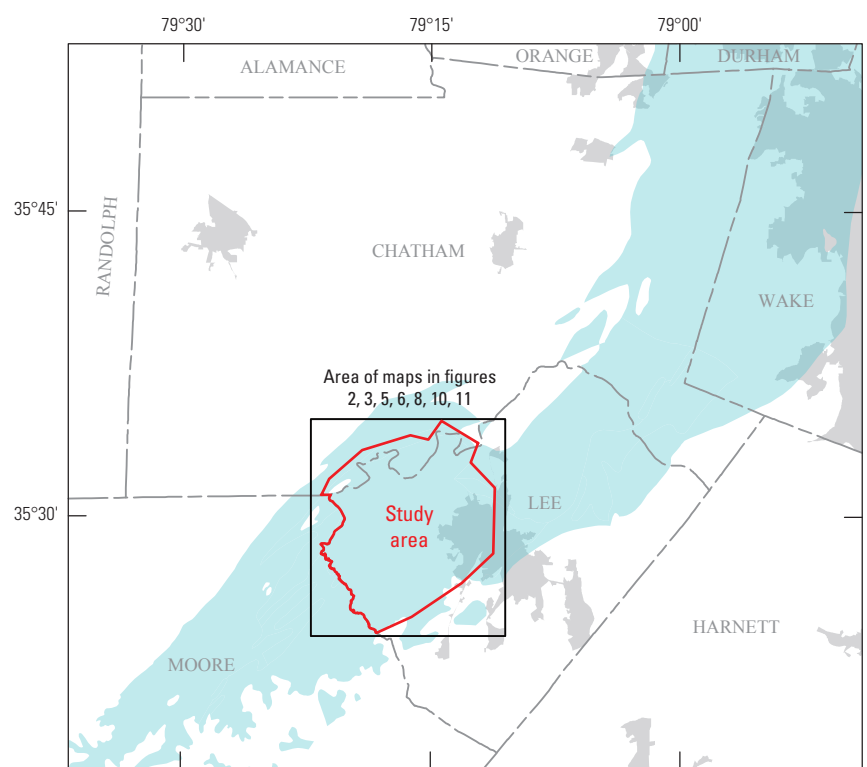
## Aquifer System

The groundwater system in the Triassic Basin of North Carolina is part of the Early Mesozoic Basin national aquifer described in Trapp and Horn (1997) within the Piedmont Physiographic Province of the eastern United States. The aquifer in the Triassic Basin of North Carolina generally consists of weathered regolith material (soil, saprolite, alluvium, colluvium) at land surface and underlying bedrock sedimentary rock layers. In some areas, bedrock is exposed at land surface and very little if any regolith material may be present. Water-supply wells typically are cased through the weathered regolith and completed as open boreholes in the more competent sedimentary rock layers.

Bain and Brown (1981) describe groundwater in the Triassic rocks of the nearby Durham subbasin (which is similar to the Sanford subbasin in rock composition and structure; located to the northeast of the study area, fig. 1) as occurring within the primary and secondary interstices of the rocks that have been enhanced by weathering and leaching of cement holding sedimentary grains in the rock together. The Triassic rocks of the Durham subbasin were described by Bain and



Basemap and geology modified from North Carolina Geological Survey (1985)  
 2010 U.S. Census Bureau Urbanized areas (<http://www.census.gov/cgi-bin/geo/shapefiles2010/file-download>;  
 accessed March 2014)



Basemap and geology modified  
 from North Carolina Geological Survey (1985)  
 Urbanized areas from U.S. Census Bureau

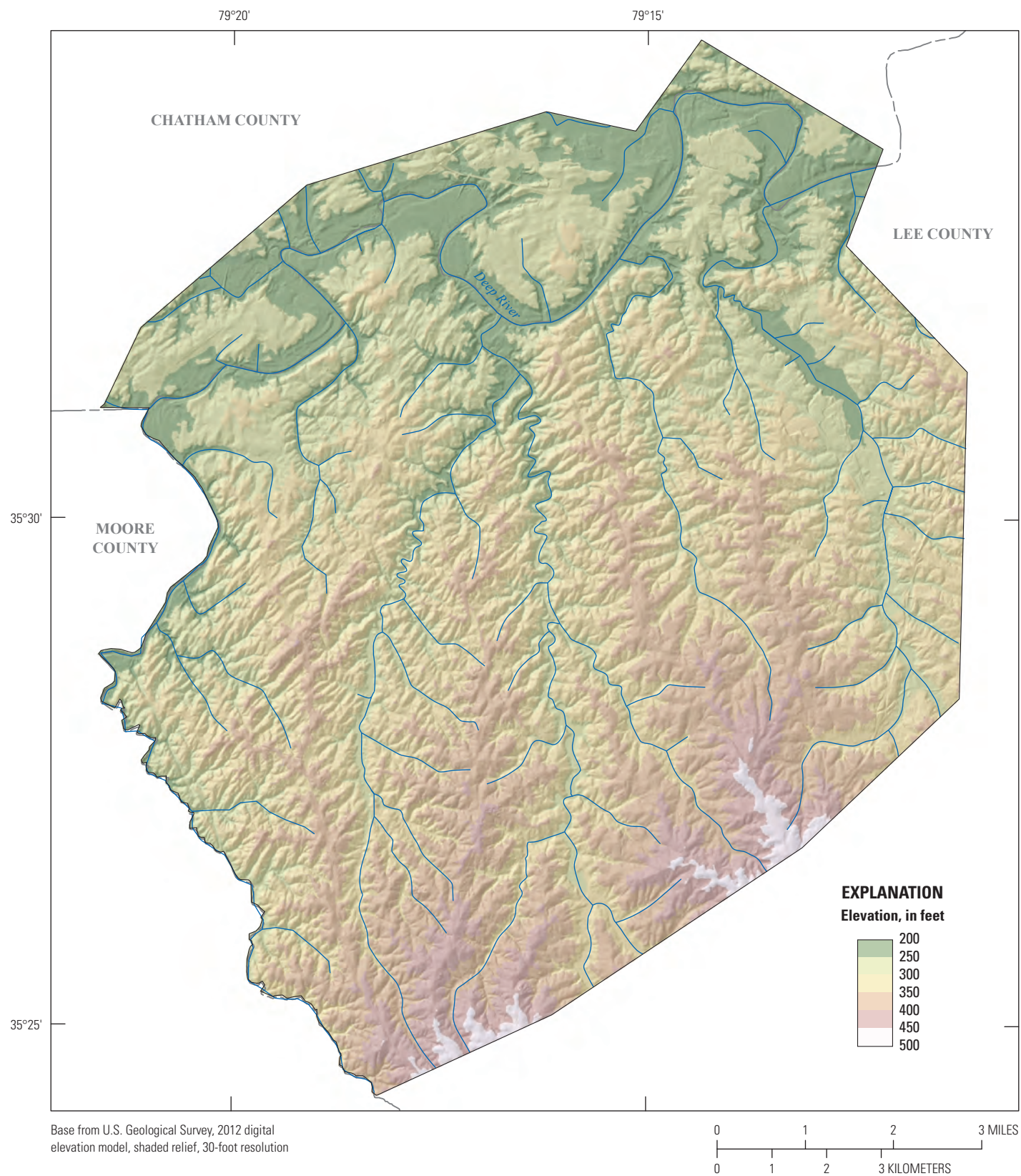
#### EXPLANATION

Triassic Basin     Urbanized area

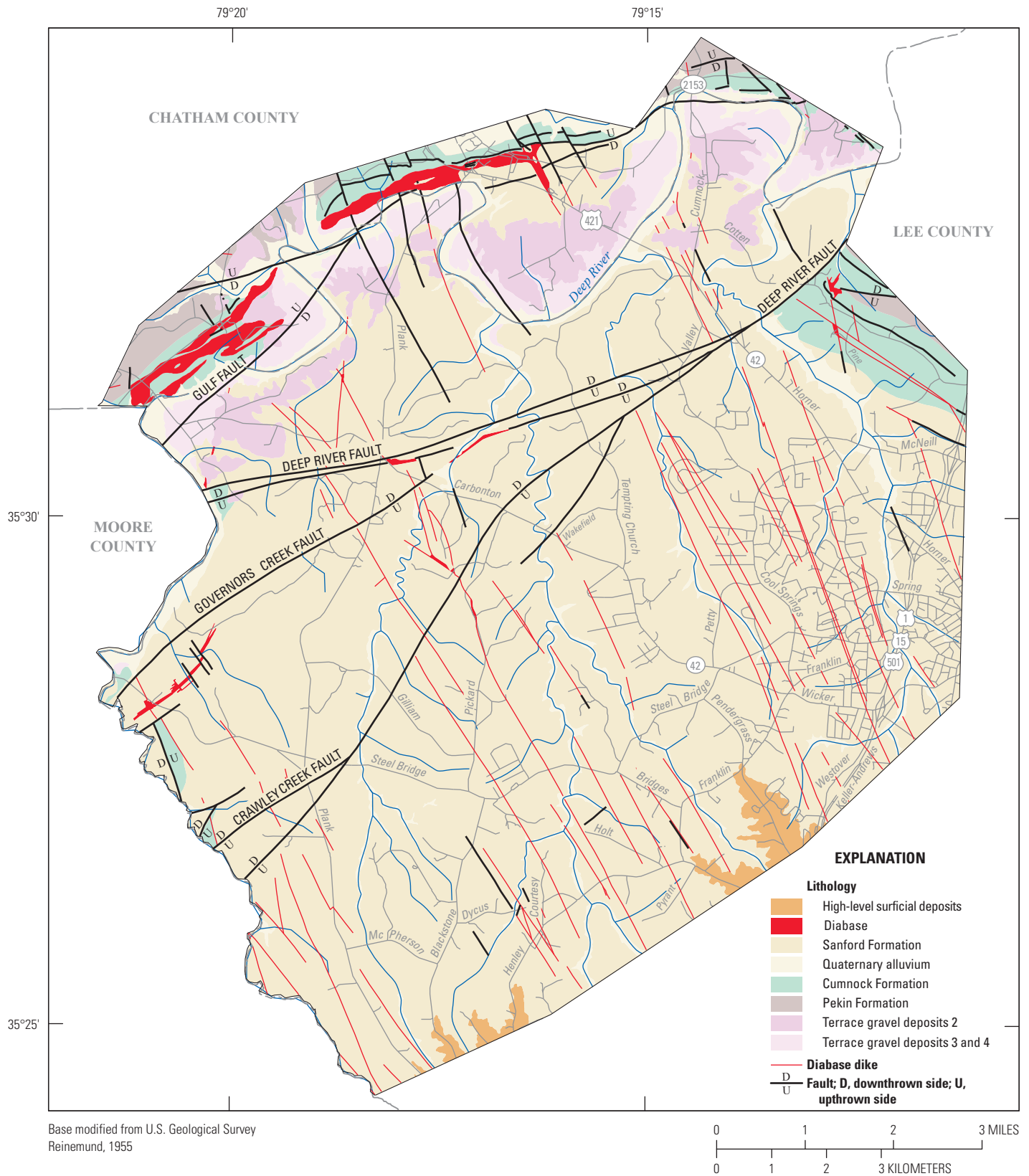
**Figure 1.** Location of the Triassic Basins, urbanized areas, and the study area within the Piedmont Physiographic Province of North Carolina.



#### 4 Baseline Well Inventory and Groundwater-Quality Data from a Potential Shale Gas Resource Area

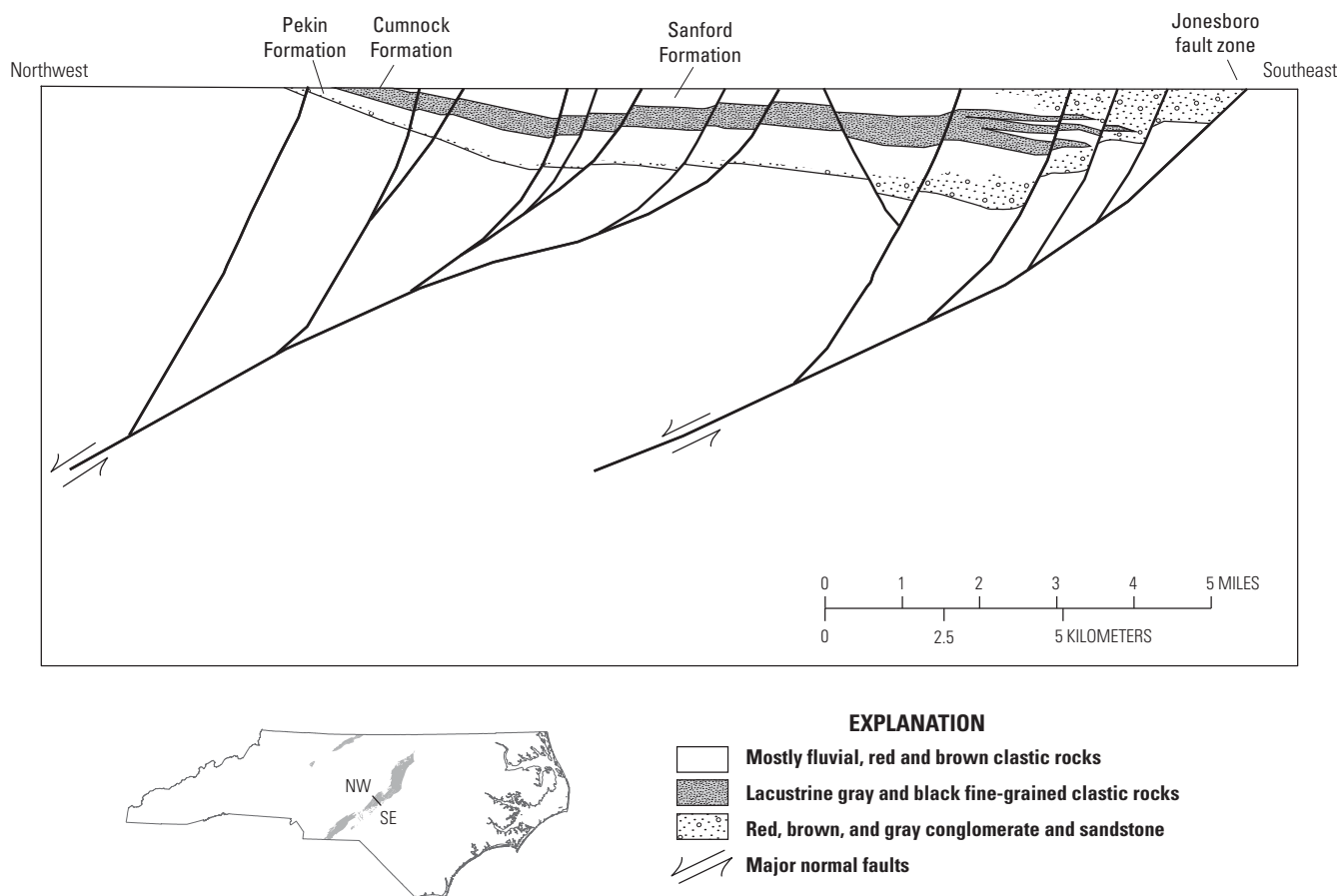


**Figure 2.** Topography of the study area showing colored shading of land-surface altitude depicting a trellised and rectangular drainage system, which suggests geologic controls.



**Figure 3.** Geologic map of the study area.

## 6 Baseline Well Inventory and Groundwater-Quality Data from a Potential Shale Gas Resource Area



**Figure 4.** Generalized geologic cross section showing Triassic-age deposits within the Sanford subbasin. Modified from Olsen and others (1991).

Thomas (1966) as having inherent low porosity and permeability because they are continental type sediments, which are not well sorted. Much of the initial or primary porosity has been lost through diagenesis, lithification, and compaction, and the average well yield was reported to be low (Bain and Thomas, 1966).

Well yields in the Triassic Basin areas generally are considered low. In fact, multiple wells sometimes were inventoried on the same property, indicating challenges associated with obtaining enough water for supply needs. Differential weathering along lithologic contacts and bedding planes may enhance permeability in the aquifer. Additionally, secondary features including faults, joints, and diabase dikes (fig. 3) may enhance permeability through openings, associated fracturing, or weathering near these features. The presence of diabase dikes may be a boundary for subsurface flow and “pooling” of groundwater resulting in higher well yields. In the study area, Reinemund (1955) presents detailed mapping of diabase dikes at the local scale. The Cumnock, Pekin, and Sanford Formations all outcrop at land surface, with the Sanford Formation being present in most of the area (fig. 3) and representing the shallowest part of the local aquifer. (The Middendorf Formation (fig. 3) is part of the younger Coastal Plain sediments rather than Triassic Basin rocks.) Specific information on

which geologic units were tapped by wells sampled as part of this study was not available at the time of this report.

### Methods

The approach for this study focused on the collection of well data, obtaining permission to sample private and public wells, and collecting water samples from selected wells. Well and spring sites in the study area were inventoried for this report from records available from the USGS National Water Information System (NWIS), the NC DENR Division of Water Resources, the Lee County Public Health Department, the Chatham County Public Health Department, and private well tag labels inventoried as part of field reconnaissance. Paper and electronic records were compiled and reviewed.

Data compiled from these well and spring records include date of construction, well depth, casing depth, static water level, yield, and owner information. Additional owner information was obtained from recent (2012) tax parcel records. Reported latitude and longitude values were used for public water supply wells and historic USGS NWIS sites. For all other sites, latitude and longitude values were estimated as the centroid of the land parcel where the well is located (with the



exception of a few sites where the centroid of the parcel was not in the parcel, and in those cases, the latitude and longitude was shifted to plot inside the parcel). New data collected during this study were entered into the USGS NWIS Groundwater Site Inventory (GWSI) database.

## Sampling and Quality Assurance/Quality Control

Fifty-six wells and one spring were selected for chemical analysis of groundwater. More than 3,770 constituent analyses were completed. These constituent suites are listed in appendix 1 (<http://pubs.usgs.gov/ds/861/Appendix1.xlsx>) and include: field properties (alkalinity, temperature, dissolved oxygen, pH and specific conductance); dissolved methane [ $\text{CH}_4$ ]; hydrocarbons (methane, ethane, propane, butane, pentane, and hexane and higher hydrocarbons);  $\delta^{13}\text{C}$  and  $\delta\text{D}$  on methane; radium isotopes ( $^{226}\text{Ra}$ ,  $^{228}\text{Ra}$ ); strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ ); four glycols; diesel-range organics (DRO); gasoline-range organics plus benzene, toluene, ethylene and xylenes (GRO+BTEX); dissolved inorganic carbon (DIC); dissolved organic carbon (DOC);  $\delta^{13}\text{C}$  on DIC and DOC;  $\delta\text{D}$  and  $\delta^{18}\text{O}$  on water; 32 major ions and trace metals; total dissolved solids; 86 volatile organic compounds (VOCs); 56 semi-volatile organic compounds (SVOCs); and nutrients (ammonia [ $\text{NH}_3$ ], nitrite [ $\text{NO}_2^-$ ], nitrate [ $\text{NO}_3^-$ ], organic nitrogen, and orthophosphate [ $\text{PO}_4^{3-}$ ]); field properties. All sample collection, handling, storage and shipping were done according to established procedures documented in the USGS National Field Manual (U.S. Geological Survey, variously dated). Field properties were monitored during well sampling purge, and samples were only collected after stabilization of those properties. Method instrumentation and reporting levels for all constituents are shown in appendix 1.

Assessment of bias and precision of the analytical results included collection and analysis of various quality assurance and quality control (QA/QC) samples including field, trip, and source-solution blanks, field replicates, analytical duplicates, and surrogate compound analyses. Field-based QA/QC samples (blanks and replicates) accounted for between 14 and 50 percent of analyses within constituent suites and about 20 percent overall. Other QA/QC measures included review of laboratory blind blank and blind sample analyses as well as long-term method performance.

## Data Summary

The following section describes the results of the study including a summary of well inventory and groundwater-quality data. All well locations (along with some construction information) and groundwater-quality data analyzed by the USGS National Water Quality Laboratory (Denver, Colorado) are stored online in the NWIS database at <http://waterdata.usgs.gov/nc/nwis/inventory>.

## Water Well Data

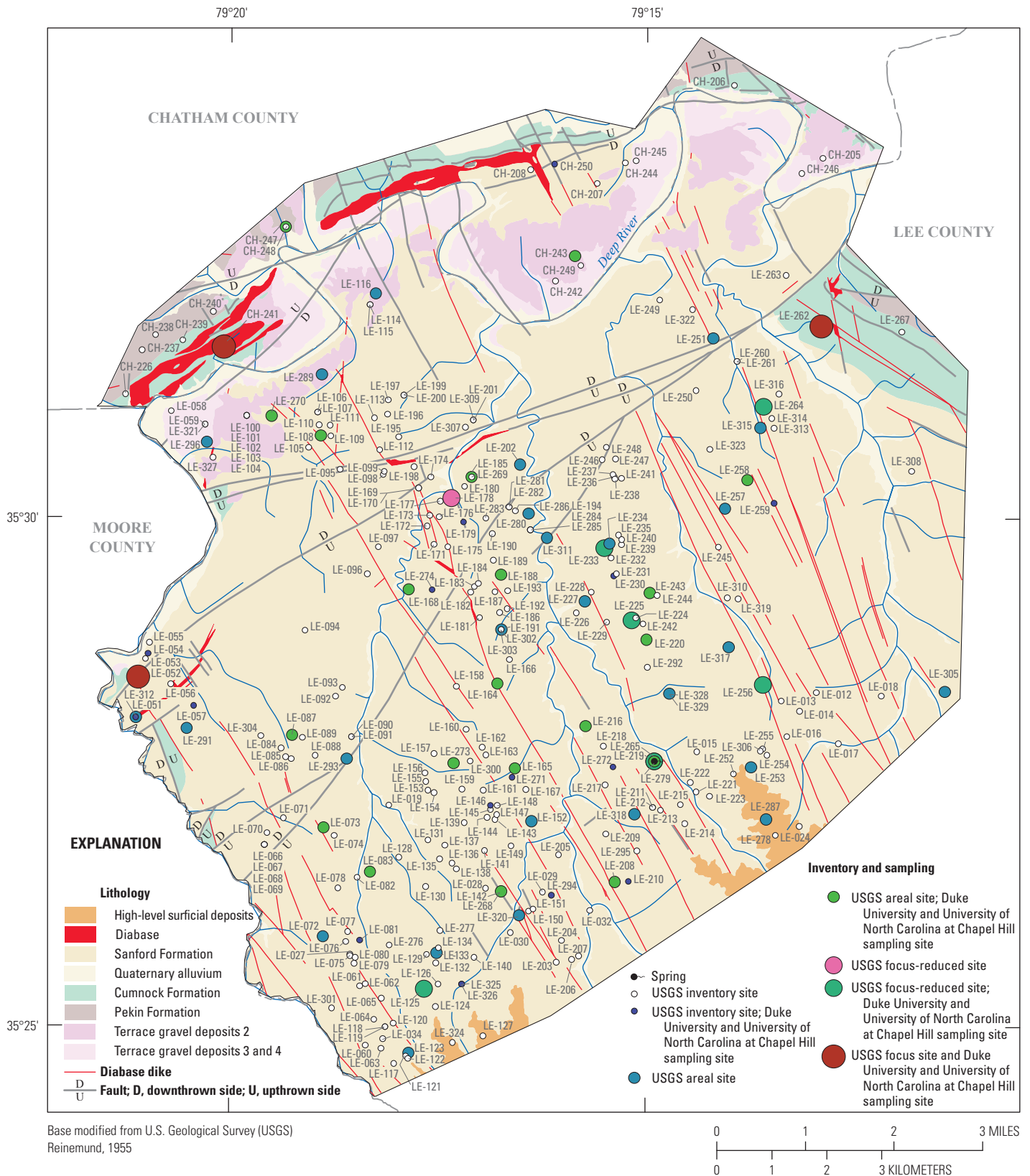
Construction data were collected for 305 wells and 1 spring site in the study area. Nineteen wells (18 drilled, and 1 hand dug) were located in Chatham County and 286 wells (282 drilled, 3 hand dug, and 1 bored) and 1 spring were located in Lee County (fig. 5, appendix 2, <http://pubs.usgs.gov/ds/861/Appendix2.xls>). Available well depth, casing depth, yield, and date of construction data are summarized in appendix 2. Well depth ranged from 26 to 720 feet below land surface (ft bls), with a median of 240 ft bls (figs. 6 and 7; appendix 2). Casing depth ranged from 5 to 211 ft bls, with a median of 42 ft bls. Yield ranged from 0.25 to 100 gallons per minute (gal/min), and median yield was 7 gal/min (figs. 7 and 8; appendix 2). Dates of construction ranged from 1850 to 2012. The oldest well was hand dug (appendix 2).

Within the compilation of inventoried wells, figure 5 also shows the locations of wells that were selected for sampling. The selection of wells for sampling was based on permissions obtained through public meetings, phone calls, e-mail requests, local newspaper articles, field reconnaissance of records compiled, location of the well within the study area, and the availability of well construction data, which at a minimum, included well depth information. A tiered approach to sampling analyses was conducted using the following groups of wells and associated analyses: the focus wells (3 total) included the most comprehensive list of as many as 204 constituents analyzed; the focus-reduced sites (8 total; 7 wells and 1 spring LE-279) included as many as 71 constituents analyzed; and the areal wells (46 total) included as many as 37 constituents analyzed. Wells were analyzed using existing pumps and evacuated for at least one casing volume and until field properties (water temperature, pH, specific conductance, and dissolved oxygen) stabilized. Duke University and the University of North Carolina at Chapel Hill also analyzed wells in the study area as part of a separate effort. Their sampling sites are shown in figure 5, but the associated data are not represented in this report.

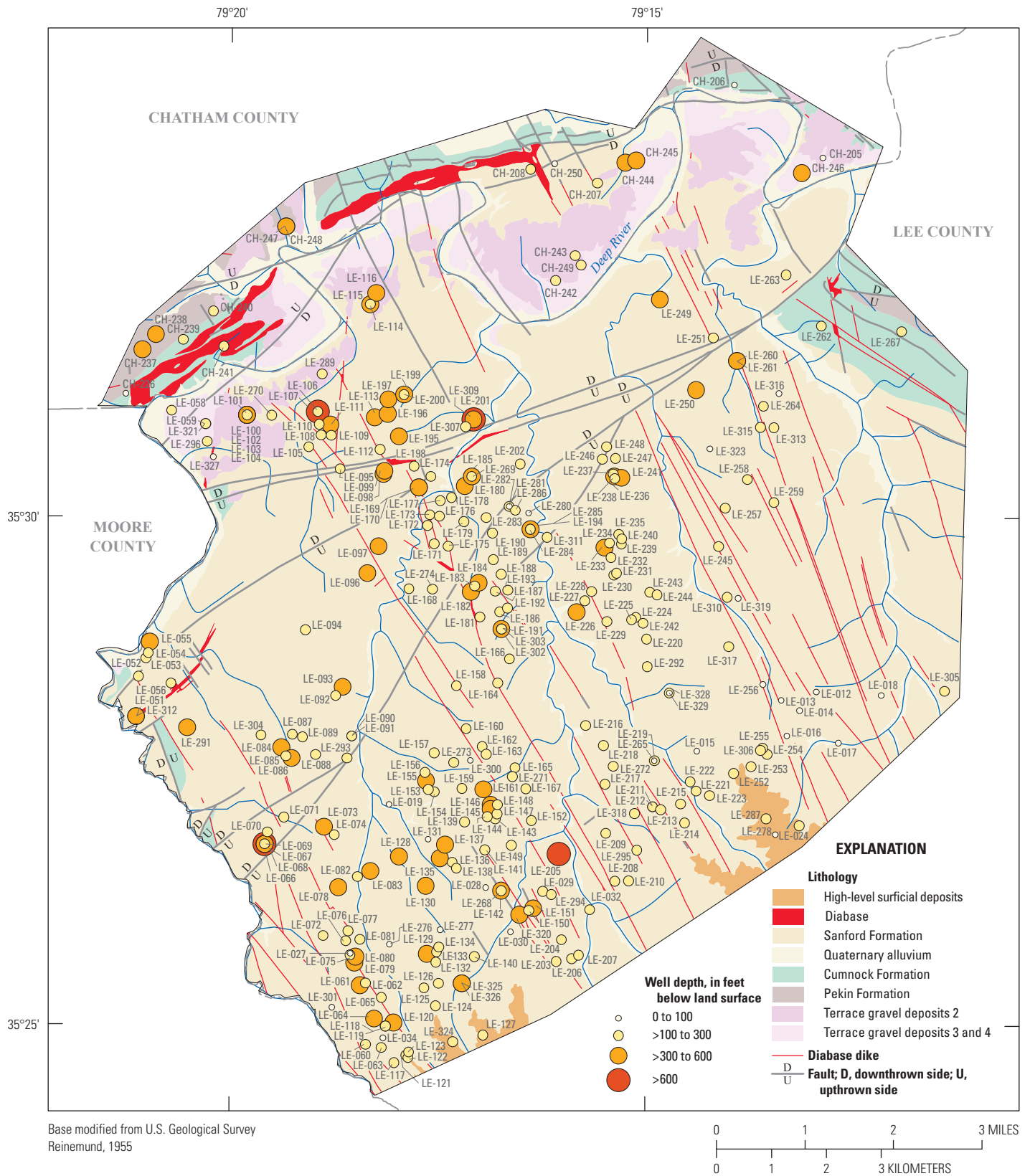
## Field Properties

The range of groundwater-quality properties measured in the field was quite variable. Dissolved oxygen ranged from 0.1 to 8.3 milligrams per liter (mg/L), with a median of 0.8 mg/L (figs. 9 and 10; appendix 3–1, <http://pubs.usgs.gov/ds/861/Appendix3.xlsx>). The pH values measured ranged from 4.3 to 8.6 with a median of 6.7. Specific conductance ranged from 48 to 2,210 microsiemens per centimeter ( $\mu\text{S}/\text{cm}$ ), with a median of 285  $\mu\text{S}/\text{cm}$ . Water temperature ranged from 16.2 to 25.7 degrees Celsius ( $^{\circ}\text{C}$ ), with a median of 17.3  $^{\circ}\text{C}$ . Field alkalinity (as mg/L calcium carbonate) ranged from 3 to 270 mg/L, with a median of 124 mg/L. Bicarbonate ranged from 5 to 329 mg/L, with a median of 151 mg/L (appendix 3–1).

## 8 Baseline Well Inventory and Groundwater-Quality Data from a Potential Shale Gas Resource Area

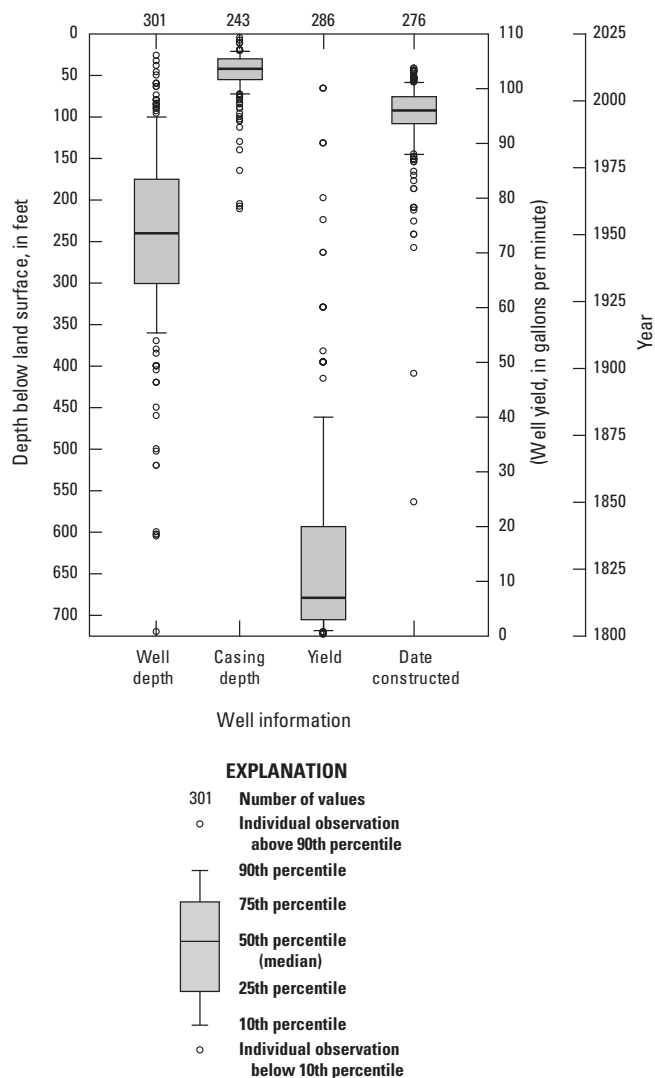


**Figure 5.** Locations of water supply wells and spring inventoried as part of this study including those where groundwater samples were collected.



**Figure 6.** Range of well depths inventoried across the study area.





**Figure 7.** Well depth, casing depth, yield, and date of construction for wells inventoried in the study area.

## Major Ions

Major ions were analyzed in all samples, and concentrations were highly variable. Cation concentrations ranged from 0.957 to 124 mg/L calcium (median of 27.2 mg/L), 0.911 to 41.4 mg/L magnesium (median of 7.41), 6.26 to 405 mg/L sodium (median of 17.3 mg/L) and 0.5 to 3.82 mg/L potassium (median of 1.36 mg/L). Anion concentrations ranged from 2.75 to 284 mg/L chloride (median of 10.5 mg/L), less than 0.04 to 0.31 mg/L fluoride (median of 0.08 mg/L), and 0.18 to 997 mg/L sulfate (median of 3.47 mg/L). Nitrate (plus nitrite, mg/L as nitrogen), which was analyzed in samples collected from 19 wells, ranged from less than 0.04 to 16.4 mg/L (median of 0.188 mg/L). One well LE-216 (appendix 3–1) had a concentration of nitrate above the drinking water standard of 10 mg/L (U.S. Environmental Protection Agency, 2009) (appendix 4–1).

Piper (1953) diagrams illustrate the distribution of groundwater types for the 35 samples, which had both major

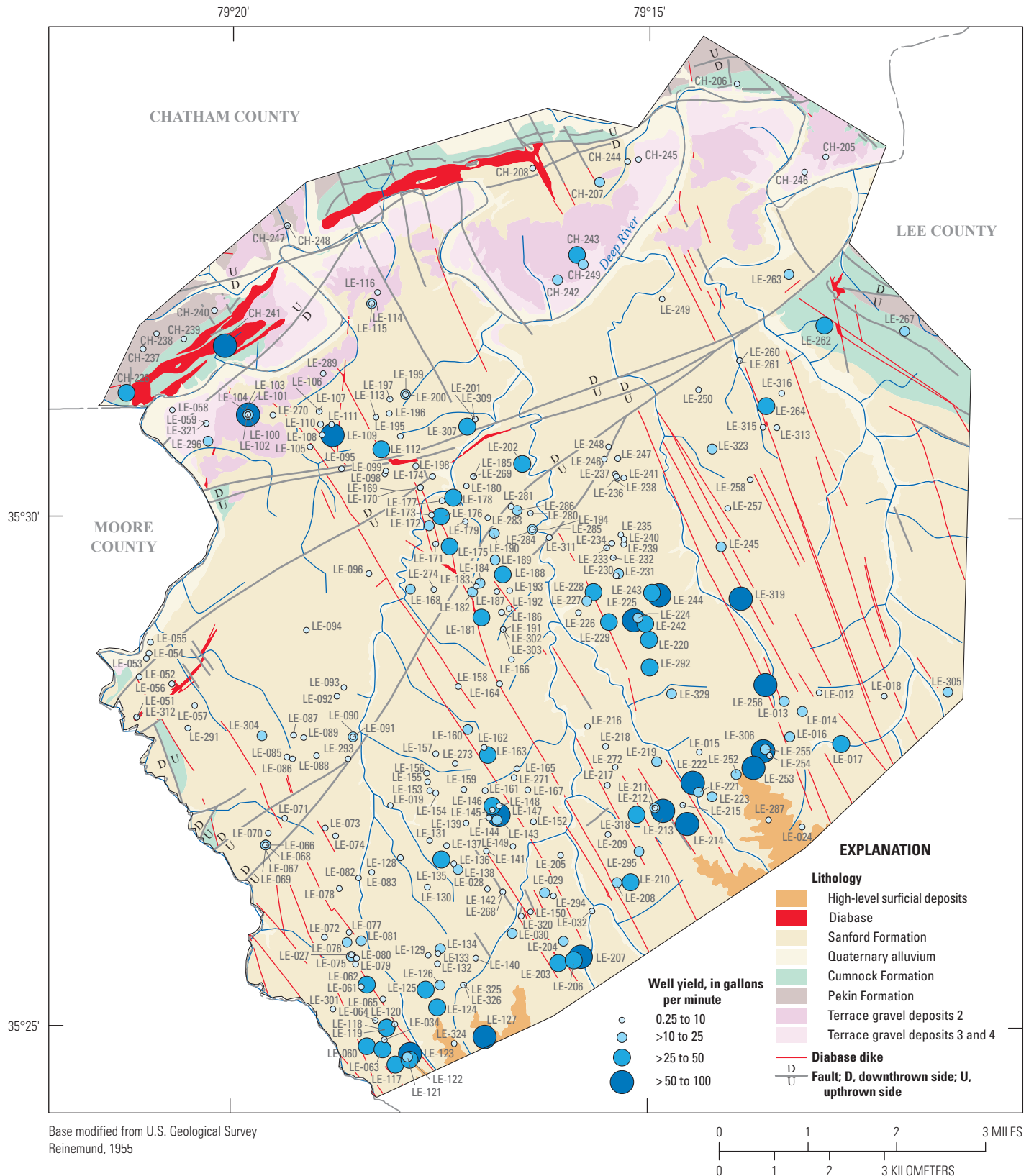
ions and nitrite plus nitrate values, and 19 samples, which had major ion analyses but lacked nitrite plus nitrate analyses (fig. 12; Note that three samples—two from the set containing nitrite plus nitrate analyses and one that did not include nitrite plus nitrate analyses—exceeded the project’s ten percent balance criteria for plotting on Piper diagrams). The more dominant groundwater type was calcium-bicarbonate, although major ion geochemistry varied widely, as indicated by the range of point distribution. The two wells having the highest specific conductance values were LE-178 and LE-185 (2,210 and 1,330  $\mu\text{S}/\text{cm}$ , respectively; fig. 12A and appendix 3–1). The sample collected from well LE-178 had a sodium-sulfate groundwater, with the highest values of those two constituents, as well as elevated calcium and chloride, and the highest values of several metals including strontium, lithium, molybdenum, and zinc (appendix 3–1). The sample from well LE-185 had a calcium-chloride-bicarbonate groundwater type that had elevated calcium, magnesium, sodium, and chloride; no metals analyses were completed for this well sample. The elevated major ion concentrations likely are the result of natural conditions with a longer residence time (exposure to the bedrock) where minerals have more time to dissolve in groundwater. Both wells are in close proximity to each other (fig. 5), located south of the Governors Creek fault and northeast and along strike of diabase dikes (fig. 3), which may suggest effects from these geologic features through control of groundwater flow.

## Dissolved Metals

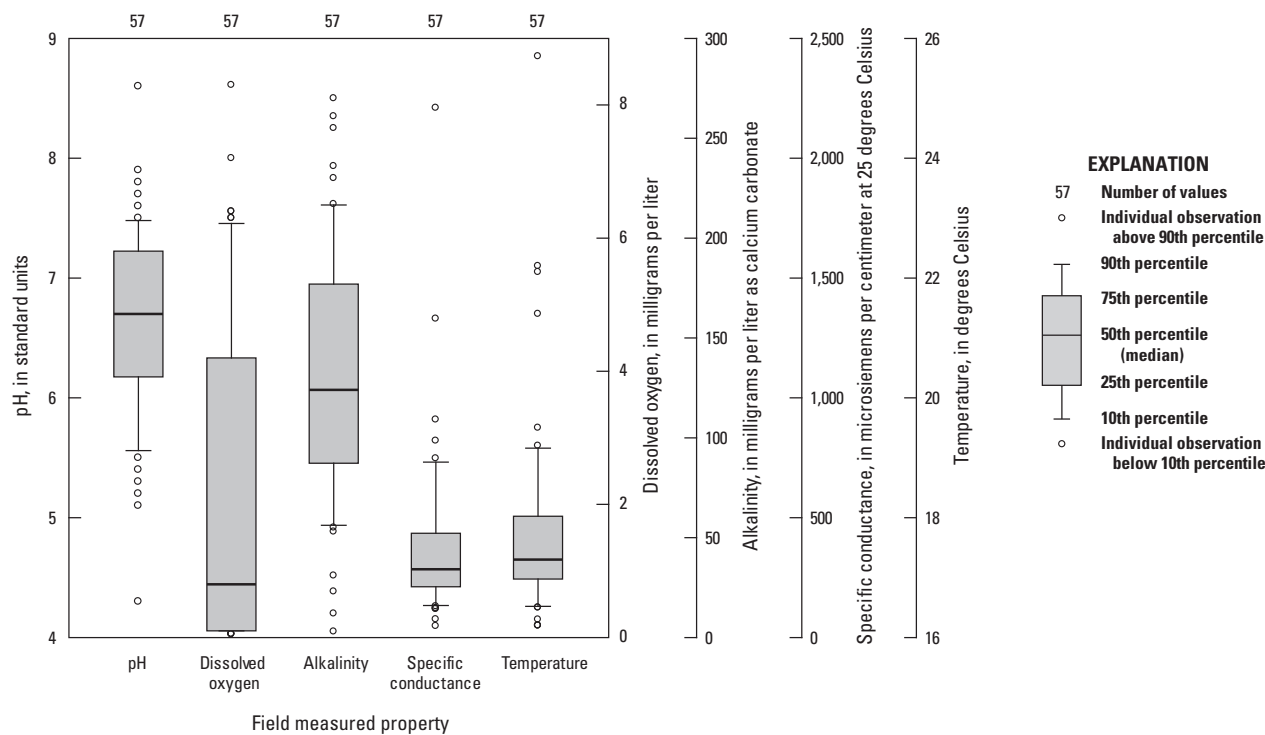
Dissolved metals with notable concentrations (generally detections above 1  $\mu\text{g}/\text{L}$ ) in groundwater samples included aluminum ranging from less than 2.2 to 14.8  $\mu\text{g}/\text{L}$  (median of less than 2.2  $\mu\text{g}/\text{L}$ ), arsenic 0.14 to 4.8  $\mu\text{g}/\text{L}$  (median of 1.1  $\mu\text{g}/\text{L}$ ), barium 11.6 to 257  $\mu\text{g}/\text{L}$  (median of 99.5  $\mu\text{g}/\text{L}$ ), boron 5 to 825  $\mu\text{g}/\text{L}$  (median of 16  $\mu\text{g}/\text{L}$ ), chromium less than 0.07 to 3.4  $\mu\text{g}/\text{L}$  (median of 0.23  $\mu\text{g}/\text{L}$ ), copper less than 0.8 to 30.8  $\mu\text{g}/\text{L}$  (median of less than 0.8  $\mu\text{g}/\text{L}$ ), iron less than 3.2 to 4,490  $\mu\text{g}/\text{L}$  (median of 5.3  $\mu\text{g}/\text{L}$ ), lithium (estimated) 1.46 to 38.1  $\mu\text{g}/\text{L}$  (median of 7.07  $\mu\text{g}/\text{L}$ ), manganese less than 0.13 to 997  $\mu\text{g}/\text{L}$  (median of 3.55  $\mu\text{g}/\text{L}$ ), nickel less than 0.09 to 1.5  $\mu\text{g}/\text{L}$  (median of 0.37  $\mu\text{g}/\text{L}$ ), strontium 24.9 to 16,700  $\mu\text{g}/\text{L}$  (median of 114  $\mu\text{g}/\text{L}$ ), and zinc 1.5 to 79.5  $\mu\text{g}/\text{L}$  (median of 10.4  $\mu\text{g}/\text{L}$ ) (appendix 3–1).

## Exceedances

Of the more than 200 field properties and constituents that were analyzed, only eight exceeded at least one water-quality standard set by either the U.S. Environmental Protection Agency or the State of North Carolina (fig. 13; table 1; appendix 4–1 <http://pubs.usgs.gov/ds/861/Appendix4.xlsx>). With the possible exception of nitrate, these constituents likely are present naturally in the aquifer. Thirty-seven percent of samples contained pH values less than 6.5. Thirty-five percent of samples exceeded the State groundwater standard



**Figure 8.** Range of well yields inventoried across the study area.



**Figure 9.** Field-measured properties of pH, dissolved oxygen, alkalinity, specific conductance, and temperature of well and spring water sampled in the study area.

for manganese of 50 µg/L [North Carolina 15A NCAC 2L .0202 Groundwater Standard ([http://portal.ncdenr.org/c/document\\_library/get\\_file?folderId=567426&name=DLFE-14952.pdf](http://portal.ncdenr.org/c/document_library/get_file?folderId=567426&name=DLFE-14952.pdf), accessed May 2014)]. Exceedances for chloride, sulfate, and dissolved solids were associated with samples having the higher specific conductance values (appendix 3–1). Maximum concentrations measured in groundwater samples exceeded standards by factors ranging from 14 percent for chloride to almost 1,900 percent for manganese (appendix 4–1).

Reporting levels for 16 organic compounds were greater than their corresponding water-quality standard (appendix 4–2). None of these compounds were detected,

**Table 1.** Number and percent of analyses exceeding at least one water-quality standard set by either United States Environmental Protection Agency or the State of North Carolina.

[TDS, total dissolved solids; <, less than; >, greater than]

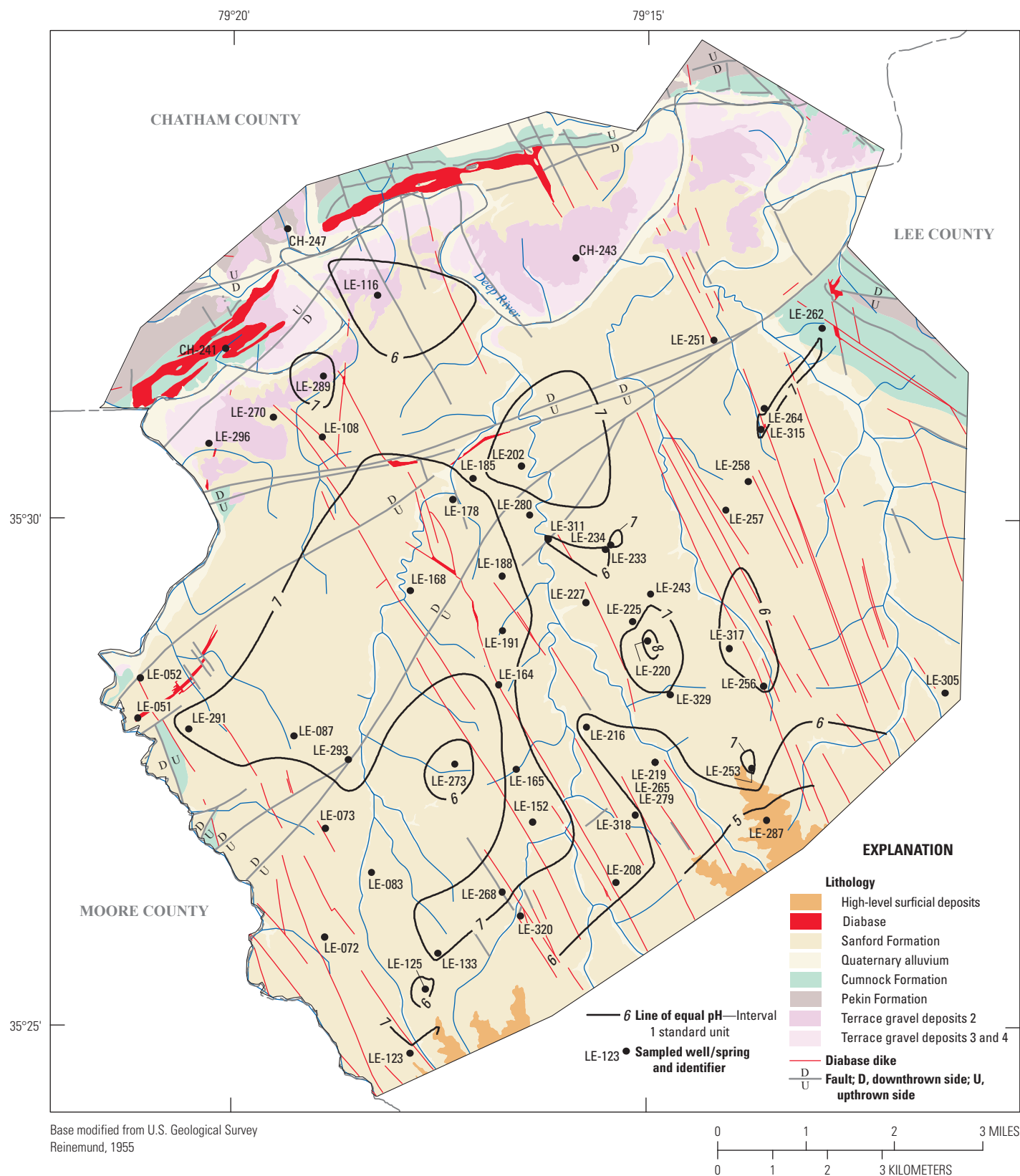
Constituent	Analyses	Number of exceedances	Percent exceedances
Boron	11	1	9
Chloride	57	1	2
TDS	57	3	5
Iron	57	3	5
Manganese	57	20	35
Nitrate	37	1	3
pH (<6.5)	57	21	37
pH (>8.5)	57	1	2
Sulfate	57	2	4

but the higher reporting level precludes evaluating whether any of these standards were exceeded. About 100 additional constituents, both natural and anthropogenic, have at least one standard but either were not detected in groundwater samples or did not exceed any standard (appendix 4–3). More than 80 constituents included in the groundwater sampling study had no published water-quality standard (appendix 4–4).

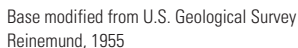
Methane

Dissolved methane was analyzed in all 57 well and spring water samples by the USGS Chlorofluorocarbon (CFC) Laboratory in Reston, Virginia (see method instrumentation and reference list, appendix 1) and also was separately analyzed in 12 samples by a second laboratory (Isotech Laboratory, see reference list appendix 1) (fig. 14; appendix 3–5, 3–6). Among all 57 samples, methane concentrations were relatively low, but ranged more than several orders of magnitude from below the reporting level (appendix 1) of 0.0005 to 0.48 mg/L. Thirty-five of the 57 samples (61 percent) had measured methane concentrations less than 0.0005 mg/L. For the subset of 12 samples analyzed by both laboratories, the USGS CFC laboratory reported a minimum concentration of less than 0.0005 mg/L, a maximum of 0.48 mg/L, and a median between less than 0.0005 mg/L and 0.0032 mg/L. The Isotech laboratory had an approximately seven-fold lower reporting level (0.00007 mg/L), and its median (between 0.00034 mg/L and 0.0031 mg/L) and maximum (0.33 mg/L) concentrations were similar to those determined for this subset of samples by

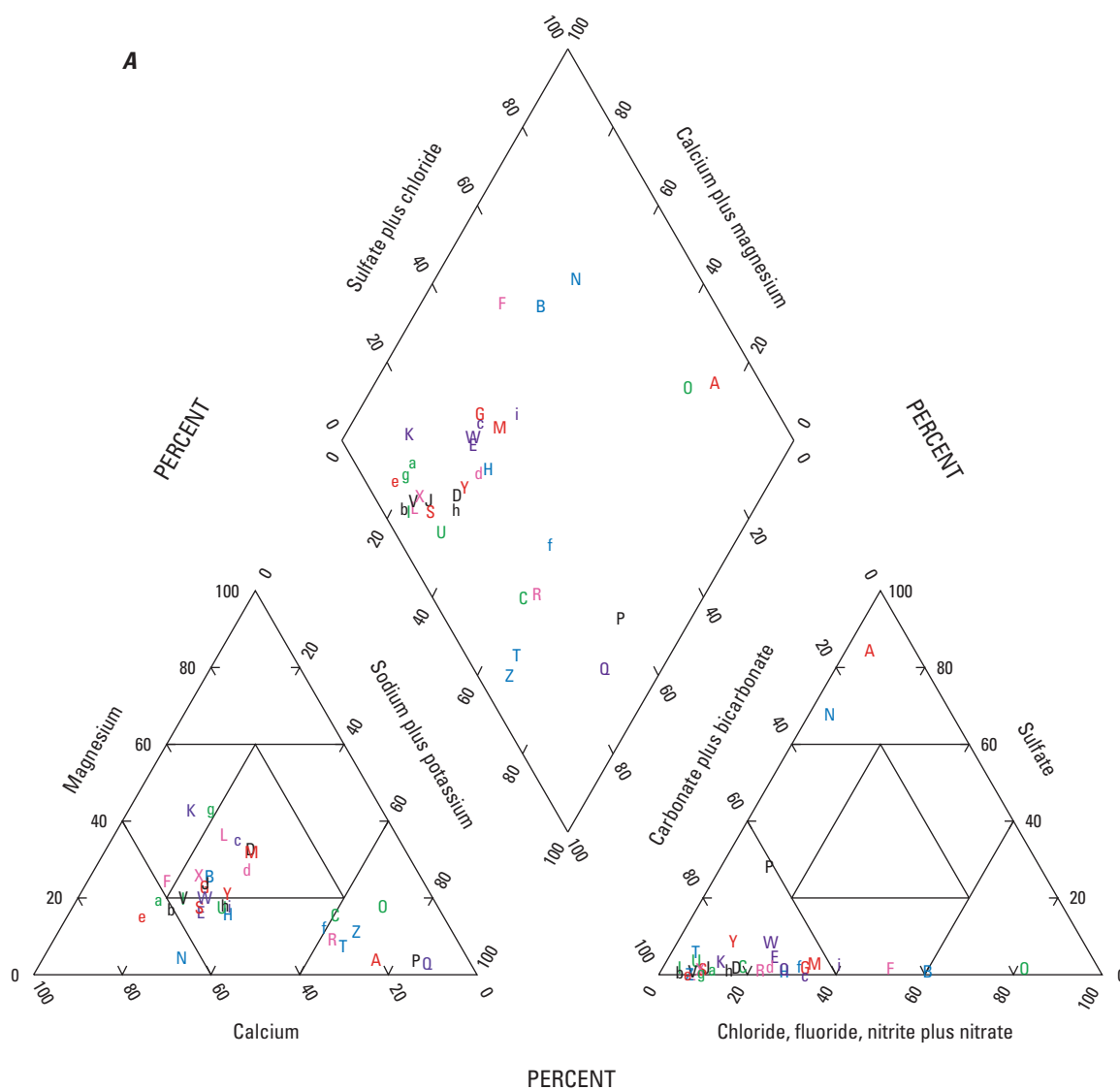




**Figure 10.** Distribution of field pH values measured in well and spring water sampled in the study area.



**Figure 11.** Distribution of field specific conductance values measured in well and spring water sampled in the study area.

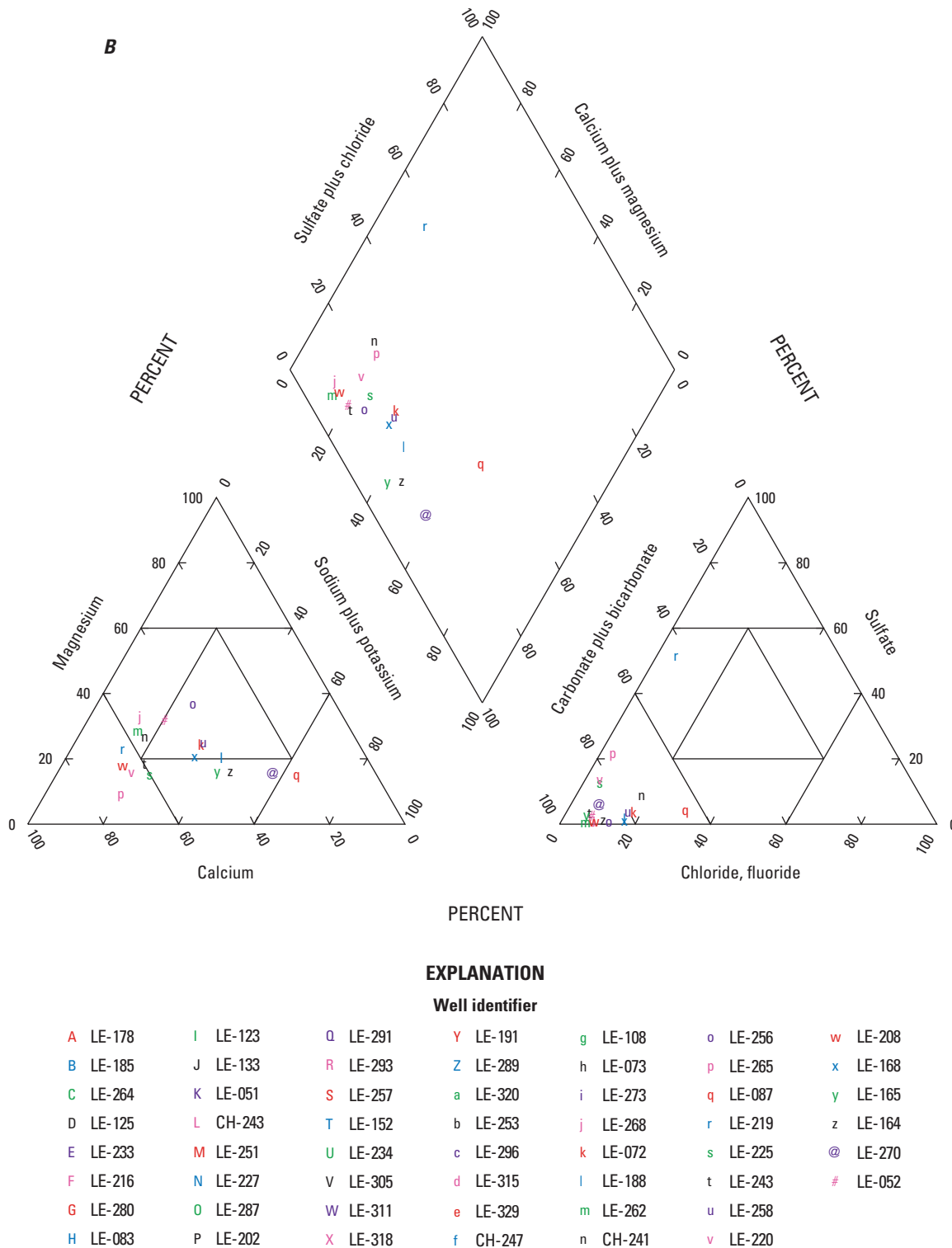


## EXPLANATION

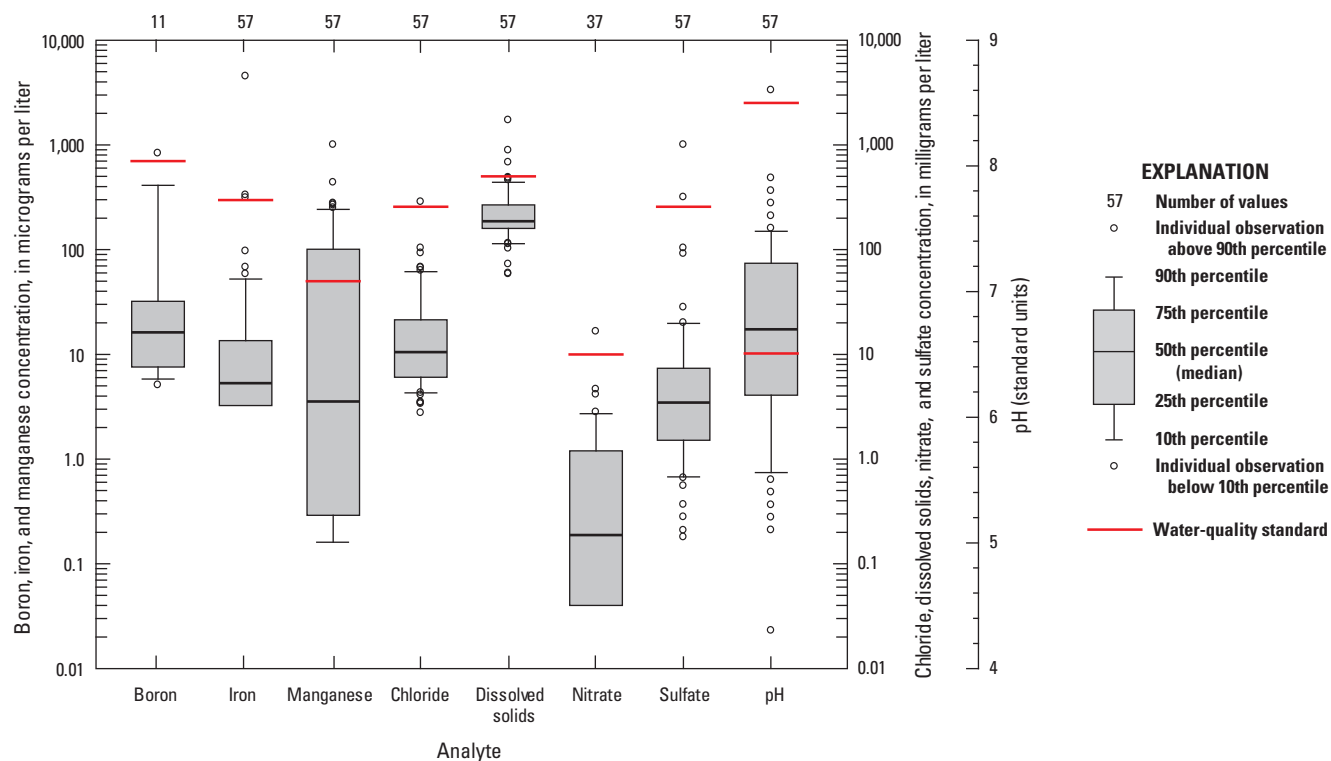
## Well identifier

A LE-178	I LE-123	Q LE-291	Y LE-191	g LE-108	o LE-256	w LE-208
B LE-185	J LE-133	R LE-293	Z LE-289	h LE-073	p LE-265	x LE-168
C LE-264	K LE-051	S LE-257	a LE-320	i LE-273	q LE-087	y LE-165
D LE-125	L CH-243	T LE-152	b LE-253	j LE-268	r LE-219	z LE-164
E LE-233	M LE-251	U LE-234	c LE-296	k LE-072	s LE-225	@ LE-270
F LE-216	N LE-227	V LE-305	d LE-315	l LE-188	t LE-243	# LE-052
G LE-280	O LE-287	W LE-311	e LE-329	m LE-262	u LE-258	
H LE-083	P LE-202	X LE-318	f CH-247	n CH-241	v LE-220	

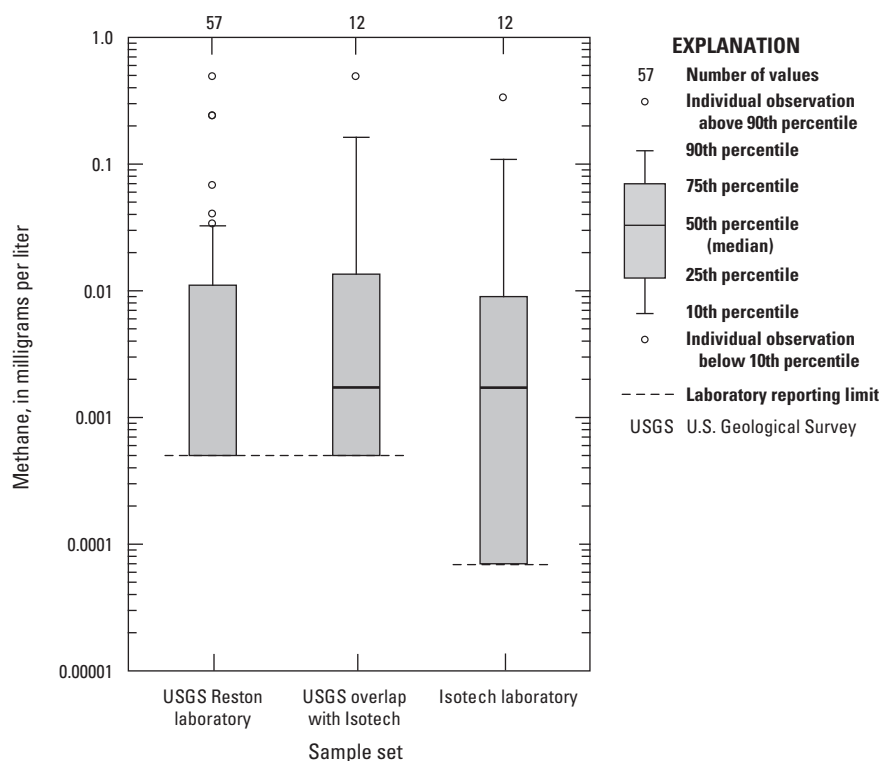
**Figure 12.** Distribution of major ion geochemistry for A, 35 groundwater samples, which included nitrite plus nitrate analyses and B, 19 groundwater samples without nitrite plus nitrate analyses in the study area.



**Figure 12.** Distribution of major ion geochemistry for A, 35 groundwater samples, which included nitrite plus nitrate analyses and B, 19 groundwater samples without nitrite plus nitrate analyses in the study area.—Continued



**Figure 13.** Constituents exceeding at least one water-quality standard set by either the U.S. Environmental Protection Agency or the State of North Carolina.



**Figure 14.** Range in detected dissolved methane gas analyses from well and spring samples in the study area.

the USGS laboratory. Only 1 sample of the 12 Isotech samples, well LE-262, had a methane concentration high enough to determine isotope concentrations (appendix 3–6). Only three samples had concentrations of dissolved methane gas above 0.1 mg/L (appendix 3). LE-262 was located in a Cum-nock Shale outcrop area, and the other two samples, LE-191 and LE-087, were located near the Crawley Creek fault (figs. 3 and 5).

## References Cited

- American Public Health Association, 1998, Standard methods for the examination of water and wastewater (20th edition): Washington, D.C., American Water Works Association, and Water Environment Federation, Method 3120, p. 3–37 to 3–43.
- American Society for Testing and Materials International, 2010, Standard test method for analysis of natural gas by gas chromatography, ASTM D1945: accessed December 10, 2012, at <http://www.astm.org/Standards/D1945.htm>.
- Bain, G.L., and Brown, C.E., 1981, Evaluation of the Durham Triassic basin of North Carolina and techniques used to characterize its waste-storage potential: U.S. Geological Survey Open-File Report 80–1295, 138 p.
- Bain, G.L., and Thomas, J.D., 1966, Geology and groundwater in the Durham area, North Carolina: N.C. Department Water Resources, Ground-Water Bulletin 7, 147 p.
- Breen, K.J., Revesz, K., Baldassare, F.J., and McAuley, S.D., 2007, Natural gases in ground water near Tioga Junction, Tioga County, north-central Pennsylvania—Occurrence and use of isotopes to determine origins, 2005: U. S. Geological Survey Scientific Investigations Report 2007–5085, 65 p.
- Brenton, R.W., and Arnett, T.L., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved organic carbon by UV-promoted persulfate oxidation and infrared spectrometry: U.S. Geological Survey Open-File Report 92–480, 12 p.
- Connor, B.F., Rose, D.L., Noriega, M.C., Murtagh, L.K., and Abney, S.R., 1998, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of 86 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than reporting limits: U.S. Geological Survey Open-File Report 97–829, 78 p.
- Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93–125, 217 p.
- Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.
- Garbarino, J.R., Kanagy, L.K., and Cree, M.E., 2006, Determination of elements in natural-water, biota, sediment and soil samples using collision/reaction cell inductively coupled plasma-mass spectrometry: U.S. Geological Survey Techniques and Methods, book 5, chap. B1, 88 p.
- Kresse, T.M., Warner, N.R., Hays, P.D., Down, A., Vengosh, A., and Jackson, R.B., 2012, Shallow groundwater quality and geochemistry in the Fayetteville Shale gas-production area, north-central Arkansas, 2011: U.S. Geological Survey Scientific Investigations Report 2012–5273, 31 p.
- Milici, R.C., Coleman, J.L., Rowan, E.L., Cook, T.A., Charpentier, R.R., Kirschbaum, M.A., Klett, T.R., Pollastro, R.M., and Schenk, C.J., 2012, Assessment of undiscovered oil and gas resources of the East Coast Mesozoic basins of the Piedmont, Blue Ridge Thrust Belt, Atlantic Coastal Plain, and New England Provinces, 2011: U.S. Geological Survey Fact Sheet 2012–3075, 2 p., accessed March 2014, at <http://pubs.usgs.gov/fs/2012/3075/>.
- North Carolina Department of Environment and Natural Resources, accessed January 2014, at <http://portal.ncdenr.org/web/guest/shale-gas>.
- North Carolina Geological Survey, 1985, Geologic Map of North Carolina: 1:500,000 scale, 1 plate, accessed December 2013 at <http://www.geology.enr.state.nc.us/maps/GeologicMaps/geomaps.html>.
- Olsen, P.E., Froelich, A.J., Daniels, D.L., Smoot, J.P., and Gore, P.J.W., 1991, Rift basins of Early Mesozoic Age, *in*, Horton, J.W., Jr., and Zullo, V.A. eds., 1991, Geology of the Carolinas—Carolina geological society fiftieth anniversary volume: Knoxville, Tenn., University of Tennessee Press, p. 142–170.
- Osborn, S.G., Vengosh, A., Warner, N.R., and Jackson, R.B., 2011, Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing: Proceedings of the National Academy of Sciences May 17, 2011, v. 108, no. 20 8172–8176; accessed May 2014 at <http://www.pnas.org/content/108/20/8172>.
- Patton, C.J., and Kryskalla, J.R., 2011, Colorimetric determination of nitrate plus nitrite in water by enzymatic reduction, automated discrete analyzer methods: U.S. Geological Survey Techniques and Methods, book 5, chap. B8.



- Patton, C.J., and Kryskalla, J.R., 2003, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Evaluation of alkaline persulfate digestion as an alternative to Kjeldahl digestion for determination of total and dissolved nitrogen and phosphorus in water: Water-Resources Investigations Report 03–4174, 33 p.
- Piper, A.M., 1953, A graphic procedure in the geochemical interpretation of water analyses: Washington, D.C., U.S. Geological Survey, Ground-Water Chemistry Notes, no. 12, 14 p.
- Reid, J.C., Taylor, K.B., Olsen, P.E., and Patterson, III, O.F., 2011, in Taylor, K.B., and Reid, J.C., eds., Natural gas potential of the Sanford sub-basin, Deep River Basin, North Carolina: Wilmington, North Carolina, Field Trip Guidebook—60th Annual Meeting, Southeastern Section, Geological Society of America. [Also available at [http://www.searchanddiscovery.com/documents/2011/10366reid/ndx\\_reid.pdf](http://www.searchanddiscovery.com/documents/2011/10366reid/ndx_reid.pdf).]
- Reid, J.C., Taylor, K.B., and Cumberbatch, K.N., 2010, Digital compilation map Sanford sub-basin, Deep River Basin, parts of Lee, Chatham and Moore counties, North Carolina: North Carolina Geological Survey Open-File Report 2010–07, 1 plate.
- Reid, J.C., and Milici, R.C., 2008, Hydrocarbon source rocks in the Deep River and Dan River Triassic Basins, North Carolina: U.S. Geological Survey Open-File Report 2008–1108, 31 p.
- Reinemund, J.A., 1955, Geology of the Deep River coal field, North Carolina: U.S. Geological Survey Professional Paper 246, 159 p.
- Révész, K.M., and Coplen, T.B., 2008a, Determination of the  $\delta(18\text{O}/16\text{O})$  of water—RSIL lab code 489, chap. C2 of Révész, K.M., and Coplen, T.B., eds., Methods of the Reston Stable Isotope Laboratory: U.S. Geological Survey Techniques and Methods, book 10, chap. C2, 28 p.
- Révész, K.M., and Coplen, T.B., 2008b, Determination of the  $\delta(2\text{H}/1\text{H})$  of water—RSIL lab code 1574, chap. C1 of Révész, K.M., and Coplen, T.B., eds., Methods of the Reston Stable Isotope Laboratory: U.S. Geological Survey Techniques and Methods, book 10, chap. C1, 27 p.
- Révész, K.M., and Doctor, D.H., 2014, Automated determination of the stable carbon isotopic composition of total dissolved inorganic carbon (DIC) and total nonpurgeable dissolved organic carbon (DOC) in aqueous samples—RSIL lab codes 1851 and 1852, chap. 20 of Stable isotope-ratio methods, sec. C of Révész, K.M., and Coplen, T.B., eds., Methods of the Reston Stable Isotope Laboratory: U.S. Geological Survey Techniques and Methods, book 10, accessed May 2014, at <http://pubs.er.usgs.gov/publication/tm10C20>.
- Schipf, R.G., 1961, Geology and ground water resources in the Fayetteville area: Ground-Water Bulletin Number 3, 55 p.
- Trapp, H., Jr., and Horn, M.A., 1997, Ground water atlas of the United States, Segment 11—Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia: U.S. Geological Survey Hydrologic Investigations Atlas 730-L, 24 p., accessed February 2012, at [http://pubs.usgs.gov/ha/ha730/ch\\_l/index.html](http://pubs.usgs.gov/ha/ha730/ch_l/index.html).
- U.S. Energy Information Administration, 2013, U.S. crude oil and natural gas proved reserves: Washington, D.C., U.S. Department of Energy, 49 p., accessed March 2014, <http://www.eia.gov/naturalgas/crudeoilreserves/pdf/uscrudeoil.pdf>.
- U.S. Environmental Protection Agency, 2009, 2009 Edition of the drinking water standards and health advisories: U.S. Environmental Protection Agency 822-R009-011, 12 p.
- U.S. Environmental Protection Agency, 1996a, Test methods for evaluating solid waste, physical/chemical methods, SW-846 (3d ed.), update IV; method 8015B, nonhalogenated organics using GC/FID, rev. 2: Washington, D.C., U.S. Environmental Protection Agency, [variously paged].
- U.S. Environmental Protection Agency, 1996b, Test methods for evaluating solid waste, physical/chemical methods, SW-846 (3d ed.), update IV; method 8015C, nonhalogenated organics using GC/FID: Washington, D.C., U.S. Environmental Protection Agency, [variously paged].
- U.S. Environmental Protection Agency, 1980a, Prescribed procedures for measurement of radioactivity in drinking water, EPA-600/4-80-032: Cincinnati, Ohio, U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Office of Research and Development, sect. 7, p. 38–48.
- U.S. Environmental Protection Agency, 1980b, Prescribed procedures for measurement of radioactivity in drinking water, EPA-600/4-80-032: Cincinnati, Ohio, U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Office of Research and Development, sect. 8, p. 49–57.
- U.S. Geological Survey, 2012, The Reston Chlorofluorocarbon Laboratory—Analytical procedures for dissolved gases N<sub>2</sub>/Ar: accessed December 10, 2012, [http://water.usgs.gov/lab/dissolved-gas/lab/analytical\\_procedures/](http://water.usgs.gov/lab/dissolved-gas/lab/analytical_procedures/).
- U.S. Geological Survey, 2007, Yucca Mountain Project Branch (YMPB) USGS technical procedure—Rb-Sr Isotope geochemistry: YMPB-USGS-GCP-12, R0, 12p.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. 1–9, accessed December 10, 2012, at <http://water.usgs.gov/owq/FieldManual/>.

Wright, P.R., McMahon, P.B., Mueller, D.K., and Clark, M.L., 2012, Groundwater-quality and quality-control data for two monitoring wells near Pavillion, Wyoming, April and May 2012: U.S. Geological Survey Data Series 718, 23 p. [Revised October 2012], accessed May 2014, at [http://pubs.usgs.gov/ds/718/DS718\\_508.pdf](http://pubs.usgs.gov/ds/718/DS718_508.pdf).

## **Appendixes 1–4**

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**Appendix 1** (<http://pubs.usgs.gov/ds/861/Appendix1.xlsx>)

Constituents measured in well and spring water collected for this study.

**Appendix 2** (<http://pubs.usgs.gov/ds/861Appendix2.xlsx>)

Construction data for 305 wells and 1 spring inventoried for this study.

**Appendix 3** (<http://pubs.usgs.gov/ds/861/Appendix3.xlsx>)

- 3–1. Field properties and constituents in groundwater samples analyzed in the field or by the United States Geological Survey National Water Quality Laboratory.
- 3–2. Dissolved constituents in field blanks analyzed by the United States Geological Survey National Water Quality Laboratory.
- 3–3. Precision among replicates for dissolved constituents in groundwater samples analyzed in the field or by the United States Geological Survey National Water Quality Laboratory.
- 3–4. Surrogate recoveries for selected analytical methods used by the United States Geological Survey National Water Quality Laboratory.
- 3–5. Dissolved methane concentrations in groundwater samples preserved with potassium hydroxide, averaged between analytical duplicates, and analyzed by the United States Geological Survey (Reston) Chlorofluorocarbon Laboratory.
- 3–6. Dissolved methane concentrations and selected isotopic ratios in groundwater samples preserved with benzalkonium chloride and analyzed by Isotech Laboratories.
- 3–7. Dissolved strontium isotopes in groundwater samples analyzed by the United States Geological Survey Denver (Zell Peterman) Laboratory.
- 3–8. Dissolved concentrations of glycols in groundwater samples analyzed by Test America Laboratories.
- 3–9. Dissolved concentrations of selected volatile and semivolatile organic compounds in groundwater samples analyzed by the North Carolina Department of Natural Resources.

**Appendix 4** (<http://pubs.usgs.gov/ds/861/Appendix4.xlsx>)

- 4–1. Constituents that exceeded a water-quality standard.
- 4–2. Constituents having water-quality standards lower than the reporting level.
- 4–3. Constituents that did not exceed an associated water-quality standard.
- 4–4. Constituents having no water quality standard.

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